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Empirical Assessment of ATCRBS

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16. Abstract

This report discusses the operational performance of the FAA ATCRBS system, as determined from data extracted from the ARTS III digital processing system. Data was gathered from several sites including Andrews Air Force Base, (Md.), Logan International Airport (Boston, Mass.), and McCarran International Airport (Las Vegas, Nevada). Quantitative performance data, as well as discussion of the problem area and possible techniques and procedures for its solution, are provided in the areas of weak/broken targets, false targets, synchronous garble, interference, erroneous decoding, improper defruiter operation, and insufficient angular resolution. A discussion of improvements that can alleviate some of the deficiences of today's secondary radar (ATCRBS) system is included.

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EMPIRICAL ASSESSMENT OF ATCRBS

I. INTRODUCTION

A. Purpose

MIT Lincoln Laboratory has been tasked with the design and development of the Discrete Address Beacon System (DABS), which was recommended by the Air Traffic Control Advisory Committee (ATCAC) [1] as an evolutionary replacement for today's Air Traffic Control surveillance systems. That work includes the development of a plan by which gradual changes can be made to today's system to achieve the needed additional capability (an evolutionary implementation plan). While much of that planning is properly centered on future system elements which will be needed in DABS but are not now part of ATCRBS, (e.g., data link), there is also a need to determine the first few modifications that should be made to ATCRBS; conclusions in this area should be based both on consistency with the overall DABS design approach, and on the performance of the present ATCRBS. The purpose of this report is to concentrate on these first few steps in the evolutionary process, to evaluate the present situation of the cooperative portion of the surveillance system (ATCRBS), and to propose some possible first steps to be taken in the direction of the final goal (DABS) which are, at the same time, responsive to the problems inherent in ATCRBS today.

B. Scope

This report discusses and analyzes a somewhat limited amount of data drawn primarily from FAA ARTS III terminal radar beacon display systems. Data from five sites has been examined manually at Lincoln Laboratory; although no automated data reduction processes have been developed here to date, approximately two hundred minutes of data drawn directly from ARTS III processors is available and has been examined; roughly one fourth of this has been analyzed in detail. Thus, the foundation of new data* upon which the bulk of this report is based is small.

In addition, a search for similar data collected and analyzed by others has yielded useful material in several areas which is generally consistent with what was observed in our data.

It is interesting to note that in several areas, the relatively small volume of new data which will be discussed reveals several facts that are not widely recognized, and permit examination of the mechanisms behind the problems in far greater detail than has been seen in the past in most other reports. This is because the relatively recent installation of ARTS III has made the task of gathering highly detailed and precise data quite simple; previously, special planning and instrumentation were necessary, including wideband video recording, scope photography, and use of special decoders. With ARTS III, reply-by-reply data can be obtained from any ARTS III site through simple and straightforward procedures; this data contains information about almost all important performance aspects of the system except direct

*Throughout this report, the term "our data" will be used to connote the data gathered and analyzed by the authors, and presented for the first time in this report.

measurement of RF link power levels (and even those can be inferred from the data). It appears that the existence of these ARTS III "extractor procedures" will soon make available much data on the performance of ATCRBS in large terminal areas which has been hitherto unavailable or prohibitively expensive to obtain. This report is one of the first few to capitalize on that fact.

This report discusses, and in most cases, presents numerical data on most ATCRBS problems which are either recognized today as being severe or will become severe in the next ten years, with increased traffic density. These include problems associated with weak and broken targets, false targets (ghosts), synchronous garble, angular resolution, improper defruiter operation, improper sidelobe suppression, improper decoding, fruit and interference, split targets, and azimuth measurement inaccuracy. It discusses the relative importance of each, and the probable operational impact of each on the future system. Finally, it proposes a number of improvements , all consistent with the long-range goal of DABS implementation, which can reduce the severity of some of the problems that are analyzed.

II. THE DATA

This section discusses the data which was gathered and analyzed in this report, its quality, its quantity, and its relevance. Several independent sources of data were used, including ARTS III derived data, gathered and analyzed both by Lincoln Laboratory ("our data"), and by the MITRE Corporation [2]. Also employed, but to a lesser extent due to its less precise and less complete nature was data gathered in several other recent programs [3, 4, 5].

Since ATCRBS suffers from a variety of difficulties, it became apparent while studying the data that the most reasonable procedure for that analysis was to examine the data associated with one particular problem at a time. Analysis, discussion, and conclusions are organized in that form in Section III of this report.

It has become evident during the course of examination of data that the amount of specific conclusions and results that can be gleaned from any set of data is certainly not directly proportional to the amount of time and effort that went into its collection. Indeed, the data which shed most light on the overall problems of ATCRBS, their general mechanisms, their consequences, and their overall operational importance was gathered with very little difficulty. Conversely, several large, expensive data collection programs conducted in the past have yielded little data of use to a study of this sort.

It appears that the proper place for highly-planned, highly-instrumented test programs is in the detailed analysis of a particular problem, once it has been determined (by a study such as this) to be a problem of severity worthy of the expense involved, and once its fundamental mechanism is sufficiently well understood to allow the proper detailed test planning. We hope that one of the results of this study will be the planning and conduct of several detailed measurement programs, each responsive to a particular problem area, as set forth in this report.

The data which was by far most useful for the purposes of this report was derived almost exclusively from ARTS III tapes and involved only targets of opportunity. No special test aircraft or special ground equipment was employed in the gathering of this data. Analysis was primarily manual; a substantial amount of additional conclusions could result from automation of the data reduction process in the future.

A. ARTS III Data

1. Our Data

The new ARTS III derived data discussed in this report was obtained primarily from three operational sites: Boston, Mass., Las Vegas, Nev., and Andrews AFB, Maryland (the ARTS III equipment associated with the Andrews ASR is actually located at Washington National Airport, approximately eight nmi away. Radar and beacon video are fed to the ARTS III installation via a radar microwave link (RML)). Andrews data was derived from a magnetic tape gathered under a different task; that task was performed also by MIT Lincoln Laboratory, and comprised a study of the relative performance of various airborne antenna configurations.

The antenna switching study concentrated on one aircraft at a time, with a discrete Mode 3/A code, and employed on the first pass a data reduction procedure which filtered replies by Mode 3/A code; many hours of test flight time were logged. Since the ARTS III extractor routine itself is not capable of filtering data on the basis of reply code, it was necessary for that experiment to record on tape all replies from all aircraft. Thus, many tapes were gathered. (Typically, a tape will hold from fifteen to fifty minutes of data including individual replies, target reports, tracks, timing, and display symbology data, depending on the traffic density, and the type of tape drive employed.)

One of the Andrews tapes, recorded during a busy period, was analyzed in detail for this report. For that purpose, no filtering on code was employed. Figure 1 is a sample of that data, showing the type of information included. All replies (defruited) from all aircraft were printed out and analyzed over several hundred scans. Certain particular portions of the data were selected at random or by some other means and analyzed in greater detail for specific studies; specific selection procedures will be described later. During the period examined approximately sixty-five aircraft were present.

Another useful form in which the data could be presented was the CALCOMP plot. Examples of such plots for several aircraft categories (sorted on the basis of reply codes) are shown in Figures 2a, b, and c. These plots were especially useful in detecting missed target reports, and correlating these with various geometrical parameters.

Several similar tapes were obtained from the Boston ARTS III installation under varying conditions; some of these were made with the defruiter switched out. The total number of aircraft observed at Boston was lower, and their distribution in space was quite different. Several phenomena such as bad

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REPLY/REPORT	CODE	ALTITUDE	RANGE	AZIMUTH (deg)	(ACP)	X	Y	GMT (hr/min/sec)	GARBLE FLAG	SPI	CODE VALIDITY	ALT VALIDITY	HITS RECEIVED	POSSIBLE HITS (incl. modec)	HIT PATTERN
A	0200	----	28.6875	278.35	3167			1/48/31							
A	2100	----	32.0000	278.35	3167			1/48/31							
C		29.0	32.0000	278.61	3170			1/48/31							
A	1100	----	26.8125	278.79	3172			1/48/31							
A	2100	----	32.0000	278.79	3172			1/48/31							
A	1200	----	22.6250	279.05	3175 •			1/48/31							
A	1100	----	26.7500	279.05	3175			1/48/31							
A	2100	----	32.0625	279.05	3175			1/48/31							
C		0.0	22.6875	279.32	3178 •			1/48/31							
C		29.0	32.0625	279.32	3178			1/48/31							
A	1200	----	22.6250	279.49	3180 •			1/48/31	G						
A	1100	----	26.8125	279.49	3180			1/48/31							
A	2100	----	32.0625	279.49	3180			1/48/31							
A	1200	----	22.6250	279.76	3183 •			1/48/31	G						
A	1100	----	26.8125	279.76	3183			1/48/31							
A	2100	----	32.0625	279.76	3183			1/48/31							
C		0.0	22.6250	280.02	3186 •			1/48/31							
C		29.0	32.0625	280.02	3186			1/48/31							
A	1200	----	22.6250	280.20	3188 •			1/48/31							
A	1100	----	26.8125	280.20	3188			1/48/31							
A	2100	----	32.0000	280.20	3188			1/48/31							
A	1200	----	22.6250	280.46	3191 •			1/48/31	G						
A	1100	----	26.8125	280.46	3191			1/48/31							
A	2100	----	32.0625	280.46	3191			1/48/31							
C		0.0	22.6250	280.72	3194 •			1/48/31							
C		29.0	32.0625	280.72	3194			1/48/31							
A	1200	----	22.6250	280.90	3196 •			1/48/31							
A	1100	----	26.8125	280.90	3196			1/48/31							
A	1200	----	22.6250	281.16	3199			1/48/31	G						
A	1200	----	22.6875	281.16	3199 •			1/48/31	G						
A	1100	----	26.8125	281.16	3199			1/48/31							
A	0200	----	28.3750	281.16	3199			1/48/31							
C		0.0	22.6250	281.43	3202 •			1/48/31	G						
A	1200	----	22.6250	281.60	3204 •			1/48/31							
A	1100	----	26.8125	281.60	3204			1/48/31							
TGT	2100	29.0	32.0625	278.61	3170	32.299	68.802	1/48/31			3	3	18	20	A AA AACAACAACAACAAC
A	1200	----	22.6250	281.87	3207 •			1/48/31							
C		0.0	22.6250	282.13	3210 •			1/48/31							
A	1200	----	22.6250	282.30	3212 •			1/48/31							
A	0200	----	28.3750	282.30	3212			1/48/31							
A	1200	----	22.6250	282.57	3215 •			1/48/31							
C		0.0	22.6875	282.83	3218 •			1/48/31							
TGT	1100	----	26.8125	279.67	3182	37.568	68.503	1/48/31			3	0	12	18	A AA AA AA AA AA A
TGT	1200	----	22.6875	280.99	3197 ←	41.728	68.324	1/48/31			3	0	17	17	ACAACAACAACAACAAC
A	1200	----	30.8125	283.97	3231			1/48/31							
C		0.0	30.7500	284.24	3234			1/48/31							
A	1200	----	30.7500	284.50	3237			1/48/31							
A	1200	----	30.7500	284.77	3240			1/48/31							
C		0.0	30.7500	284.94	3242			1/48/31	G						
C		0.0	30.8125	284.94	3242			1/48/31	G						

VALIDITY 0 ⇒ NO CONFIDENCE
1 ⇒ SOME CONFIDENCE
2 ⇒ MORE CONFIDENCE
3 ⇒ CERTAINTY

X,Y IN NMI; ORIGIN OF RADAR (R=0) AT ⟨64,64⟩

A,C IN COLUMN 1 ARE REPLIES

TGT INDICATES A TARGET DECLARATION

REPLIES MARKED • RESULTED IN DECLARATION MARKED ←

Fig. 1. Typical Data From ARTS III Extractor.

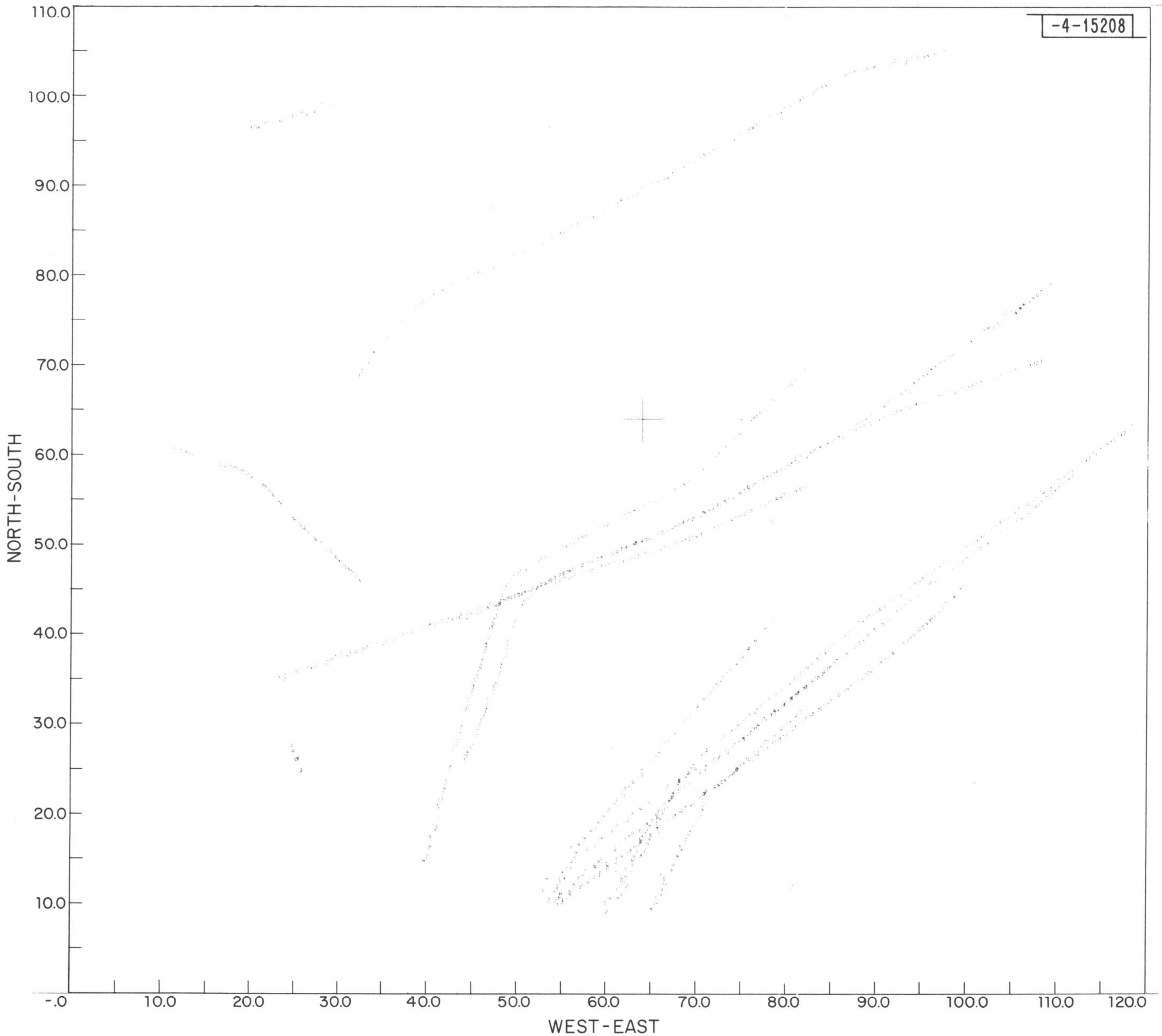


Fig. 2a. Typical Aircraft Tracks IFR Aircraft in the PCA.

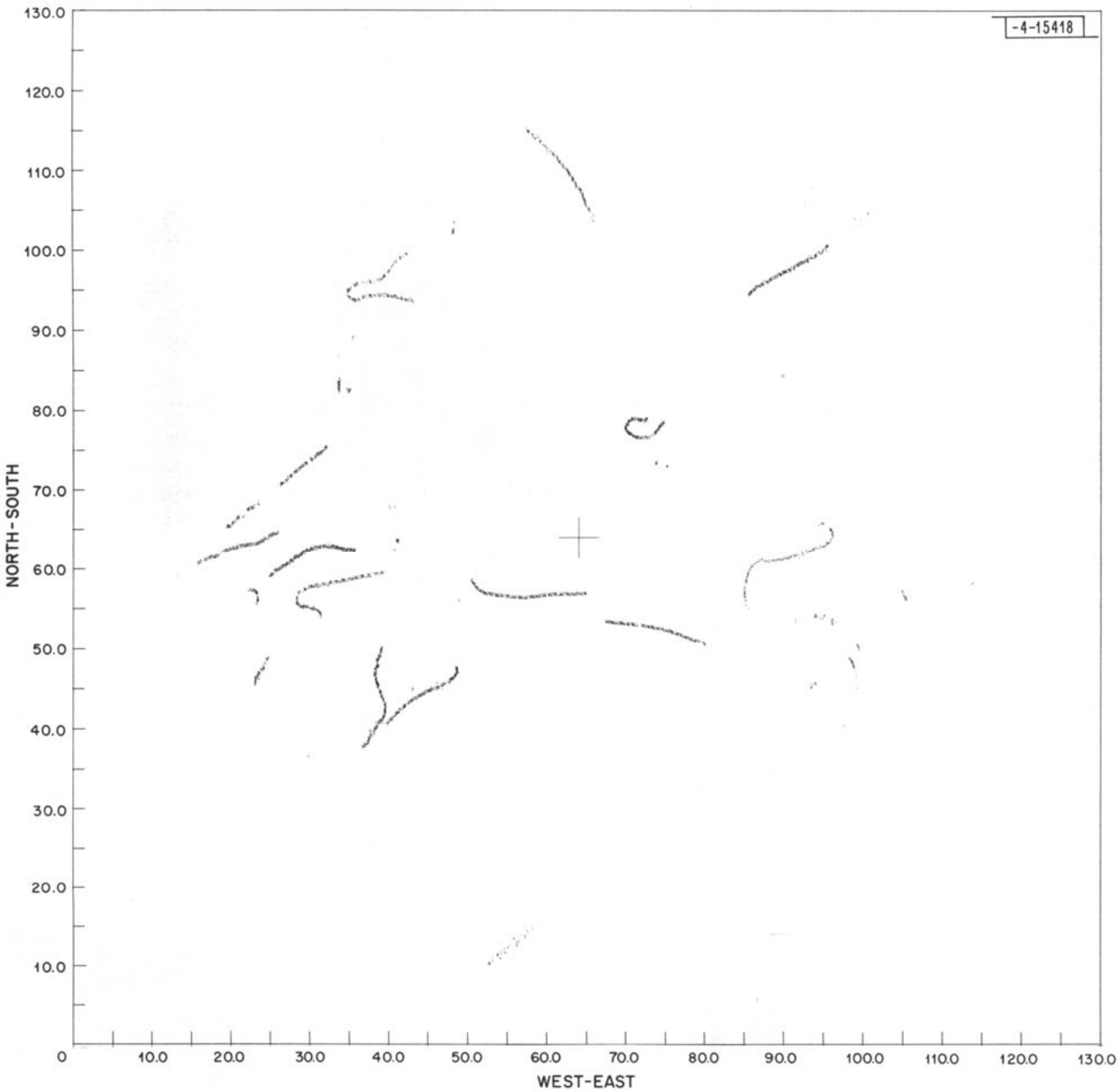


Fig. 2b. Typical Aircraft Tracks VFR Aircraft.

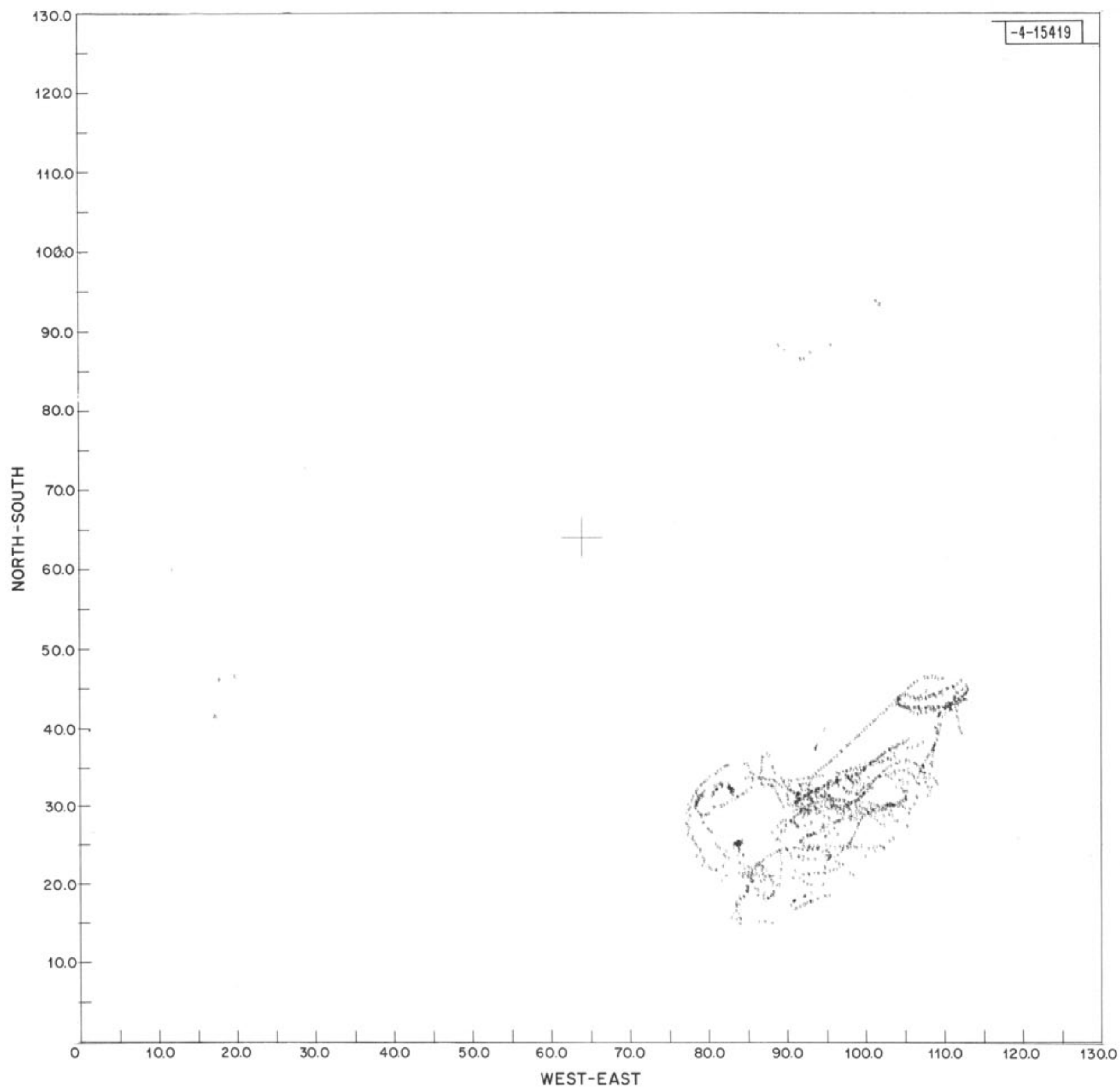


Fig. 2c. Typical Aircraft Tracks Military Aircraft.

decodes and a peculiar false target mechanism, were frequently observed in the Boston data, and were not present at Andrews; conversely, other effects including a more conventional but quite severe false-target mechanism were noted in the Andrews data. The facts that the two sites exhibited different performance in some areas and similar performance in others, and that the differences correlated well with differences in site parameters, confirmed the original notion that data from more than one site should be examined.

Both the Andrews and Boston data were examined for false targets; in spite of the limited quantity of input data, many false-target producing mechanisms were found. It is noteworthy that the limited study performed in this area appears to pursue the false target problem in greater detail than other reports to date; again, this is because ARTS III derived data is of sufficient precision and quality to allow such detailed study.

During the course of the study, it was noted that severe, and somewhat peculiar, false target problems were associated with the McCarran International Airport (Las Vegas, Nev.) ASR. Accordingly, two tapes were obtained from that site, and the mechanism behind the problems was analyzed. False target analyses similar to those performed on the Andrews AFB data were also performed for other selected sites, and appeared generally consistant.

Examination of the performance of the ARTS III decoding system under conditions of synchronous garble was also possible with the data gathered. The number of aircraft present in the Washington data led to a sufficiently large number of synchronous garble occurrences to allow statistically sound conclusions to be drawn.

Andrews AFB and Boston employ two different types of defruiter; Boston uses a digital defruiter, type MX-8757/UPX, recently developed for the U.S. Navy; the defruiter at Andrews is of the more traditional storage-tube type. This difference was easily recognizable in the performance data; spots on the storage-tube face were accountable for more erroneous decoding errors in the Andrews data than all other mechanisms combined.

As noted, the data reveals only which codes were decoded on each sweep, and at what range they were received. No direct measure of RF signal level nor video waveform was available. It was necessary (and surprisingly straightforward) to infer conclusions about those from such observed data as run length, decoding quality, and so forth.

2. MITRE Data

In connection with its long-term activities in the ARTS III project, the MITRE Corporation (Washington Operations) has performed a study [2] of the beacon environment, based on ARTS III derived data. The most thorough presentation and analysis to date, the study report concentrates on gross performance parameters, such as long-term fruit rates, round reliability levels, and so forth; it appears to have required a substantial amount of automated data reduction. Thus, to a fairly large extent it complements the new data presented in this report, which focuses more on those problems suited to microscopic rather than macroscopic analysis.

The MITRE study examined six parameters in detail: target angular width, fruit, reply probability, ARTS-III parameter assignments (e.g., the number of replies needed for declaration of valid target), code error rate, and beacon target population. Under the "fruit" category are included all unwanted interfering replies, including false targets and ring-around.

Regarding angular width, the MITRE study determined the probability distribution of this parameter, based on several scans of Newark and Chicago data. It noted that while gross statistics of this sort are valuable, study of the scan-to-scan correlation of angular width (or equivalently, runlength) was of considerable importance in determining digitizer design, especially when turning or marginally powered aircraft were involved. No data of this sort was presented in the report.

Total fruit levels were measured directly by MITRE, and found to be surprisingly low (e.g., a peak of 528 fruit per scan at Newark, with an average of 87 targets per scan). This is somewhat surprising, but consistent with the anticipated results of the Beacon Management Team (BMT)-sponsored power reduction and SLS installation programs. The MITRE study considered the role of the defruiter in ARTS III in the light of this finding, and suggested that its removal be considered at some sites, due to the performance degradations it imposes on the system in terms of shorter runlengths, azimuthal accuracy, reduced round reliabilities, and so forth. This is consistent with what was observed in our Boston data.

The effects of high asynchronous fruit levels on system performance when a defruiter is employed were considered in the MITRE study, especially with regard to decoding performance, as well as the effects of imperfect defruiter operation. In both cases, conslusions were in close agreement with our data.

The areas of sidelobe replies (ring-around), reflections, and second-time-around targets were covered somewhat superficially, in the MITRE study, on a probabilistic basis. Analysis of our data reveals that these mechanisms are quite deterministic, and these areas are amenable to detailed examination.

Detection probabilities, code error probabilities, azimuth error distributions, and similar global parameters were directly measured and presented in detail in the MITRE report. However, such performance measures were calculated on an ensemble average basis, due to time and processing limitations, although the author recognized (and strongly recommended) that a more detailed analysis using scan-to-scan correlation was essential in order to draw any more meaningful conclusions. Our analysis was of this type; our results suggest that scan-to-scan correlation analysis is central to the entire weak target issue.

It is of interest to note that while the two studies (MITRE's and Lincoln Laboratory's) were basically in search of the same thing (i.e., a more quantitative understanding of the quality of ATCRBS operation when tied to a semi-automatic processing system), the fundamental approach taken was quite different for the two. The MITRE study made substantial use of automated data processing and reduction; Lincoln has concentrated to date on manual analysis of reply-by-reply printout. In spite of the basic difference in approach, the conclusions drawn from the two studies agree closely, and no areas of significant disagreement exist. These points will be amplified in Sections III and V of this report.

B. Other Data

A study [3] of the New York City area beacon system performance was conducted jointly in 1968 by FAA and the U.S. Air Force. This study reported significant numbers of missed replies and lost targets, as well as other phenomena, but insufficient control made it impossible to determine uniquely the causes of these phenomena. Vertical lobing was suspected in some cases; blockage due to buildings and hills was suspected in others. Both hypotheses are reasonable, but neither can be proved with the data available.

In addition, several false targets were noted in the New York study. The mechanism responsible for these was well-understood, and the locations of the reflecting surfaces were determined; these correlated well with known building locations. This direction has been pursued further with our data, and is discussed in Section III-B.

Several other studies by FAA [6, 7], dealing with specific problems (and their fixes) at particular sites were also examined. To the extent that their conclusions can be generalized, they agree well with the conclusions reached in this report and in the MITRE report.

Several recent flight tests have been conducted by MITRE to determine the details of the uplink environment, and fruit rates on the downlink. These contained many results that were in agreement with the MITRE and Lincoln results, although the results were somewhat questionable in some areas, due to faulty equipment.*

C. General Discussion

It is apparent that in many areas the ATCRBS performance data which was gathered and discussed in the referenced studies and this one are quite consistent. While various approaches were employed, the results were in most cases similar. In some areas, these do not agree with previously held notions (e.g., fruit rates were unexpectedly low, reply probabilities were surprisingly high). This is due partly to the fact that ATCRBS is continuously evolving, and the implementation of several directives of the Beacon Management Team has changed the system environment considerably, and partly to the fact that simply too little actual operational environmental data has been readily available prior to the deployment of ARTS III.

*Notably an I^2SLS interrogation counter which sensed P_3 to determine the interrogation mode. Since P_3 is not present in an ISLS interrogation, not many interrogations were measured.

Although many ATCRBS performance models exist, and are generally internally consistent with one another, these generally suffer from the same problems as past predictions, since they are of necessity based on many assumptions, and, in many cases, insufficient raw data. With the likely rapid increase in the amount of actual empirical information made possible by ARTS III in the terminal environment, of which this report is but a precursor, sufficient raw data should become available to allow proper calibration of these models to the present-day situation, so they yield results consistent with today's observed performance. When this has been accomplished, these models will serve as valuable tools in predicting future system performance.

The reader will note that little attention has been paid in this report to the performances of the en route system. This is for several reasons: 1) reply-by-reply data is not readily available in that system since radars are sited remotely from ARTCC's, and this information gets reduced to a single target declaration per scan at the radar prior to transmission to the ARTCC, 2) the semi-automated en route system (NAS - Stage A) equivalent to ARTS III is not yet operational to the extent of ARTS III, and 3) the en route environment appears in many ways less demanding to the surveillance system than the terminal. It is expected that it will be relatively simple to gather and analyze en route data, once NAS Stage A become fully operational; a limited amount of en route system performance data can be gleaned from Lincoln Laboratory report ATC-18, which includes both en route and terminal data.

III. ANALYSIS

A study of the data described in the previous section, as well as other FAA documentation (such as the results of controller surveys, Beacon System Interference Problem Subcommittee meeting minutes, etc.) has led to the following subjective listing of the ATCRBS technical problems present in the terminal as they will exist over the next decade in order of decreasing importance:

1. Weak/Lost/Broken Targets*
2. False Targets*
3. Synchronous Garble
4. Insufficient Angular Resolution
5. Improper Defruiter Operation
6. Fruit/Interference
7. Other Problems

This listing was developed in the following manner:

- a list was made of all ATCRBS problems, known and alleged
- for each, available documentation and its conclusions were listed
- similarly, performance data was listed
- conclusions drawn from analysis of original data were listed

*It will become clear in the discussions that follow that these two problems are so interrelated that they should be solved jointly. Therefore, their relative order of importance is not critical.

- prognosis was made of the likely growth (or diminution) of the problem

- more general conclusions were drawn

This entire procedure is summarized in matrix form in Table 1. (References for Table 1 are contained in Table 2.) (Table 1 pertains primarily to ARTS III performance, although in some instances its conclusions can be extended to the remainder of the terminal installations, and the en route system.)

The problem areas listed above are addressed in detail in the remainder of this section.

A. Weak/Lost/Broken Targets

1. Introduction

Whenever one talks of a system "problem," it is appropriate to spend a few words at the outset to put that problem in perspective. One look at the target declarations pouring out of the ARTS III system makes it clear that ATCRBS is "seeing" many targets. Thus, evidence of target weakness or loss is not immediately apparent. When such evidence is found, it must be considered in light of the surveillance system objectives in order to assess the seriousness. Thus, if one or two target declarations are lost when an aircraft turns, is there any real system impact if the aircraft is not being tracked? If the target is of more interest to the system, and is being tracked, does an isolated lost declaration have much impact if the tracker has difficulty following the maneuver even with perfect data continuity? If a low-altitude aircraft is lost in some azimuth sector because of obstructions in the interrogation-reply path, what are the consequences? They are perhaps slight in the context of today's semiautomated ATC system with the majority of the aircraft in question operating VFR, but are likely to be severe in the context of an IPC system providing separation assurance service to all the aircraft in sight.

Several different target weakness and loss mechanisms are apparent in our data; the following sections will focus on these one at a time, and in doing so will tend to elevate them to the rank of "problems." It should be emphasized that the extent to which these "problems" affect the performance of the system depends strongly on the extent of automation assumed, and that under many reasonable sets of assumptions, these "problems" are hardly

Table 1. Summary of ATCRBS Problems, Pertinent Data, and Impact on System Performance.

PROBLEM	CAUSE	DISCUSSED IN	DATA (Taken by Others)	M.I.T. LINCOLN LABORATORY DATA (presented in Chapter III)
Weak/Missed Targets	Marginal RF Link Power	Refs. A, C, D, F. Ref. B gives airborne parameters; Refs. A and F discuss mechanism for processing weaker targets in ARTS.	Ref. A includes runlength distributions, but no scan-to-scan correlation. Transponder power and sensitivity distributions in Ref. B. Various controllers surveys presented in Ref. J provide incidence figures.	A number of targets tracked to determine how signal strength relates to beamwidth & miss patterns. Correlations noted with blocking structure azimuths, aircraft maneuvers.
Weak/Missed Targets	Close-In Multipath (typically vertical lobing)	Ref. I and many others.	Target misses attributed to it in Ref. K.	A few aircraft tracked in elevation. Variations exist in runlength vs elevation, but are not significant. No target misses due to this phenomenon were noted.
Broken/Missed Targets	Broken due to low P_R (over interrogation)	Refs. C, D, F, G. Problem has been simulated extensively by TSC and ECAC. Numerous reports pertain.	Controller surveys, Refs. A and I, suggest it is rare. Measurements reported in Refs. G and H support this.	Several aircraft were tracked at both sites Round reliability measured high. Single breaks noted frequently; this infers that overinterrogation not the primary loss mechanism.
Broken/Missed Targets	Near-synchronous interrogations	Ref. J.	Apparently none ever reported on.	None seen.
Broken/Missed Targets	Antenna switching (military aircraft)	Refs. J and M. Many studies sponsored by USAF (AIMS/TRACALS P.O.) pertain. See Appendices to Ref. L for more references.	Alternate antenna switching configurations compared in Ref. M.	Observed occasionally in antenna tests, reported in Lincoln Lab report ATC-
Broken/Missed Targets	Poor angular resolution	Ref. A relates to other problems; Ref. N pertains to NAS.	No data noted in any reports.	Phenomenon noted. Only cause noted for failure to declare strong target. Happens rarely.
Broken/Missed Targets	Synchronous garble	Ref. E derives analytical model and discusses relationship between synchronous garble and aircraft population. Ref. A derives model.	Ref. A presents limited, statistically insufficient, data. No lost targets observed.	Not seen.
Broken/Missed Targets	Storage tube spots (defruiter)	Manuals on specific interrogators discuss the mechanism. Noted as a source of problems in Ref. K.	Ref. K suggests that several misses were due to this problem.	Seen on several occasions. Results in alternating replies. Usually reduces runlength sufficiently to cause a miss.
Azimuth Splits	Low P_R (over interrogation)	Refs. C, D, G, J. This effect is rarely noted. Ref. A discusses mechanism. Ref. D simulates.	Ref. J discusses "hotspots". Relation between them and this phenomenon unclear. Ref. A measures fruit and concludes from these measurements that this phenomenon is rare.	Not seen. Data collected implies P_R quite high. No targets missed or split due to low P_R.
Azimuth Splits	Antenna switching (serration)	Ref. I. Mechanism understood; rarely observed.	Lincoln Lab report ATC- discusses. No other good data.	Not seen in our data.
Range Splits	Poor transponder turnaround time stability	No good references noted.	None available.	Range variation at beamedges (apparently due to this mechanism) observed occasionally. No general statistics.
False Targets	Reflections	Ref. J: many Spingler reports including Ref. I. Ref. C. Observed by Lella in Ref. K.	Incidences measured, modeled, and displayed in Ref. A; mechanism apparently not well understood. Ref. K notes and discusses.	Many false targets observed. Mechanism determined conclusively and well-understood. Very high accuracy possible. Identification as a false target done with certainty in all cases.
Ringaround	Sidelobe interrogation and reply	Ref. J; many early reports. Source well understood and addressed. Recent reports show problem diminishing.	Controller surveys reported in Ref. I show problem disappearing. Ref. A measures level of incidence; concurs.	Very little observed. What was seen was for the most part in discrete bunches rather than excessive length reply sequences. Data quantity far too limited to be conclusive. Excessive runlength due to diffraction noted more freq.
False Targets	High asynchronous fruit	Discussed in Ref. A. Analysis suggests how related to fruit rate. Refs. D and F suggest problem so minimal that defruiter be removed from ARTS III input line.	Fruit level data in Ref. A. Apparently no evidence of any false target occurrence. This is consistent with fruit level data.	A small number of single replies apparently due to this mechanism noted. Consistent with low fruit estimates made by MITRE. Average less than 2 single replies per scan.
False Targets	Second-time-around replies	Refs. A, D, J. Well covered in many sources. Probabilistically modeled in Ref. A and included in analysis of Ref. C.	Incidence not found in Ref. A. No other known data. Appears to occur only at a few sites where geography and weather permit.	None observed.

Effect Discussed in Section-	FAA FIX AND ITS EFFECTIVENESS	FUTURE PROGNOSIS	CONCLUSIONS	RANK OF SEVERITY	Numerical Rank
III. A	None presently operational. Transition from manual to ARTS system tends to aggravate rather than correct this problem.	Insensitive to increases.	A serious problem, worthy of correction. Several available. Can be improved by reducing digitizer settings.	Most severe. Frequent cause of lost tracks.	1
III. A	Many mentioned, rarely implemented. Involve ground preparation, fences, etc. Problem generally not severe; fixes help.	Insensitive.	A problem, but not too serious. Amenable for the preceding problem.	Questionable if it is a general problem. Might be worthy of correction at a few field sites.	
III. A	BMT coordination program has effectively reduced overall interrogation rates to point where no longer a problem. I^2 SLS tends to counteract that trend but probably not badly.	Insensitive or will improve as more sites shut down.	Not severe, if BMT progress continues.	Not severe. BMT can control indefinitely.	
III. A	BMT-related actions (particularly PRF assignment) have apparently reduced or eliminated this effect.	Shouldn't ever be a problem.	Same.	Not severe. BMT can continue indefinitely.	
III. A	Diversity (Hartlobe) antennas under consideration. Not yet clear that problem severity warrants associated expense.	Insensitive.	Probably not severe. Pertinent report will contain more firm conclusion.	Questionable. Hartlobe will fix, but is it worth it?	
III. D	None.	Will become more severe as densities increase.	Severe. Causes complete loss of target.	Severe; will get worse.	4
III. C	None	Will become more severe as densities increase.	Not yet severe, but will perhaps become so someday.	Severe. Not as likely as bad decode due to synchronous garble. Fixes to that will fix this.	7
III. E	Digital defruiters will eliminate.	Insensitive. Will improve as more digital defruiters are procured.	Severe. More of a problem at ADW at present than any of the above, except weak RF.	Severe. Defruiter should be improved or replaced.	6
III. H	BMT activities have apparently reduced overinterrogation to point where rarely seen.	Insensitive or further improvements.	Not a problem. Will not be if BMT progress continues.	Not severe. Will not be if BMT continues.	
III. H	No fix being implemented. Not clear that one is needed in terminal area. ARTS III parameters now set to resist effect.	Insensitive.	Not a problem. Will not be.	Questionable.	
III. H	Transponder policing program should control. Not clearly worthy of solution.	Insensitive in ARTS.	Not a problem. Will not be.	Not a problem.	
III. B	Improved ISLS implemented widely. Data (plus that in Refs. C and G) strongly suggest it helps very little.	Will get worse as building continues around airports.	A severe problem; expected to get worse. No good fixes universally known.	Most severe. (Site dependent.) Will get worse.	2
III. G	ISLS implementation appears to have reduced this to where it is no longer significant. When program completed, the problem should be eliminated.	Insensitive.	Not a problem any more.	No longer serious	
III. F	BMT activities have reduced overall uplink interrogation rate, hence fruit, hence this problem. ARTS parameters are set quite high to further control.	Will perhaps become a problem someday.	Not a problem. Will probably never be.	Certainly no problem now. Will probably never be.	
III. D	Pulse staggering (2-pulse and 6-pulse) routinely incorporated into all recent I/Rs, both for this and other (radar-related) reasons.	Insensitive.	No longer a problem. Need never be.	No problem.	

Table 1. Summary of ATCRBS Problems, Pertinent Data, and Impact on System Performance (Continued).

PROBLEM	CAUSE	DISCUSSED IN	DATA (Taken by Others)	M.I.T. LINCOLN LABORATORY DATA (presented in Chapter III)
Improper Decoding	High asynchronous fruit	Thoroughly analyzed in Ref. A. Both mechanisms (additive and subtractive) considered in detail. A function of fruit level; not anticipated to be severe at present.	Fruit level data in Ref. A. No data on this phenomenon known or reported. None expected, based on analysis and reported low fruit level.	None observed. None expected, for fruit rates noted.
Improper Decoding	Synchronous garble	Cursory discussion in Ref. A. Probabilistic model for potential situation in Ref. E. Thorough analysis in UNIVAC ARTS III system description, section describing DAS operation.	Incidence measured insufficiently in Ref. A. Performance during a garbling situation has apparently never been reported on.	Usually happens and is recognized (G-flag set) whenever synchronous garble situation is present. Always very deterministic. Can be routinely corrected. Additive in nature.
Improper Decoding	Weak RF Link	Mechanism analyzed in Ref. A. Included in simulation in Refs. C and D. Well understood in a number of other reports.	Incidence measured in Ref. A. Relatively frequent (on one edge or the other of roughly 5% of the reply sequences).	Happens about as often as Ref. A. suggests. Subtractive in nature.
Improper Decoding	Bad transponder	Briefly discussed in Ref. A. Provision made for inclusion in simulation described in Ref. C.	No data available, other than limited data reported in Ref. B.	Several noted, especially in mode C.
Improper Decoding	Bad defruiter (storage-tube spots)	Discussed briefly in Ref. A. in connection with other problem this causes (loss of targets). Mechanism well-known.	No data. No reason to expect that this would be recognized as the source of problems if they were observed.	See at ADW at 6 different range intervals in mode C, 4 in mode A. Apparently a significant problem, though rarely recognized as such.
Improper Decoding	Long Δt multipath	Cursory discussion in Ref. A. Not a universal problem.	Only known data limited (Ref. J). Only occurs at a few installations that are peculiarly sited. Apparently severe at those sites.	Not seen. Site-dependent. Geometry at both sites studied in this report such that none would be anticipated.
Interference (analog channel)	Near-synchronous fruit	Ref. J mentions. Mechanism and incidence as a function of all system parameters well understood.	Controller surveys reported in Ref. J give some data. Not quantitative. Just sufficient to recognize that it can be a real problem.	Not visible in our ARTS III data.
Interference (analog channel)	High asynchronous fruit	Ref. A analyzes. Refs. C and D allow for effects. Does not occur presently with defruiters.	No data in any reports on occurrence when a defruiter is used. Ref. A suggests that the incidence is low even without a defruiter.	Not available directly from data, but by inference (if total fruit estimates are correct); probably not present.
Bad Position Data (azimuth)	High asynchronous fruit	Ref. A analyzes process of insertion of extra replies at beam edges. Speculative. Has apparently never been noted.	No data. Simulation in Refs. C and D questionable. Fruit rates presented in Ref. A suggest that it rarely occurs at present.	Analysis indicates 2-3 ACP typical rms errors in azimuth due to this mechanism, overinterrogation and defruiter action.
Bad Position Data (azimuth)	Synchronous garble	Ref. A touches upon. No good analysis, since target loss mechanism due to synchronous garble not well understood.	No data.	Not observed at all in any synchronous garble incidents. Apparently no more effect than other θ-error mechanisms, since garbled replies still usually used in beamsplitting.
Bad Position Data (azimuth)	Resolution failure	No analysis noted. Generally, this phenomenon results in failure to declare, rather than bad azimuth declaration.	No data.	Appears to occur in conjunction with missed targets due to poor resolution. Error severe.
Bad Position Data (azimuth)	Diffraction	No published discussions noted. ECAC models allow for effect.	No data.	Noted regularly when expected. Typical error on order of one degree. Affects only aircraft which are low on the horizon.
Bad Position Data (azimuth)	Over-interrogation	Analyzed in Ref. A. Simulated in Refs. C and D. Discussed in Ref. F.	Data in Ref. A; limited validity.	Not noted.
Bad Position Data (azimuth)	Defruiter	Discussed in detail in Refs. A and F.	Limited data in Ref. A.	Data exactly as expected, except many single misses noted which affect θ-accuracy. Not attributable to defruiter.
Bad Position Data (range)	Poor transponder Δt	Discussed mainly in conjunction with NAS. Not noted in ARTS III.	No data.	No significant Δt variations noted, except as mentioned above under range splits. Never more than two range bins involved. Bias errors in Δt not observable in our data.
Broken Targets	Out of specification transponder reply pulse spacing	Not discussed in any references noted, except ref. B.		Single missed replies (not due to defriuter action) occur far more frequently than do conventional missed replies. Most rational explanation of this (although not conclusive) to out-of-tolerance reply bracket (F_1-F_2) spacing, such that defruiter gate is opened but ARTS III BDAS bracket detection fails. Easily correctable by releasing bracket detection tolerance.

Effect Discussed in Section-	FAA FIX AND ITS EFFECTIVENESS	FUTURE PROGNOSIS	CONCLUSIONS	RANK OF SEVERITY	Numeri-cal Rank
III. F	BMT activity to reduce fruit has eliminated this problem.	Will get worse as fruit levels increase, due population.	Not a problem. Will probably never be. Several decoding fixes can improve.	No problem now. Not likely to become serious.	
III. C	None.	Will get worse.	Not yet a problem. Will be as traffic increases. Several fixes need evaluation.	Will become most severe. (Not a problem yet.)	3
III. A III. F	None. Σ-Δ monopulse would help, but is not used presently by FAA.	Insensitive.	A problem. Somewhat amenable to weak/missed target fixes.	Potential problem.	
III. A III. F ATC-9	Policing will correct, if properly done.	Insensitive. Will degrade if additional regulations (MOCs) not implemented.	No problem anticipated.	No problem.	
III. E	Digital defruiters will fix, and are being procured.	Insensitive; will improve as more digital defruiters used.	Most frequent cause of bad decodes presently. Can easily be fixed. Should be.	Should be corrected quickly.	5
III. C	None. Regions have attempted to fix problem themselves.	Insensitive.	A problem at a few sites. Not universal. Should be fixed.	Severe at some sites. False target fixes can help substantially.	8
III. F	BMT-related activities in PRF assignment, power reduction areas have apparently cured problem.	Insensitive or will get worse.	Not a problem. Can be handled.	No problem.	
III. F	BMT-related activity has greatly reduced fruit level to point where not observed.	Will get worse, but a long way to go.	Not a problem. Likely never will be.	No problem if defruiters left in analog line. At some sites, no problem if defruiters not left in analog line.	
III. F III. I	Same comment applies.	Same comment.	Same comment. Could become significant if IPC, etc. demand better accuracy.	No problem.	
III. C III. I	None. Probably none warranted.	Will get worse with increased density.	Could become a problem. Fixes to decode errors due to synchronous garble should help here, too.	Potential problem. Corrections closely related to those applicable to the more frequently noted problems cause by synchronous garble.	
III. D III. I	None	Same comment.	Tied closely to missed target problem, which is more severe.	Potential problem. Fix closely related to those applicable to missed targets.	
III. I	None	Insensitive except will happen more often as more building occurs.	Could become more significant if IPC, etc. demand better azimuth accuracy. Not clear that problem is significant.	Potential problem.	
III. A III. I	BMT activity to reduce PRF has cured this problem.	Insensitive.	Not the most important azimuth-error mechanism; nor will it be.	Minor problem.	
III. F III. I	None. Present policy aggravates rather than cures. Tradeoff taken in this manner to minimize interference effects. Appropriate at some sites, not at others.	Insensitive.	Will limit azimuth accuracy as other problems are corrected.	Potential problem.	
III. H III. I	Policing policy will control, if set up properly.	Insensitive	As above, only an order of magnitude less severe. Bias errors, which probably predominate, do not affect velocity estimation.	Minor problem.	
	None	Easily corrected	Should be corrected.	Minor problem.	

Table 2. References For Table 1.

A. J.E. Freeman, "A Survey of the Beacon Environment in the Terminal Area, TOS23A," Report WP-8753, MITRE Corp. (21 June 1972).

B. G.V. Colby and E.A. Crocker, "Final Report -Transponder Test Program," Project Report ATC-9, Lincoln Laboratory, M.I.T. (12 April 1972).

C. S. Jone, "Evaluation of ATCRBS Performance in an Interference Environment," Report MTR-6239, MITRE Corp. (4 August 1972).

D. J.E. Freedman and K. Levin, "ARTS III Detection and Tracking Performance as a Function of Degraded Beacon Environments," Report MTR-6245, MITRE Corp. (5 September 1972).

E. S. Jones, "An Estimate of Synchronous Garble Probabilities in ATCRBS," Report MTR-6160, MITRE Corp. (13 March 1972).

F. J. Freedman, K. Levin and M. Niccolai, "ARTS III Engineering Performance Assessment - Interim Test Report; TOS #38," Report MTR-6075, MITRE Corp. (3 January 1972).

G. G. Glatfelter, W. Goldberg, R. Rubin, I. Smith, "ATCRBS Measurement Program-Final Report," (New York Area), Report MTR-2334, MITRE Corp. (24 March 1972).

H. C. Cook, I. Smith, "DABS Channel Loading Measurement Program-Task 1, Final Report," Report MTR-2459, MITRE Corp, (13 September 1972).

I. G. Spingler, "Experimentation and Analysis of ATCRBS Siting Criteria," NAFEC Report (September 1969).

J. Minutes of the Meetings of the Beacon System Interference Problem Subgroup, DOD/FAA, J. Herrmann, Chairman. (Various dates, 1968 to present.)

K. R.L. Lella, "Evaluation of the 1968 FAA/DOD Beacon Flight Test in New York," FAA Report FAA-RD-70-60, Airborne Instruments Laboratory (September 1970).

L. Report of the DOT Air Traffic Control Advisory Committee (December 1969).

M. J. Blazej, "Dual Input Transponder Study," NAFEC Report.

N. "C40: Final Report on System Errors Related to Separation Standards for NAS Stage A, Model 1 (TOS 19)," Report MTR-4417, MITRE Corp. (8 April 1970).

worthy of the title. For example, in today's en route system, the problem of weak targets is not especially severe, since the majority of participating aircraft are well above the horizon, and employ powerful and sensitive transponders. In a new situation such as IPC, however, their solution could be critical to the success of programs to achieve higher levels of automation.

We consider broken targets separately from weak and lost targets at the outset.

2. Broken Targets

The classical mechanism alleged to result in breakup of target reply sequences is overinterrogation. As is well known, the ATCRBS transponder suppresses, or becomes insensitive to interrogations, for on the order of 30 μsec following reply to what it perceives as a valid mainbeam interrogation. The rationale is to render the transponder insensitive to possible reflected interrogations arriving a short time later (as well as to prevent spurious replies due to leak-through from transponder transmit to receive stages). In addition, if the interrogator and transponder are ISLS (interrogation sidelobe suppression) equipped, the transponder will not reply to what it perceives as a sidelobe interrogation, and will similarly suppress for approximately 30 μsec whenever it receives one. This eliminates sidelobe replies, which appear in their worst form as "ringaround," and also mitigates against responses to reflected interrogations. So-called "improved" ISLS (I^2SLS) (discussed in detail in the following section on the False Target Problem) takes a further step in attempting to deal with reflections in the situation where the sidelobes of the I/R antenna are too low to result in a detectable P1 signal at the aircraft; when that occurs, only the P2 pulse is sensed, and the transponder is unsuppressed when a reflected interrogation arrives. In "improved" ISLS, the interrogator antenna sidelobe levels are raised artificially during P1 transmission by routing RF energy to the SLS omni-antenna as well as through the directional antenna, thus ensuring that the transponder is in suppression before a reflected interrogation can arrive. The proper P1-P2 ratio must be maintained to assure proper sidelobe suppression performance. From the viewpoint of neighboring interrogators, the effect of "improved" ISLS is to create a hemisphere around the "improved" interrogator, in which it suppresses all transponders once every interrogation (several hundred times per second).

What is being traded for these improvements in reflection and sidelobe performance is an increase in the possibility that a transponder will be suppressed when a valid mainlobe interrogation arrives, resulting in a break in the response sequence seen for this aircraft. Our data indicates that the trade is a good one. Reply probability in the Andrews AFB vicinity is high enough to make other causes of reply sequence breakup predominate.

Reply sequences from eight aircraft squawking 2100, flying in the PCA, at around 30,000 ft altitude were analyzed in detail. These are strong targets; that is, for each aircraft scan, replies are received over a large number of sweeps. A median of 20 is typical for these targets which corresponds at Andrews to a beamwidth of 4.7°. Since these sequences were all strong, it was possible to analyze breakup by examining their internal structure; this served to isolate breakup from weakness. Their high altitude exposed these aircraft to a number of interrogators. It is estimated that at least two dozen were active and in view. While it is conceivable that a low-flying aircraft within SLS range of a few interrogators could be subject to more suppression than these higher altitude aircraft which were probably beyond the ISLS range of all interrogators, we did not observe significantly more breakage in other portions of our data, which could be attributed to this mechanism.

The data analysis proceeded as follows. Each aircraft was tracked over about 50 scans. We note at the outset that a target declaration occurred for every aircraft on every scan (eight aircraft, 434 declarations). Thus breaks in the reply sequence never resulted in a detection failure for these strong targets. Each reply sequence was corrected for defruiter operation and the number of single, double, triple, and higher-order missed mode A and C returns were tabulated. Because of the 2:1 mode interlace and separate mode A and C defruiters, the mode A and C reply sequences were considered separately. An example appears in Figure 3. Since the appearance of a reply implies that the previous reply of the same mode had to be present in order to open the defruiter gate, we can reconstruct which missing replies had to be present in the ATCRBS receiver output.

The statistics we gathered can be related to various reply loss mechanisms through largely deterministic reasoning; however, in a few cases some intuitive guesswork is necessary; this does not affect the results appreciably. Table 3 presents the results, which are discussed below. The total number of sweeps on which the RF link was established was 8768. This is measured by replacing the leading mode A and C returns which had been removed by the defruiter, and summing the resultant target reply sequences over all 434 aircraft scans. If there were no defruiter operating and no breaks occurred in the reply sequences for any reason, the total number of replies seen at the BDAS output would have been 8768. The number actually observed

18-4-15337

```
  A _ A A C _ A C _ _ _ A A _ A _ C _ A C   ORIGINAL SEQUENCE
A A C A A C A A C   A   A A C A   C A A C   CORRECTED FOR
                                             DEFRUITER ACTION

      A A A _ A _ _ A A A _ _ A             ORIGINAL A SEQUENCE
      C C _ _ C C                           ORIGINAL C SEQUENCE

    A A A A A A _ A A A A _ A A             CORRECTED A SEQUENCE
    C C C _ C C C                           CORRECTED C SEQUENCE
```

```
              REPLIES LIST:
                  1  LEADING A
                  1  LEADING C
                  1  SINGLE A
                  2  DOUBLE A's
                  1  DOUBLE C
                  9  REPLIES MISSING
                 12  HITS
                ____
TARGET WIDTH     21  REPLIES
```

Fig. 3. Example of Reply Sequences.

Table 3. Target Reply Statistics - Eight IFR Aircraft in the PCA.

Aircraft:	8	
Aircraft scans:	434	
Total sweeps:	8768	
Total replies received:	7261	
Total replies missing	1507	(17.2%)

Missing Reply Analysis:

Leading As and Cs due defruiter	868	(9.9%)
Single missing As and Cs (not attributable to defruiter)	299	(3.4%)
Misses due to suppressions	160	(1.8%)
Associated misses due to defruiter action	160	(1.8%)
Remainder (see text)	20	
Classical Round Reliability	98.2%	

was 7261; thus the gross probability of missing a reply at the BDAS output was 17.2%. Of the 1507 missed replies, 868 were leading mode A and mode C replies removed by defruiter action; this accounted for 9.9% out of the total 17.2% missing replies. Of the remainder, 299 missed replies were single misses, surrounded by proper replies of the same mode, representing 3.4% out of the total 17.2%. Had these replies been missing at the defruiter input, this would have resulted in elimination of the following replies, due to defruiter action. Since this was not observed in the case of these 299 missed replies, they must have passed the defruiter properly, and were probably eliminated within the ARTS III DAS. Although no definite conclusions can be drawn from out data regarding why these replies were lost, the most plausible explanation is that they failed DAS bracket detection because they were slightly out of tolerance with regard to F_1-F_2 spacing. Since the DAS is a sampled-data system, slight consistent departures from nominal standards would result in a probabilistic reply loss mechanism, consistent with what was observed.

The notion that these single replies were lost due to bracket pulse spacing inaccuracy is supported by the observation that certain aircraft displayed this phenomenon more often than others. One aircraft (not one of those considered in the previous discussion) had reply sequences which were particularly badly broken; this aircraft was observed over 50 scans in the Boston data; a summary of its missed reply statistics appears in Figure 4. From this data it appears that the reply loss mechanism was a cascade of two mechanisms, the conventional transponder suppression mechanism (responsible for some of the double misses), and the mechanism leading to single misses discussed above. In this case, the probability of a missed

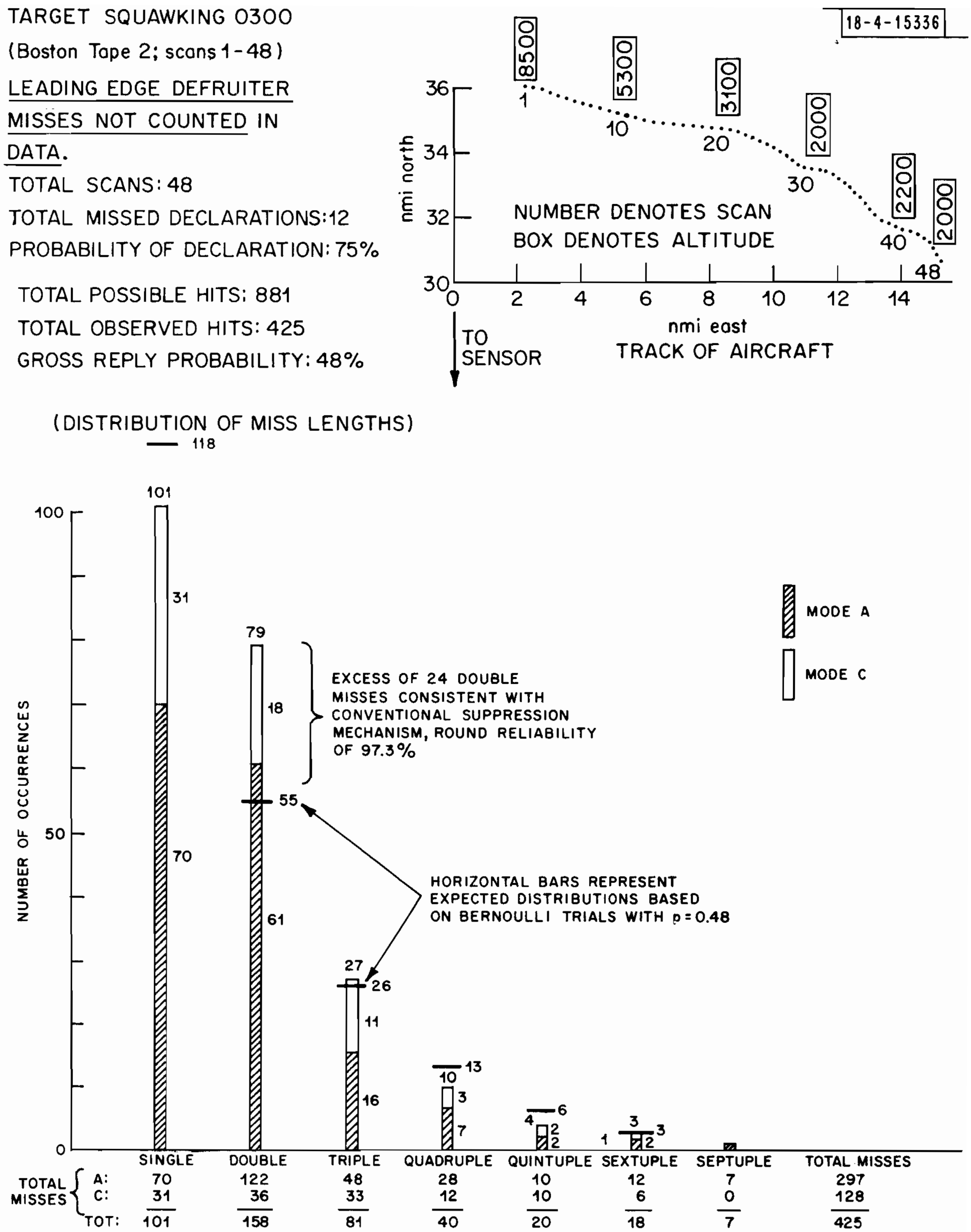


Fig. 4. An Especially Low Reply Probability Situation.

reply at the DAS output due to the latter mechanism was about 50%. The relative frequency of longer miss sequences suggests that this probability was statistically independent from sweep to sweep. Indeed, the miss-length distribution data follows almost exactly what one would expect from a series of Bernoulli trails (coin tosses). This again supports the notion that misses were caused by out-of-specification brackets which, depending upon the relationship between arrival time and sampling times, passed or failed bracket detection on a purely probabilistic basis. The DAS input sampling timebase is not synchronized with range at present; thus one would expect the bracket detection acceptance process to be statistically independent from sweep to sweep.

Returning to the Andrews data of Table 3, an additional 320 misses occurred in pairs; all of these were assumed* to be due to the conventional transponder suppression mechanism; half were not transmitted by the transponder (1.8% of the total number of replies). The remaining half were eliminated by defruiter action. Thus the conventional round reliability observed with these eight IFR aircraft in the PCA was 100-1.8 = 98.2%.

The remaining twenty missed replies occurred in sequences of three or more; whenever these were observed, it was assumed that the first two replies comprised a double miss, due to the conventional transponder suppression mechanism and defruiter action, and that the remainder were due to the mechanism responsible for the single misses. The double misses were

*Actually, some of these could have resulted from two sequential occurrences of the single loss mechanism. From its statistics, approximately ten such occurrences would be expected. However, all were counted as being due to transponder suppression.

included in the round reliability figures calculated above; addition of the remaining twenty misses to those in the single miss category raises the percentage of missed replies due to this mechanism to 3.6% of the total. Thus, it appears that some mechanism other than transponder suppression was responsible for as many missed replies in our data as were the combined mechanisms of transponder suppression and defruiter action on the following replies.

Our conclusions regarding broken reply sequences are as follows:

(a) The gross probability of a missing reply can approach one in five.

(b) For strong targets, this reply sequence breakage has essentially no effect on detectability or code validation.

(c) Most of the missing replies occur at the beginning of the reply sequence, and are due to defruiter action.

(d) Significant numbers of replies are lost in the DAS. A possible way to recoup these is to loosen up the tolerance required on bracket pulse spacing.

(e) The round reliability corresponding to transponder suppression is high, over 98.2% in our data. Defruiter action inside the reply sequences reduces this to 96.4%.

(f) For weak targets, breaking can make the difference between proper detection and target declaration failure. Improvements would result from modifications to target declaration parameters, and elimination of the defruiter from the ARTS III input line. The latter step would be feasible at those sites if fruit levels are low enough to allow defruiting by adjustment of parameters without simultaneously overloading the computer with spurious fruit-generated records.

3. Weak/Lost Targets

Weak and, in the extreme, lost targets come about through various mechanisms which attenuate the RF link power to the point where the number of replies received is inadequate to pass the various thresholds applied in the target declaration process. A gross descriptor of target strength is the so-called "target width," which is the angular extent over which replies are recieved on a particular scan. The width behavior of a target, exemplified not only by its distribution function, but also by its temporal behavior or scan-to-scan correlation, is affected by a number of mechanisms. Among those alleged to be significant are vertical lobing in the I/R antenna pattern due to multipath, airborne antenna shielding due to aircraft maneuvers, and blockage of the RF path by natural or man-made structures. We will present below some general data on target widths, and follow this with more detailed discussion pertinent to these three mechanisms.

a. Target widths

The most global form of presentation of target width data is a distribution or density function collected over an ensemble of aircraft of different types flying in various regimes at various locations and altitudes in the field of the sensor. Freedman [2] presented such data, reproduced as our **Figure** 5. He recognized that a great deal is hidden in this presentation. The data of Figure 5 correspond to a large number of aircraft sampled a small number of

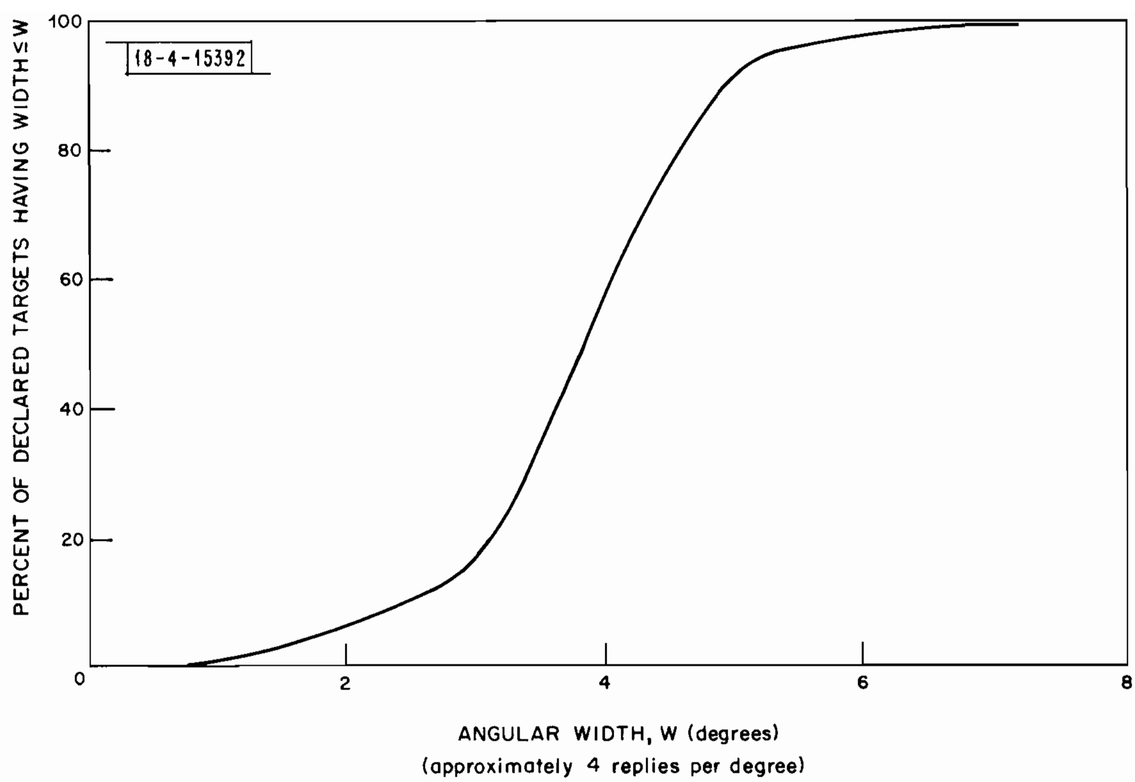


Fig. 5. Cumulative Probability Distribution of Runlengths.

times. Our data is derived from a smaller number of aircraft sampled a large number of times. This allows the more detailed examinations of the following sections.

Figure 6 shows the target width distribution corresponding to the eight aircraft flying straight and level in the PCA near 30, 000 ft altitude (squawking 2100) which were discussed in the previous section. As noted there, each aircraft was sampled over about 50 consecutive scans (over three minutes of flight times), and the target widths have been corrected for the leading mode A and C replies eliminated by the defruiter. The median width is about 20 sweeps or 4.7°. Not surprisingly, these aircraft, flying well up in the coverage volume, straight and level, minimally affected by obstructions, and with sensitive transponders, are considerably stronger than the "average" target of Figure 5.

At the opposite end of the spectrum, Figure 7 shows width distributions for a pair of lower flying aircraft (VFR flights somewhere below 10, 000 ft, squawking 1200) in an azimuth sector where blockage due to obstructions near the I/R is significant. These data are not corrected for defruiter action, which introduces a negative bias of between one and two sweeps, or between $1/4^{\circ}$ and $1/2^{\circ}$. No replies at all were received on more than half the scans. Whether many of the scans containing no replies actually contained one or two replies eliminated by the defruiter is a point of interest which we will return to later. One target went undeclared on 92 of 110 scans, while the other went undeclared on 92 of 138 scans.

Figure 8 is intended to show that not only can a particular target look drastically different from a composite "average" target, but furthermore,

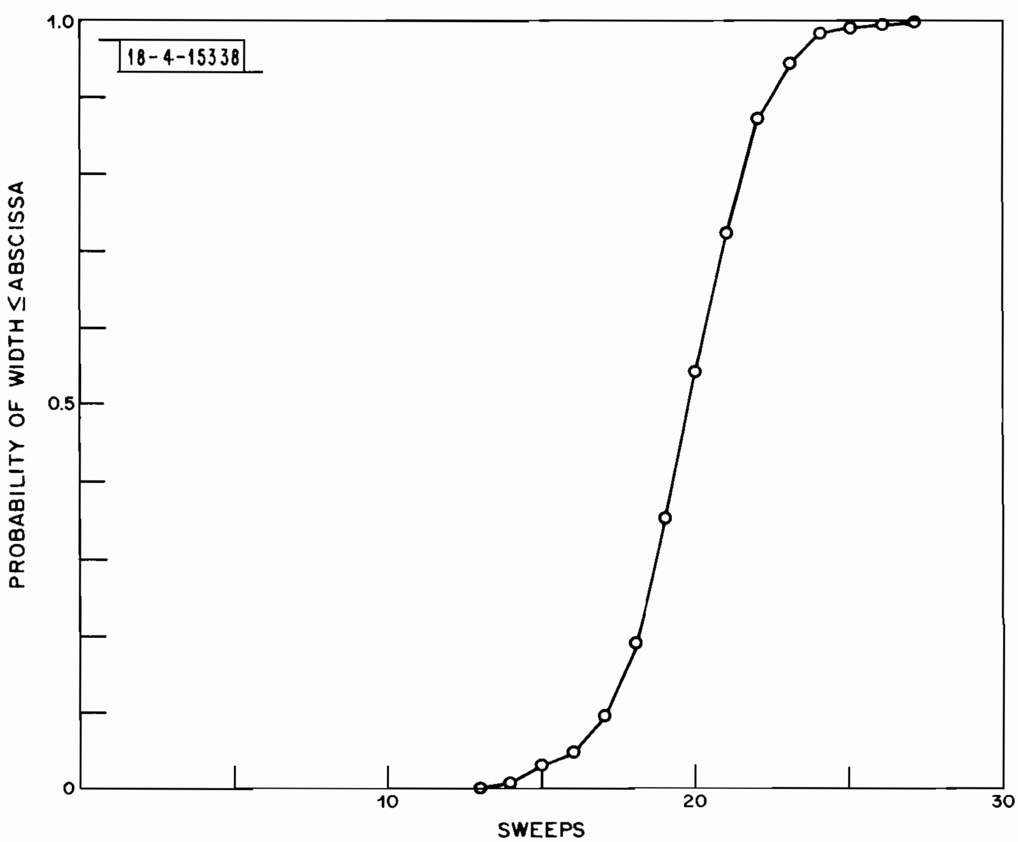


Fig. 6. Gross Runlength Statistics - IFR Aircraft in the PCA.

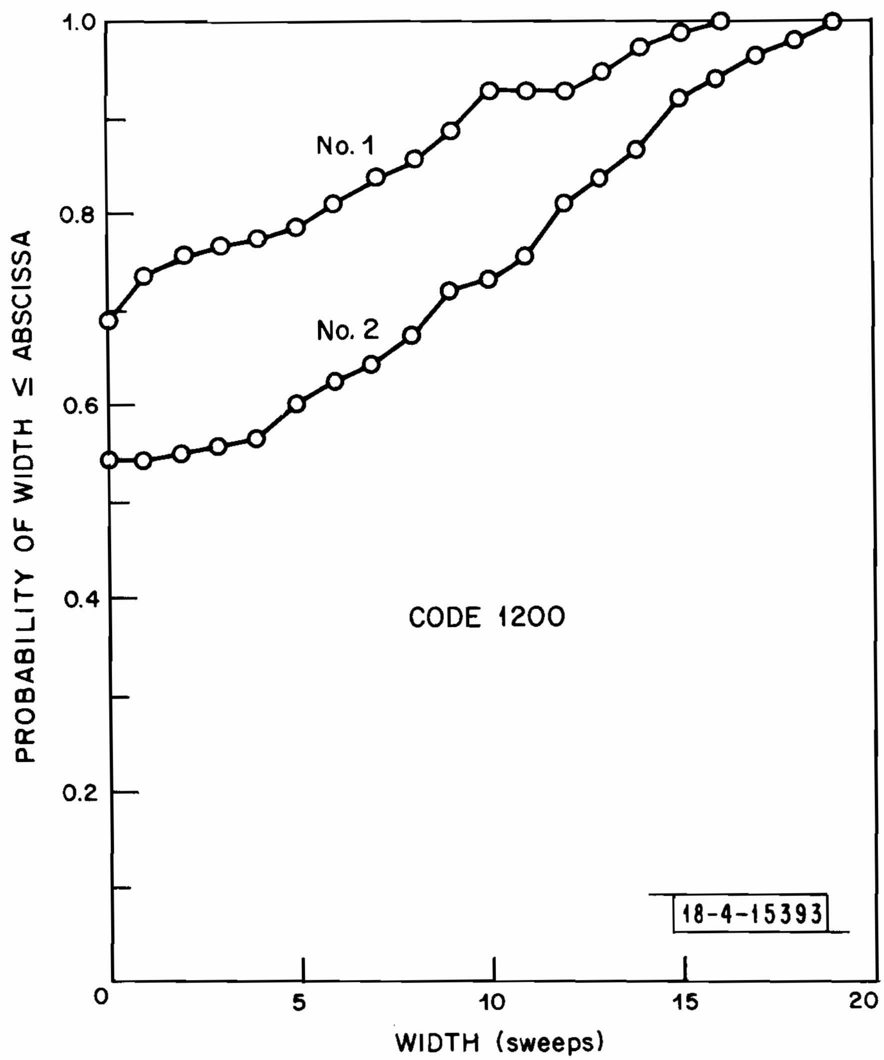


Fig. 7. Runlength Statistics For a Pair of VFR Aircraft.

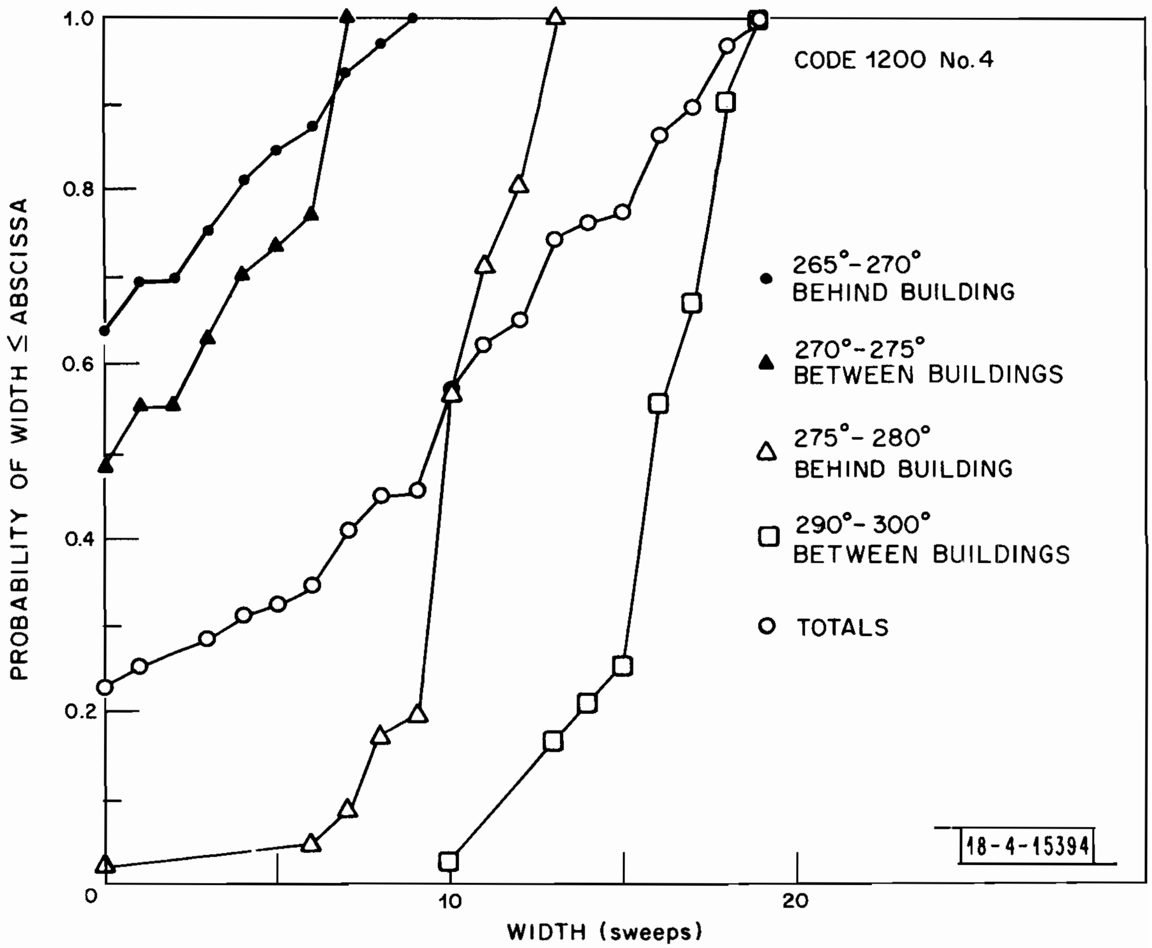


Fig. 8. Runlength Statistics - A Single VFR Aircraft at Various Locations.

its appearance can change significantly if examined at different times. Segments 1 and 3 each represent approximately 5° azimuth sectors in which the RF path was subject to significant blockage due to obstructions on the ground. Segment 2 represents a gap between obstructions about 5° wide, and segment 4 represents a similar gap about 10° wide. We see that over a few minutes a target can vary from almost invisible to quite solid and back again. The corresponding composite distribution encompasses these extremes with no indication of the correlations involved.

Figure 9 indicates the effect of altitude on target width. The aircraft depicted in this figure (another VFR squawking 1200) flew across the same band of azimuths as the first target of Figure 7 and at greater range; yet, it appears considerably stronger. It went undeclared on only 20 out of 127 scans. Thus, target width is a function of target location in three-dimensional space.

When targets are clear of obstructions, the effects of maneuvers on target strength are of interest. Figure 10 presents data for another VFR target flying a sequence of loops about 30 nmi from the I/R. During three distinct segments, the aircraft was banked away from the I/R, yet, in terms of total statistics, the effect of this on target width was not great. This target went undeclared on only nine out of 154 scans. Figure 11 presents similar data for another aircraft flying a multiple-looped pattern about 24 nmi from the I/R. While examination of the width sequence of the previous aircraft revealed definite correlation with aircraft attitude consistent with a belly-mounted antenna, the data for the aircraft of Figure 11 did not exhibit any noticeable correlation with attitude. This difference is discernible in the lower tails of the two distributions, and the related fact that the latter target was declared on every one of 220 scans.

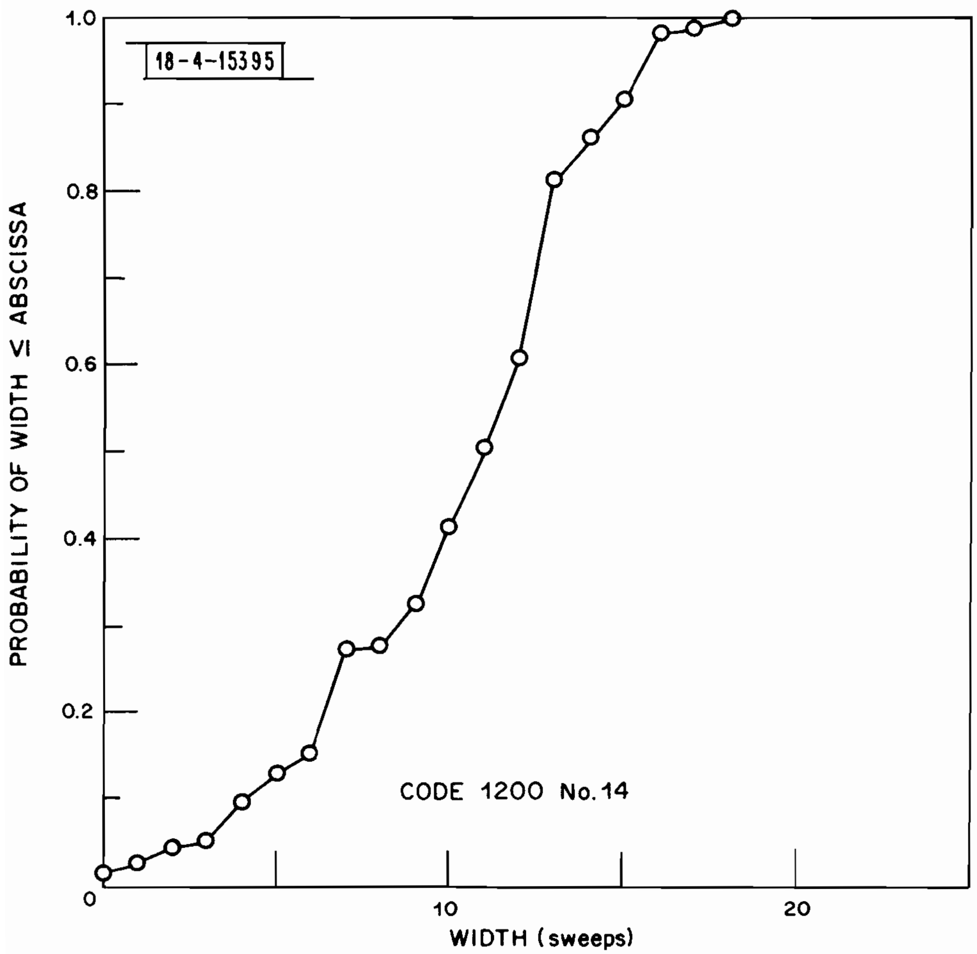


Fig. 9. Runlength Statistics - Higher Altitude Aircraft.

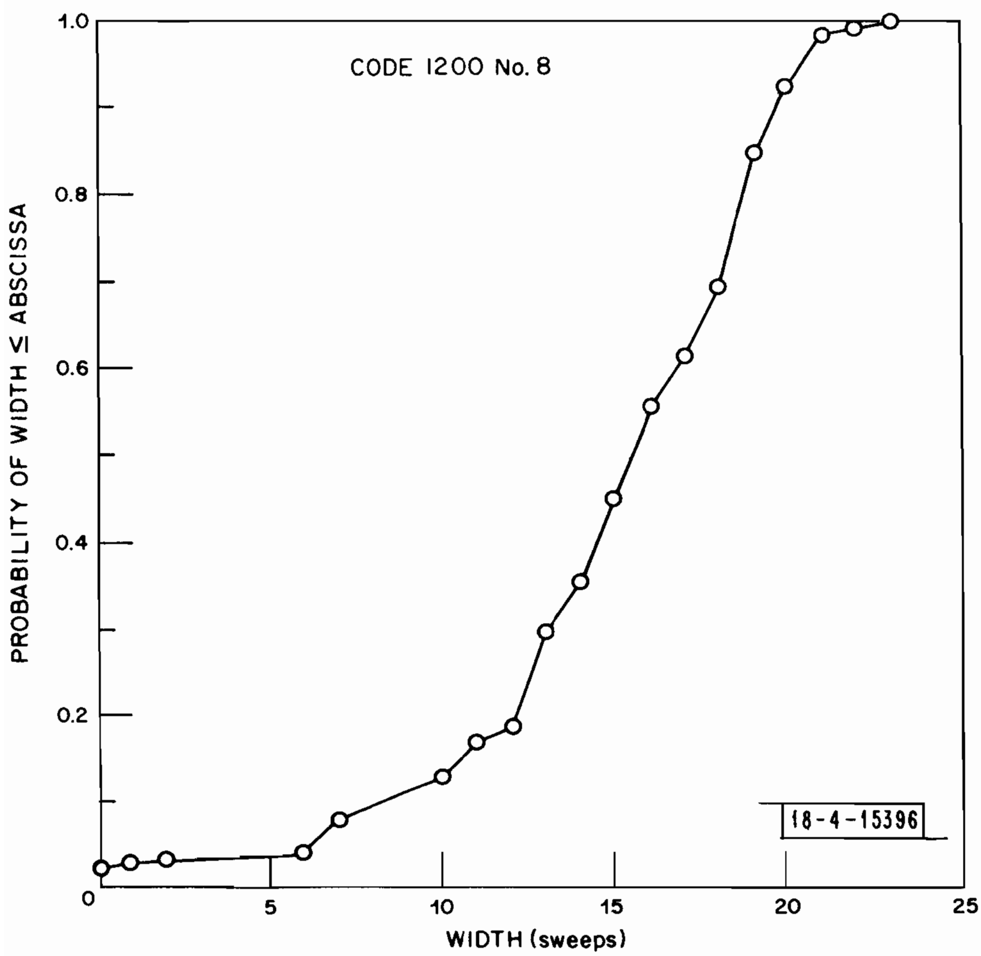


Fig. 10. Runlength Statistics - VFR Target at 30 nmi.

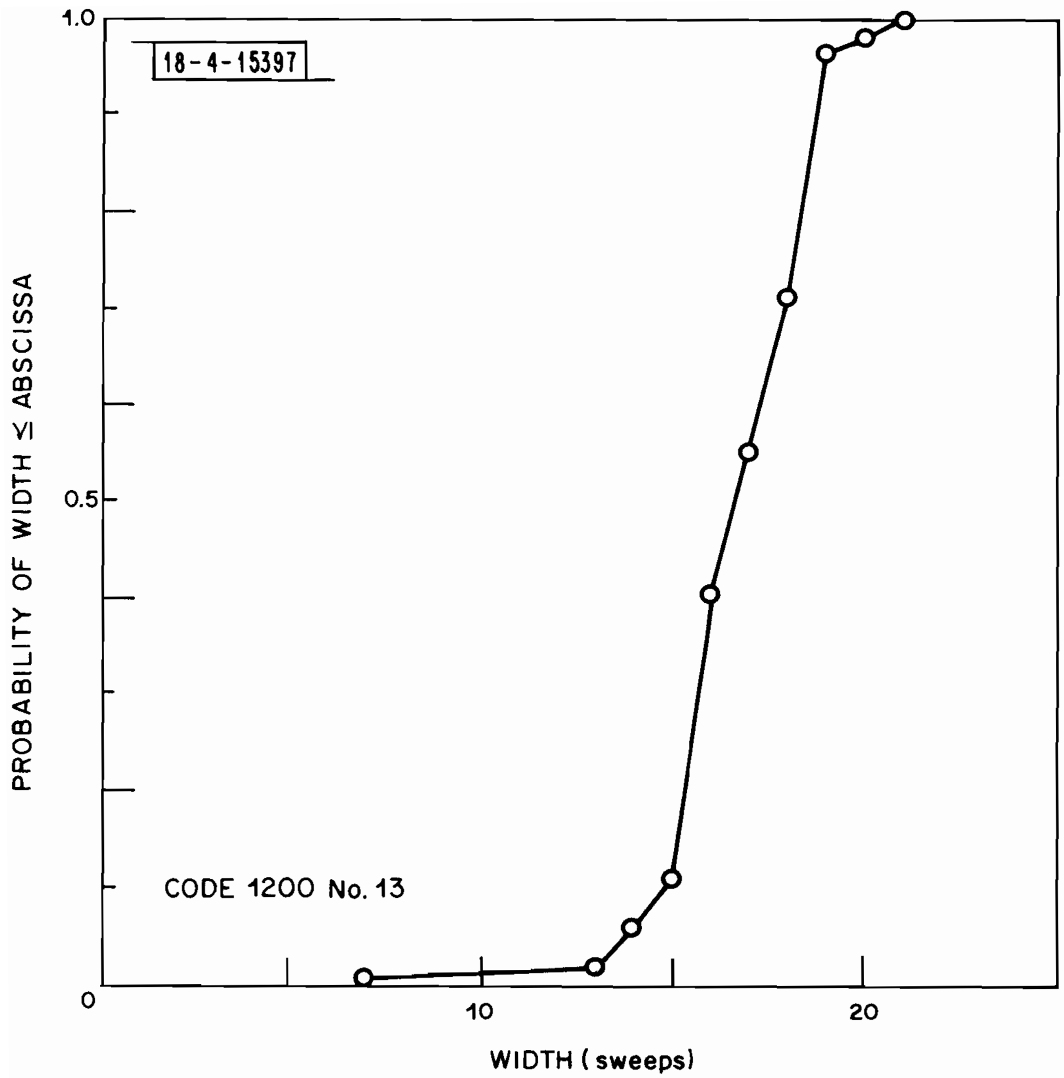


Fig. 11. Runlength Statistics - VFR Aircraft at 24 nmi.

Figure 12 presents data for a single aircraft during two flight segments separated by about four minutes. The first segment consisted of essentially straight and level flight except for one abrupt change of direction which did not occupy more than a few out of 77 scans. The second segment consisted of a complicated pattern (somewhat pretzel-shaped) centered about 43 miles from the I/R, such that the aircraft was essentially "in maneuver" for the entire 110 scans. Declaration failed only one time in each segment, and the median target width is virtually identical for the two segments. Again, for these data samples, the effect of maneuver on total statistics (or equivalently overall target weakness) is small.

To summarize, we have presented above a variety of target width data from the Andrews data base. We have illustrated that, relative to a global norm, targets exhibit a wide range of width behavior. This range is characterized by dependence on flight regime, including target location, altitude, and attitude, and includes significant variations not only of distributions or first-order statistics, but also of scan-to-scan correlation or time dependence. A global distribution akin to Figure 5, lumping all this data together, has not been computed, since we feel it has no great significance. Clearly, it is formed as a weighted average of smaller distributions, with the weights depending on such things as the weather (relative fraction of VFR traffic), time of day (relative fraction of IFR traffic on approach or departure with respect to hub airports), etc. We would expect such a distribution to exhibit a good deal of variability, even at a given site, but to shed little light on the issues of why the variability occurs, and how its effects can be compensated. In the sections below, we expand on some of the mechanisms noted above.

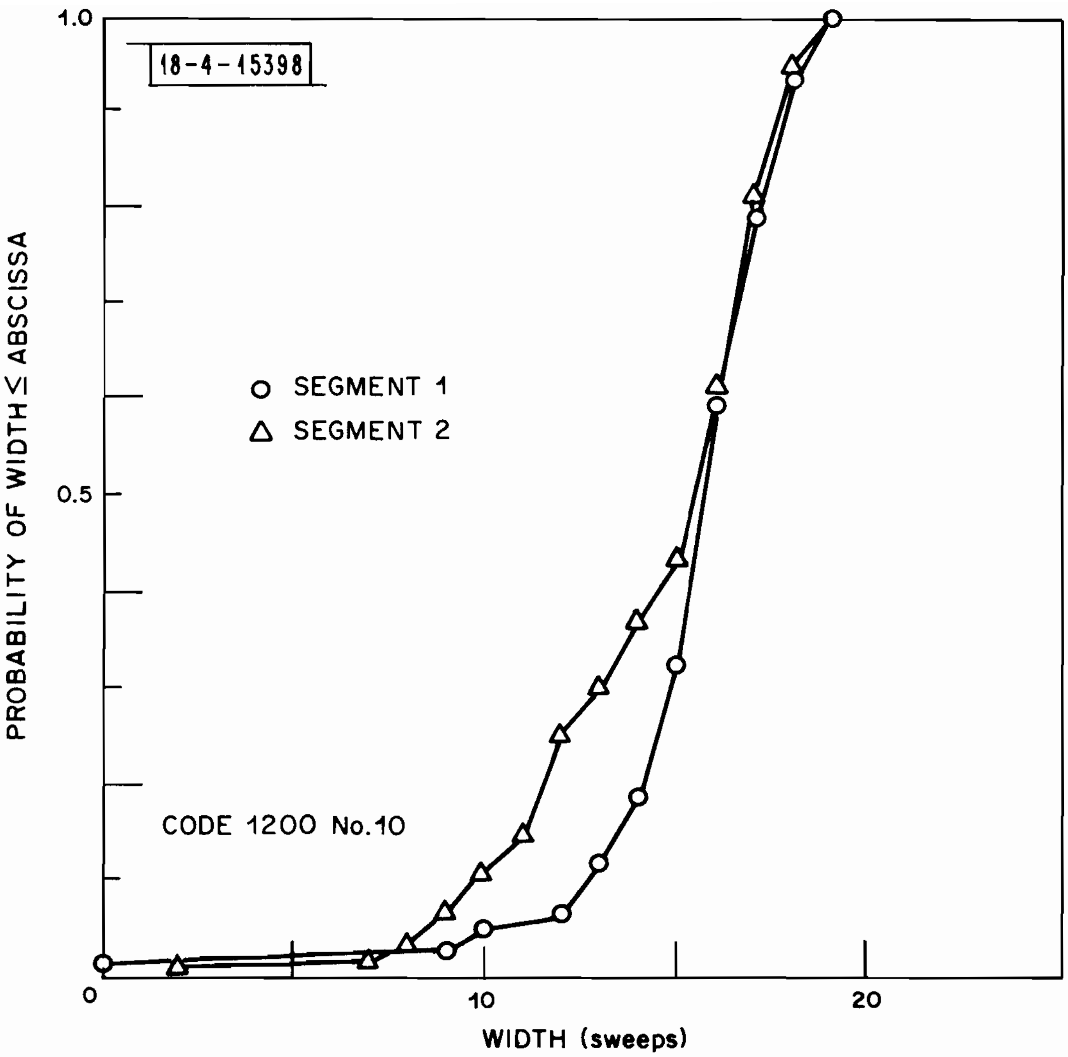


Fig. 12. Runlength Statistics - VFR Aircraft Changing Heading.

b. Effect of ground-based obstructions

In the previous section, we have presented statistical data on target width or strength, and have alluded to mechanisms responsible for the variations seen. We present examples, in this and the following sections, which indicate that there is a basis for connecting target width statistics with different mechanisms. It is important to avoid wishful thinking in this area, by searching for "patterns" in the data which are not really there. At the other extreme, if one is too insistent on perfect agreement between the data and an oversimplified model of a mechanism, the result will be to reject any "explanation" of the data. This leads to a default conclusion that all the variation seen is "random," which just is not the conclusion that one arrives at upon working with the data base.

In Figure 13 we present data from several aircraft pertaining to the mechanism of RF link obstruction by ground-based obstacles. This is an x-y plot of target declarations as a function of time. The aircraft generally have different epochs; that is, they pass through a given azimuth at different times. The correlations between azimuth and declaration failure are striking. As the figure shows, it is possible for aircraft traversing these sectors to experience no failure in target declaration. This does not mean that these targets experience no width fluctuations, but rather that they are not severe enough to depress the targets below the detection thresholds. Although the data does not permit definite conclusions, we suspect that these differences are due to altitude differences. (None of the aircraft were mode-C equipped.) It would be valuable to gather more data of this sort, using an aircraft equipped with an encoding altimeter. The blockages in the sector south of east and

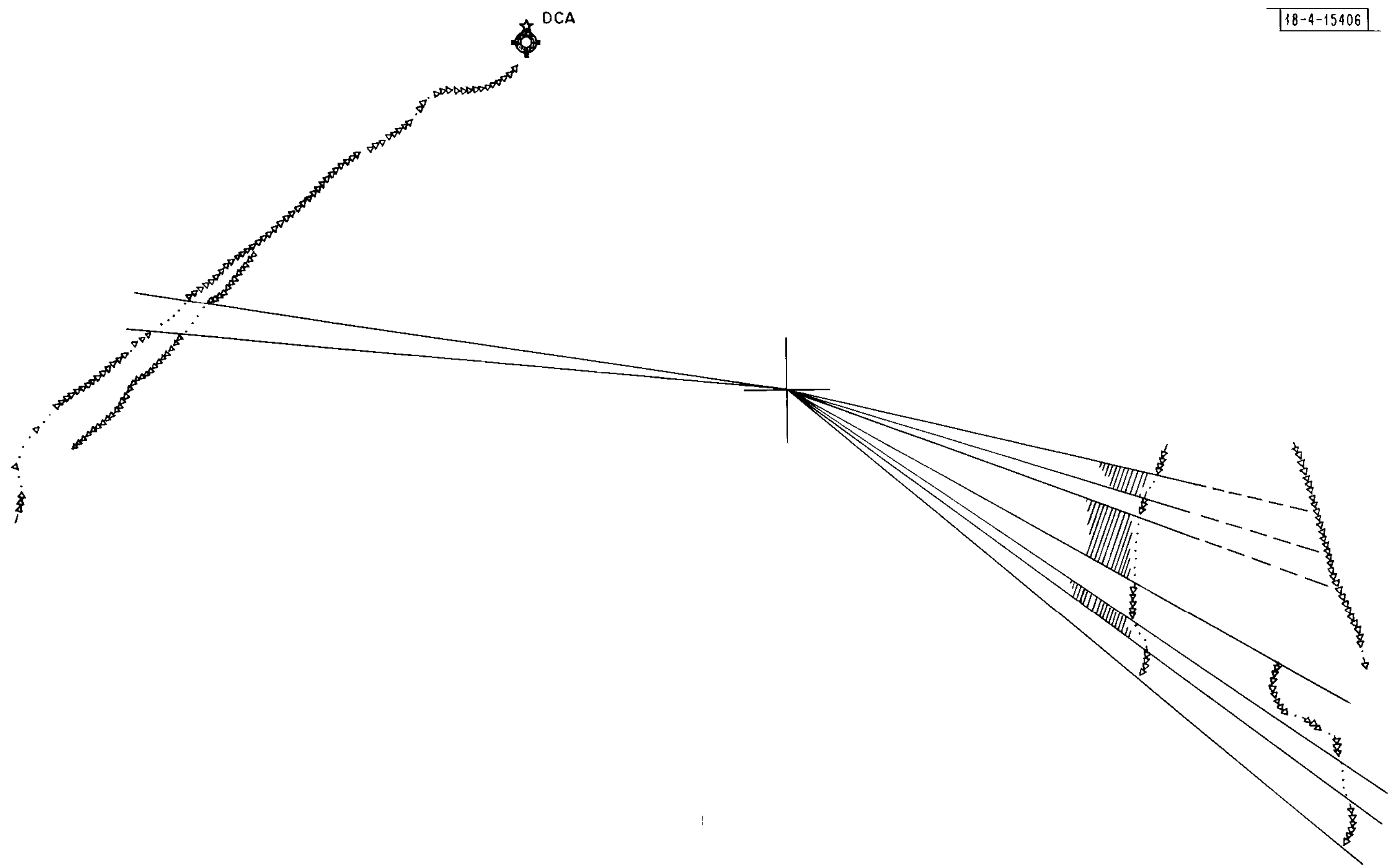


Fig. 13. Target Tracks - Obstruction.

and approximately due west correlated well with the complexes of buildings in these sections (see Figure 29). The effects of these buildings are detectable in less severe form in a number of other data samples. These include not only low-altitude VFR (code 1200) aircraft, but also IFR aircraft climbing to altitude after departure from DCA (presumably of more interest to the current semiautomatic ATC system). Boston data suggests that blockage is more likely to affect targets of interest to the current ATC system than is the case at Andrews. The problem is, of course, coupled to the false target problem, discussed in Section III. B. If the interrogator power level must be set to burn through obstructions, false targets due to reflections are bound to increase. There is also hope that the solutions can be coupled. If false targets could be eliminated in the system software, it would be possible to reduce system thresholds and improve the weak and lost target performance. Data on this point will be presented further below.

c. Effect of aircraft maneuvers

Another potential mechanism for target weakness or loss is obstruction of the airborne antenna by some part of the aircraft, such as a wing or tail section. In our data base, we see evidence that such blockage does occur, but that it does not represent a cause of sustained target weakness or loss. Our approach was to examine a number of VFR aircraft which can often be found exhibiting complicated maneuvers resulting in multiple-looped or pretzel-shaped paths (Figure 14). Our first observation is that one sees essentially the complete flight path in each case; the simple model in which antenna pattern cutoff is assumed everywhere above the aircraft horizon certainly does not appear to apply in this case. It can be seen by examining

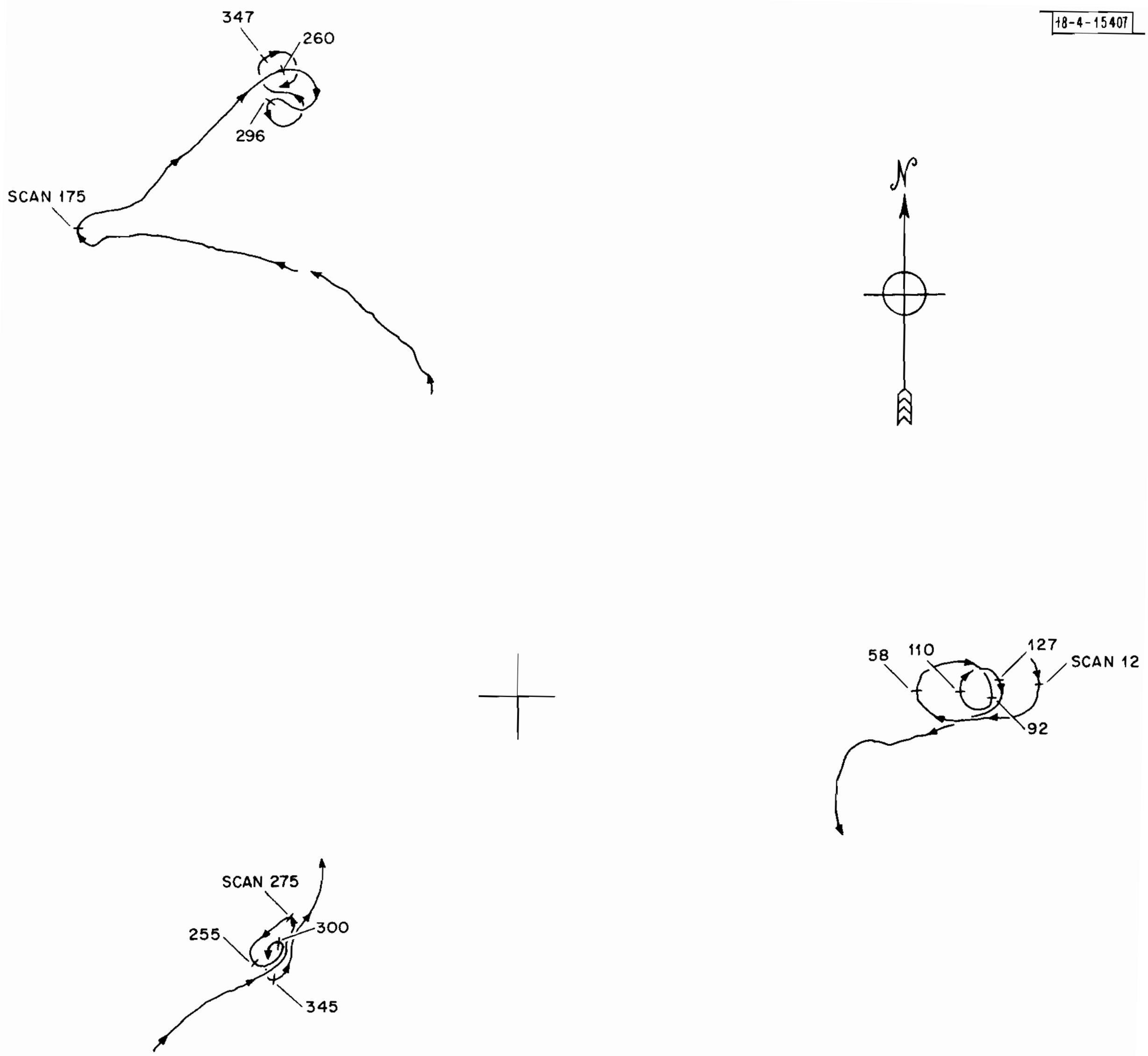


Fig. 14. Target Tracks - Maneuvering.

Figure 15 that evidence of blockage correlated with the maneuver does occur in some cases. This figure presents the target width history of the aircraft flying east of the I/R, in Figure 14. The data are consistent with a belly-mounted antenna and show that lost declarations do indeed occur which correlate with location along the trajectory. Note that the last fade is deeper and lasts longer than those preceding. This is consistent with the fact that the radius of the last loop is tighter, which would suggest that the bank angle is steeper.

Figure 16 shows the width history for the aircraft flying the "pretzel" pattern slightly west of north. The occurrence of the sharp right hairpin turn is clearly apparent near scan 175. The top of the first (clockwise) loop is marked by a milder fade near scan 260. The aircraft apparently continues its right bank through the bottom of the loop, then straightens and banks left sharply as it enters the tight counterclockwise loop, resulting in the fade near scan 296. The path continues counterclockwise around the bottom of the "pretzel" and the aircraft banks left and heads back up in a northwesterly direction, accounting for the fade near scan 330. It then levels out and banks right to enter the clockwise loop at the top of the "pretzel," resulting in the strong fade near scan 347. The target width then recovers up to scan 365, after which it becomes erratic, as the (descending) aircraft drops below the coverage and lands. Again, in this case, there is definite correlation with the maneuver, but little impact on target loss. Only two declarations were missed in about 250 scans, and this aircraft was maneuvering about 43 miles from the interrogator at low altitude.

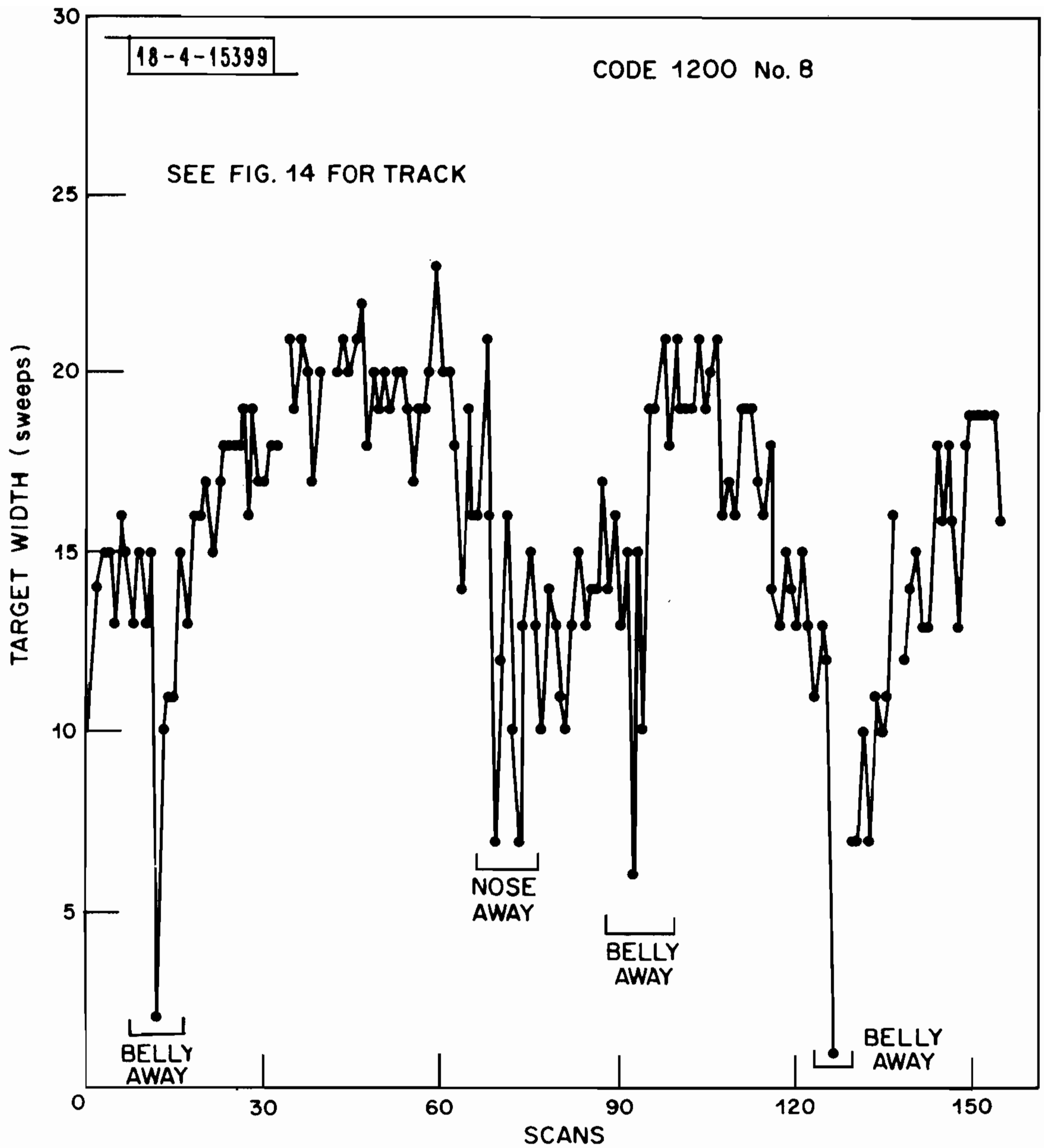


Fig. 15. Variation in Runlength Due to Maneuvering - VFR Aricraft to East.

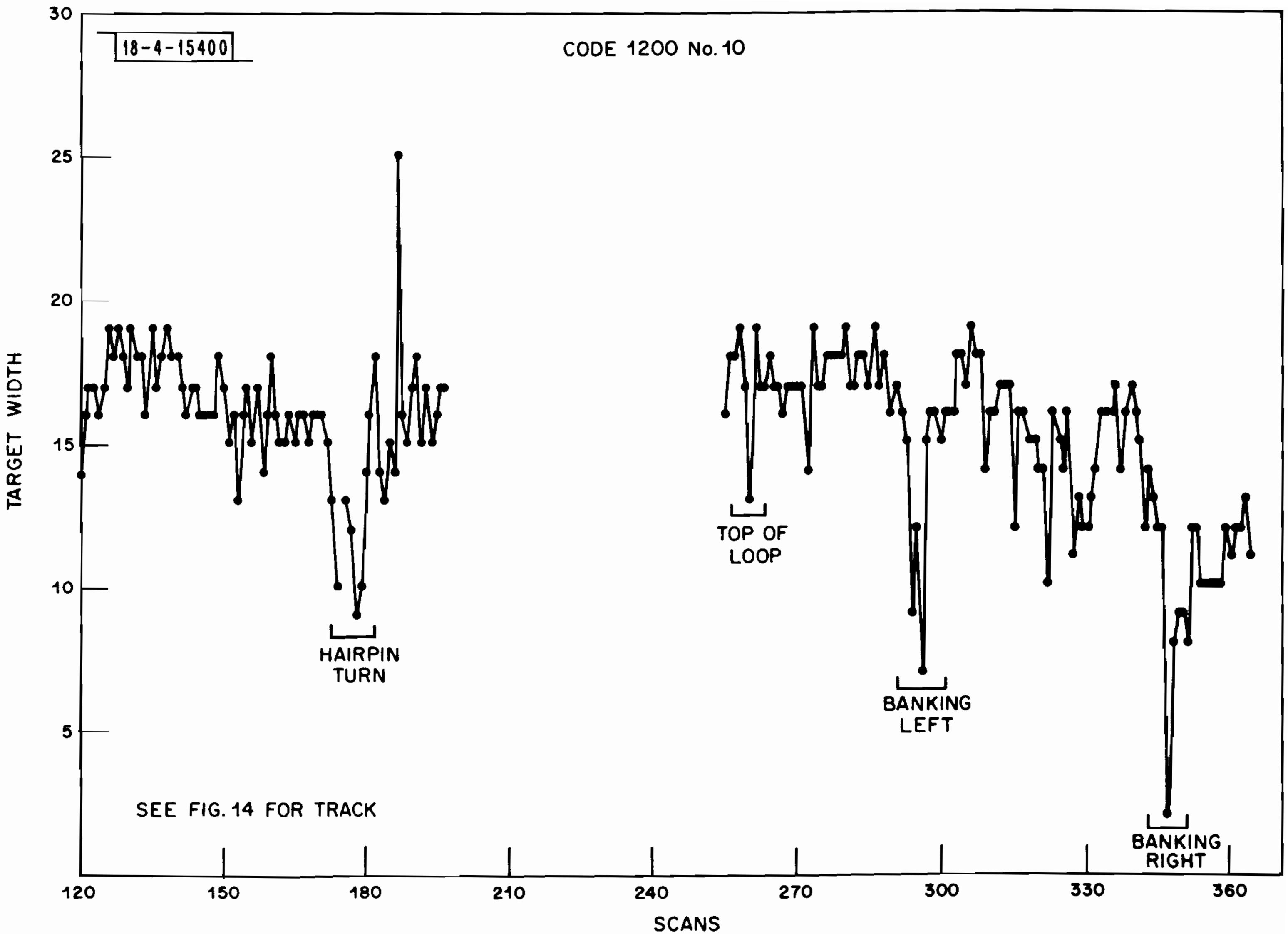


Fig. 16. Variations in Runlength Due to Maneuvers - VFR Aircraft to North.

Figure 17 shows the width history for the target looping southwest of I/R. This aircraft maneuver is counterintuitive, in that it does not exhibit any width fluctuations which correlate with its maneuver, although they might be expected based on the appearance of the flight path. Only one noticeable dip occurs shortly after the aircraft passes through minimum range on the first (smaller) of its two counterclockwise loops. No fading is visible as the aircraft completes its double-looped pattern and heads off to the north.

To summarize, we have examined our data base for evidence of target loss due to blockage of the airborne antenna because of aircraft maneuver. We find that while definite correlations do occur, shielding does not always occur; that when it occurs it does not always lead to loss of declarations; and that when loss of declaration occurs its duration is on the order of a scan or two. No evidence of sustained target loss due to this mechanism was found in any of our data.

Again, general inferences must be made with caution. The mechanism coordinating fades to aircraft attitude depends heavily on aircraft type and antenna location, and position and altitude relative to the I/R, which together with all other factors in the link power budget determine available margin and, thus, beamwidth. With respect to IFR departures from a hub airport, the Andrews I/R is atypical, since it is remotely sited from DCA. We cannot conclude that shielding effects do not occur in the system. All we can conclude is that a brief look at this mechanism in our data base does not support the notion that a serious target loss problem exists. We are not dealing with scenarios in this report; consequently, such questions as whether isolated target loss is serious in the light of tracker performance, whether dropouts

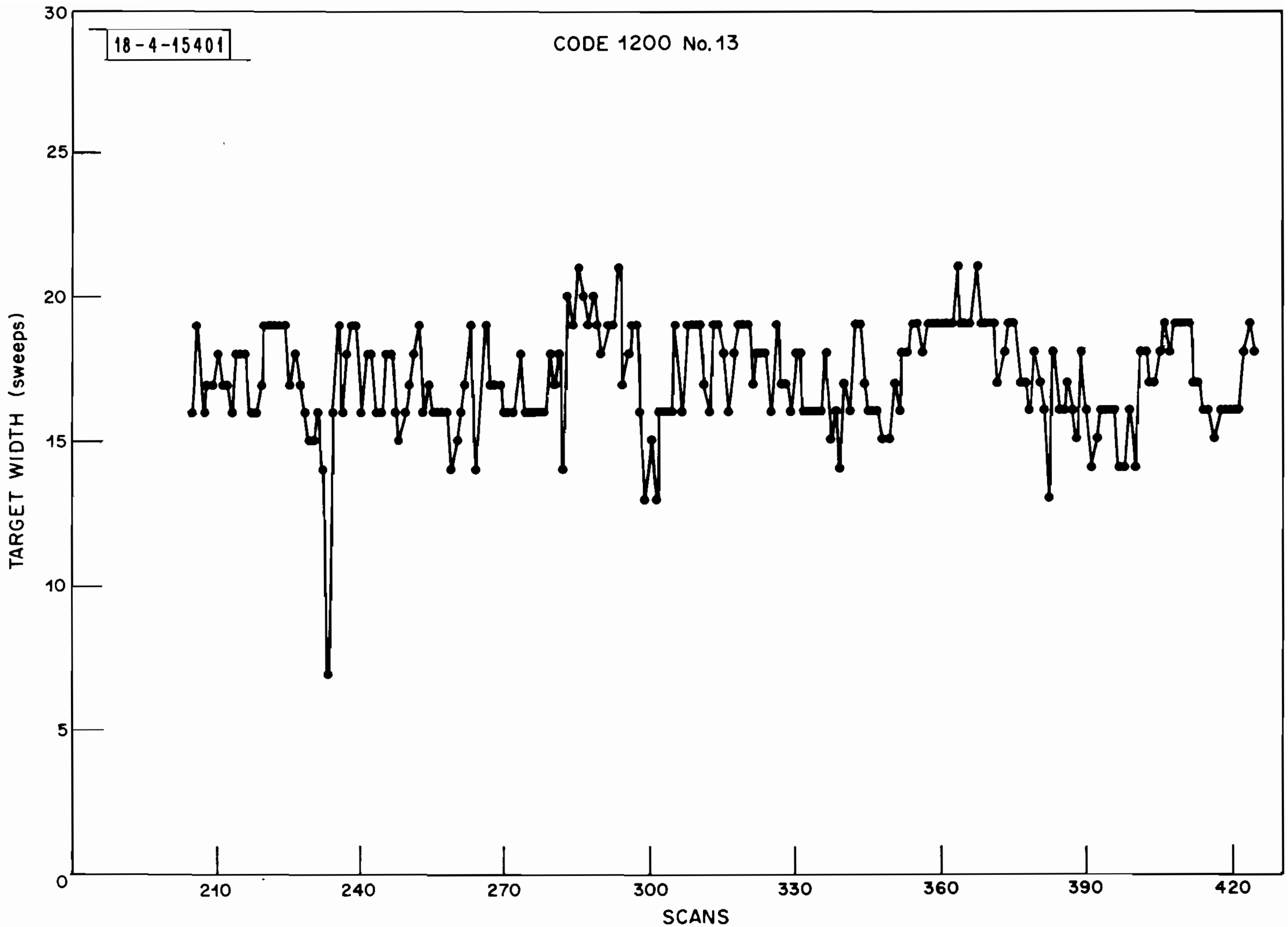


Fig. 17. Variations in Runlength Due to Maneuvering - VFR Aircraft to Southwest.

of an aircraft performing a standard instrument departure are significant, etc., are not addressed.

d. Vertical lobing in the I/R antenna pattern

The phenomenon of vertical lobing (RF phase interference between the mainbeam and a beam reflected from the ground) has been alleged as a cause of missed target declarations in ATCRBS. Our data on this phenomenon, gathered primarily at Andrews AFB, hardly suffice to allow general conclusions to be drawn about the impact of vertical lobing throughout the FAA surveillance system, but does support some interesting observations. Of the eight aircraft discussed previously (the 2100s in the PCA), four were flying tangentially, at essentially constant elevation angles, and the remaining four were approaching or departing the Andrews I/R on radial courses. Since their altitudes remained essentially constant, their elevation angles were changing. Thus, the presence of vertical lobing would be manifested in regular cyclic variations in the runlengths of these latter four aircraft, perhaps with target declaration failures at the minimum runlength portions of the cycles. Examination of the tracks revealed that no target declaration losses whatsoever occurred. Thus, vertical lobing does not appear to affect the gross operational performance of the Andrews ATCRBS in any manner.

Since nominal runlengths were well in excess of the minimum necessary for target declaration, we examined the runlength histories of these aircraft to determine whether vertical lobing was affecting signal levels (and therefore runlength), but not to the extent of causing target declaration failure. Our procedure was to develop these histories for all eight aircraft, and to look for differences in them attributable to vertical lobing. All of the aircraft on radial tracks were near FL-300. They entered the system at 55 nmi range, corresponding to about 4-1/2° elevation angle, and were tracked inward at constant altitude to under 30 nmi range. The elevation angle thus varied from 4-1/2° to about 9-1/2°. The null spacing, if present, would be about a degree, since the antenna is approximately 30 ft above the ground. Thus, several nulls should have been crossed by these aircraft. The other four aircraft tracks were perpendicular to the line-of-sight. Their elevation angles changed very little in this region. Figures 18 and 19 show the target width histories for the two sets of targets. No differences are apparent; there is just as much variability in the tangential set as in the radial set. Whatever the cause of variability, be it variations in the airborne antenna pattern, "random" irregularities in the I/R antenna pattern, P1-P2 relationship, or any other mechanism, we believe that much wishful thinking would be needed to conclude that a more regular variation was superimposed in the radial case. Figure 20 shows width distributions for the two sets of data. The median widths and lower tails are virtually identical.

There were only two aircraft present in the Boston data whose tracks and altitudes were suitable for vertical lobing analysis; no evidence of vertical lobing was noted in that data, either. Since the ground area surrounding both interrogators is relatively flat, and there are few obstructions on the horizon in the directions in which the measurements were made, this is somewhat surprising. While it is hardly proper to conclude from this information that vertical lobing in ATCRBS is a fictitious problem, our data strongly suggests that it is hardly a universal problem. We are well aware that data gathered at other sites, by more direct means, has clearly indicated vertical lobing, with depths of fades well in excess of 10 dB. Based upon the nominal target

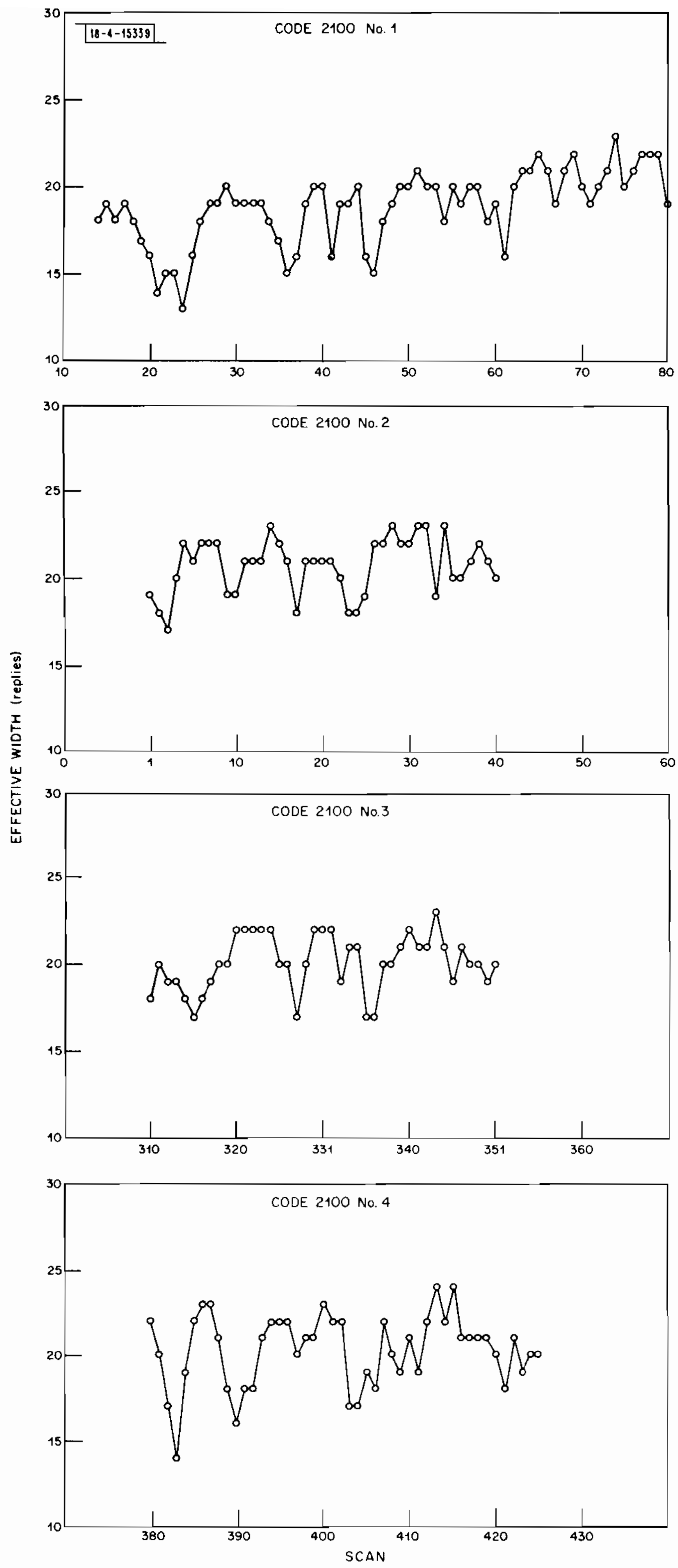


Fig. 18. Target Width Histories - Radial Courses.

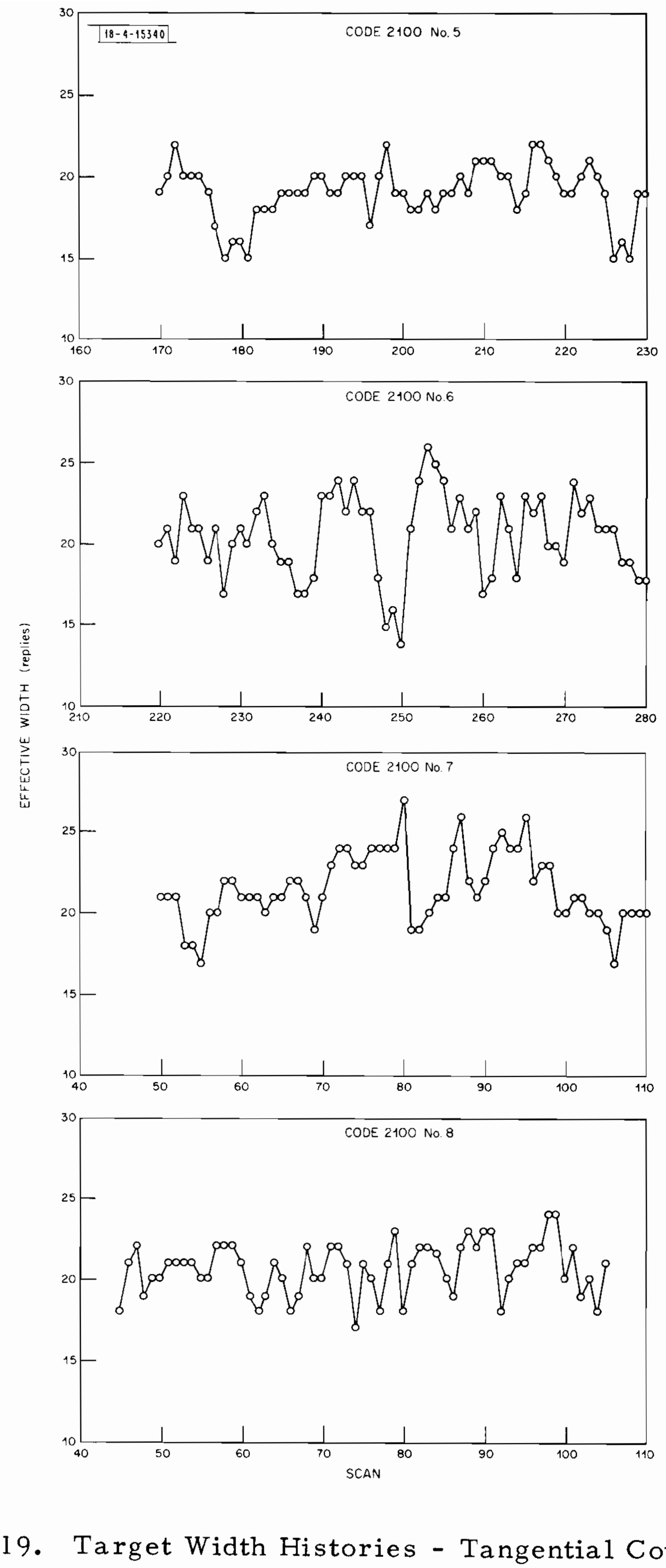


Fig. 19. Target Width Histories - Tangential Courses.

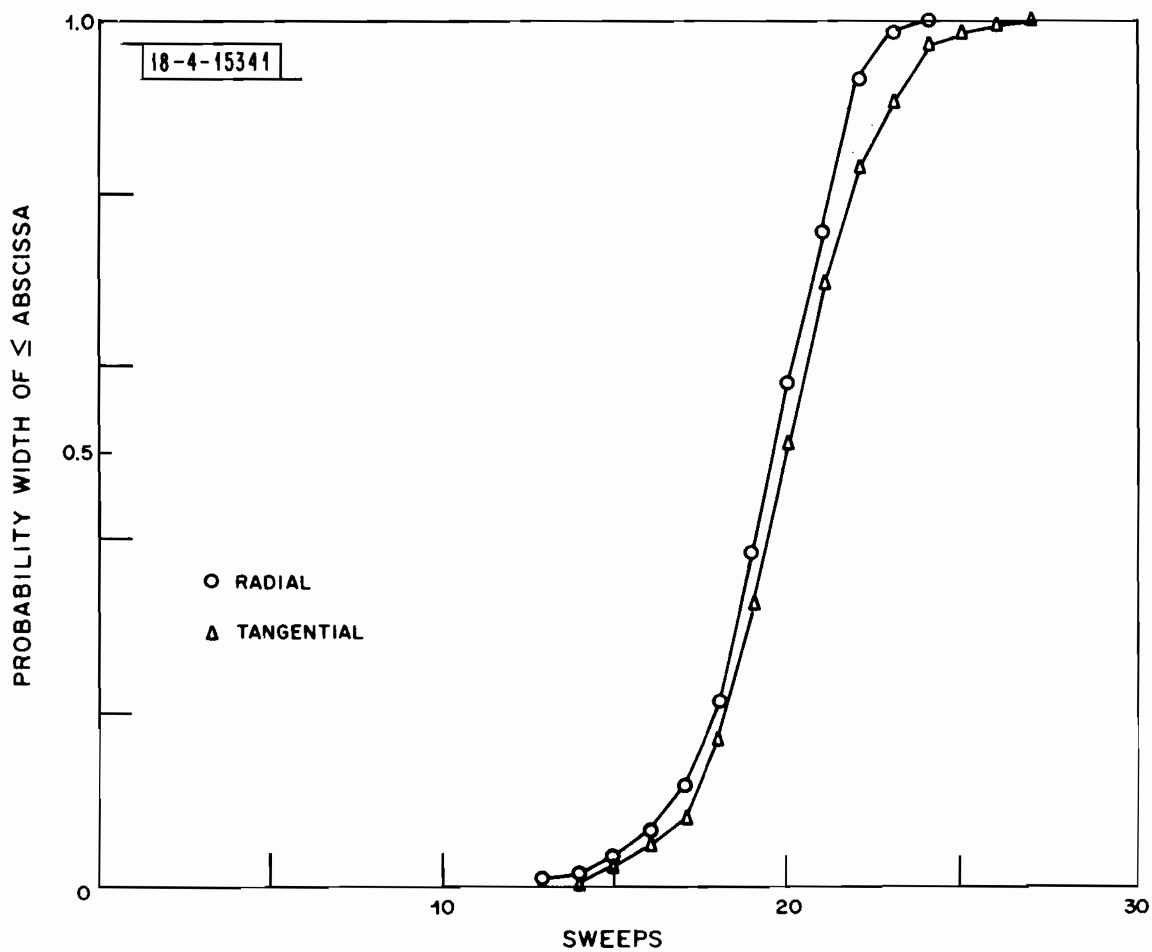


Fig. 20. Target Width Distributions - Both Sets of Targets.

widths we observed and measured ATCRBS antenna patterns, we would expect fades of this depth to be readily visible in our data. What appears to be the situation in actuality is that serious vertical lobing only exists along some azimuths at some sites. Exact numbers are not known; they could be determined by analysis of this sort performed on ARTS III-derived tapes from the various sites.

On the basis of the above information (and lack of it), it appears to us that the "blanket" solution to vertical lobing, development of an antenna with a significant amount of vertical aperture as a universal replacement for today's "hog-troughs," is not desirable. While such an antenna should certainly be developed, it need only be applied to those sites where vertical lobing is definitely a problem. A program to determine which sites those are is clearly necessary. We suspect there may not be many.

4. Software Improvements

Basically, all software improvements applicable to weak targets are based on the supposition that, for situations in which declaration currently fails, at least <u>some</u> replies are actually present. If no replies at all are returned from the target, only "physical" improvements, such as resiting the antenna, or removing the obstruction, can help. The operation of the defruiter is critical here. In our data, when no replies occur on a particular scan, we have no way of knowing whether replies were lost in the defruiter. Comparative data with the defruiter on and off would be valuable to determine this. Despite this limitation, we can get some idea of the potential for improvement from our data.

Figure 21 shows a history of hits received versus time for a military aircraft (code 4000) flying far from the I/R (43-50 nmi), and apparently at quite low altitude. This target was never declared in 52 scans, yet, we can see that between scans 1 and 32, replies were present on 21 scans, and no more than three consecutive scans occurred in which no replies were present. If this aircraft were of interest to the ATC system and had entered this flight segment as a tracked target, by lowering target declaration thresholds (perhaps adaptively), it could be kept in track for at least the first 32 scans (over two minutes) of this segment.

Another example from a similar flight regime (near NAS Patuxent River is shown in Figure 22. In 36 scans, 16 declarations were missed, yet, there was only one scan on which no replies emerged from the defruiter. Figure 23 shows yet another example, This aircraft was 30 nmi north of I/R. Only seven declarations occurred in 26 scans, yet only one scan contained no replies.

The above data, while fragmentary, are suggestive of what could be gained for targets which are "generally marginal" due probably to a combination of link parameters including range and low altitude rather than predominance of any specific mechanism such as blockage. In the case of maneuvering targets, we find, for example, that of the nine scans on which the first target of section c was undeclared, six contained replies at the defruiter output. The second example of that section contained only two missed declarations, and replies were present on one of them.

With regard to the examples in section a of blockage due to ground-based obstructions, the first VFR aircraft described (Figure 7) was un-

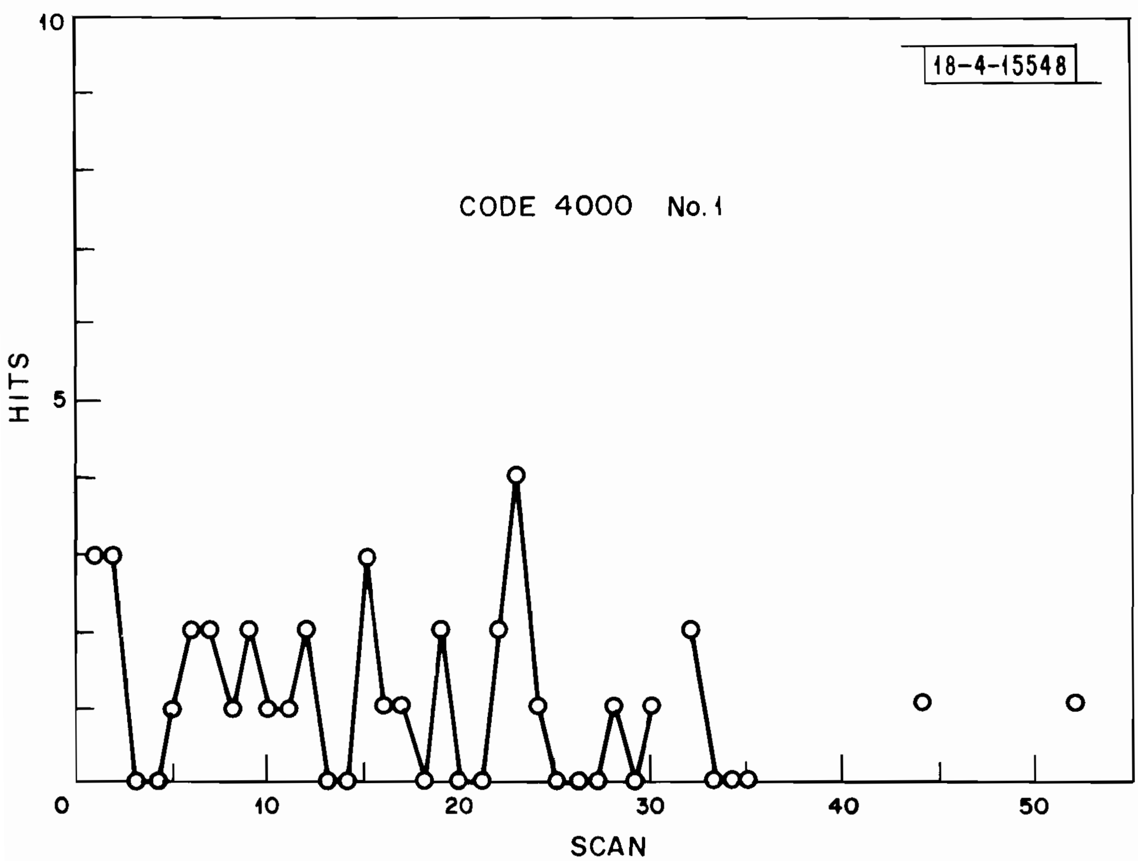


Fig. 21. Hit Statistics - Weak Aircraft #1.

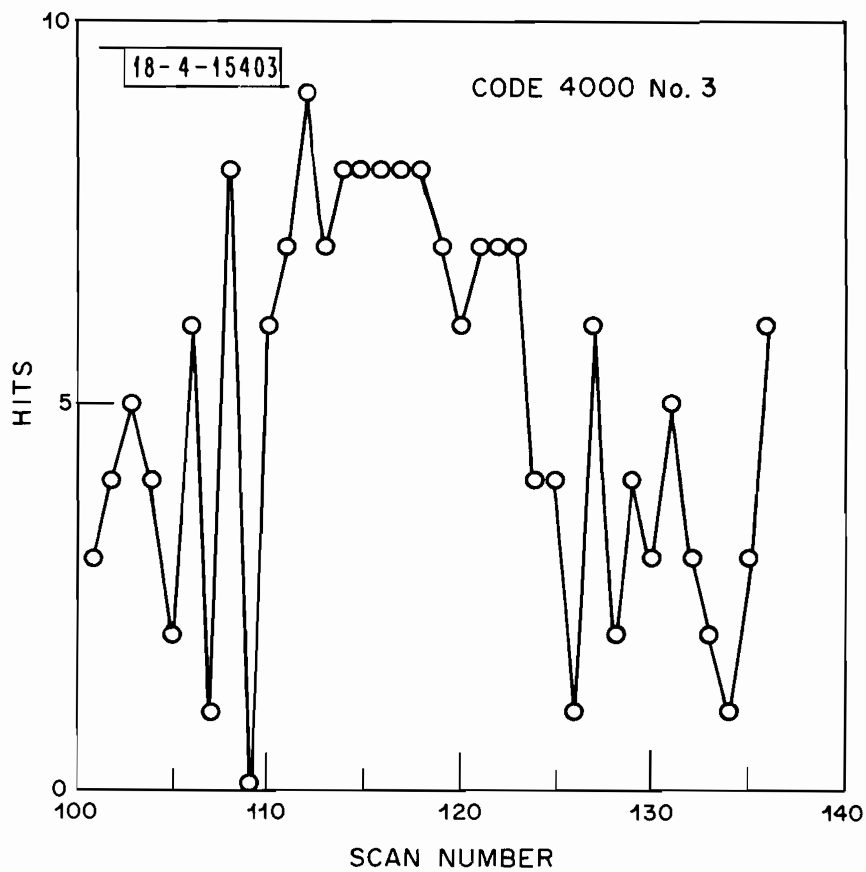


Fig. 22. Hit Statistics - Weak Aircraft #2.

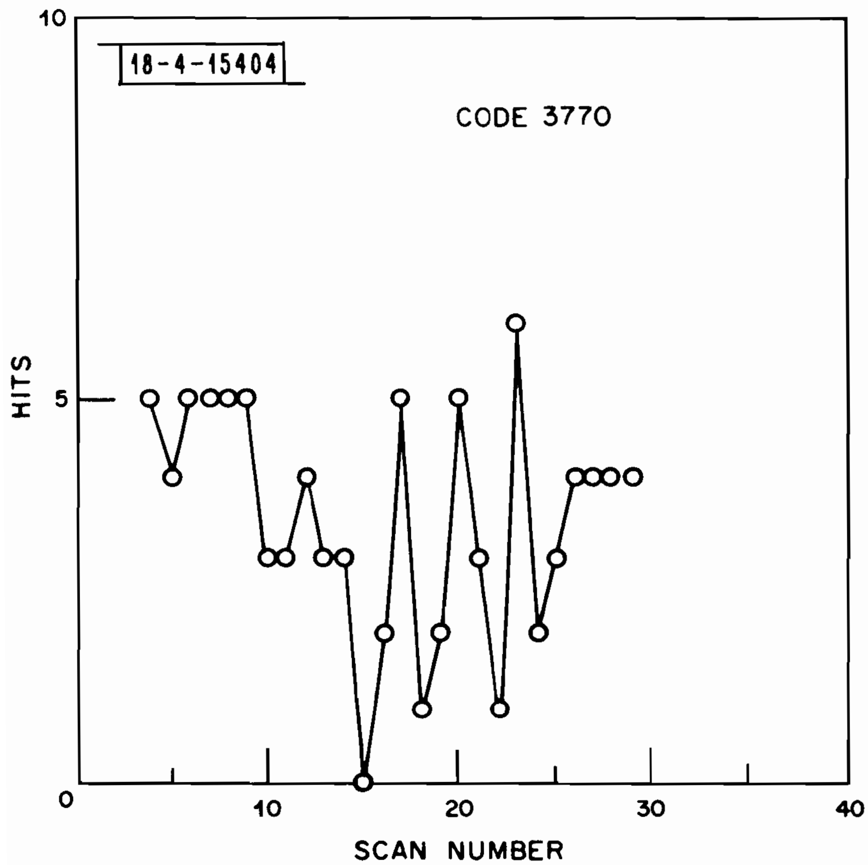


Fig. 23. Hit Statistics - Weak Aircraft #3.

declared on 92 of 110 scans. Of these 92, only 17 contained replies at the defruiter output, leaving a significant number with no apparent replies. Here, the effect of the defruiter is unknown; its removal could perhaps improve tracking capability somewhat. The second VFR aircraft of section a was undeclared on 92 of 138 scans. Of the 92, 16 contained replies at the defruiter output. Not just these totals, but also the distribution of the scans on which various numbers of replies were received are of interest. Figure 24 compares histograms of consecutive declaration failures with histograms of consecutive scans containing <u>no</u> replies at the defruiter output, for these two aircraft. It can be seen that some long runs in which <u>no</u> replies are received remain. This is less amenable to tracking improvements than a uniform sprinkling of replies through the runs of failed declarations.

An examination of the other target, whose width data is shown in Figure 8, indicates that in the two segments where blockage was significant there were 30 of 33 and 21 of 27 failed declarations, respectively. Of the 30 scans in which declaration failed, nine contained replies. Of the other 21 failures, eight contained replies. Histograms of consecutive declaration failure versus consecutive scans containing no replies are shown in Figure 25. Some improvement in cutting down on the long runs of declaration failures is apparent.

While more statistical data of this sort, particularly with the defruiter switched out, is needed, it is clear that software improvements directed toward weak targets have potential. There are two avenues of approach. One is to couple a solution of the false target problem with a lowering of target detection thresholds to improve weak target visibility in general. The other

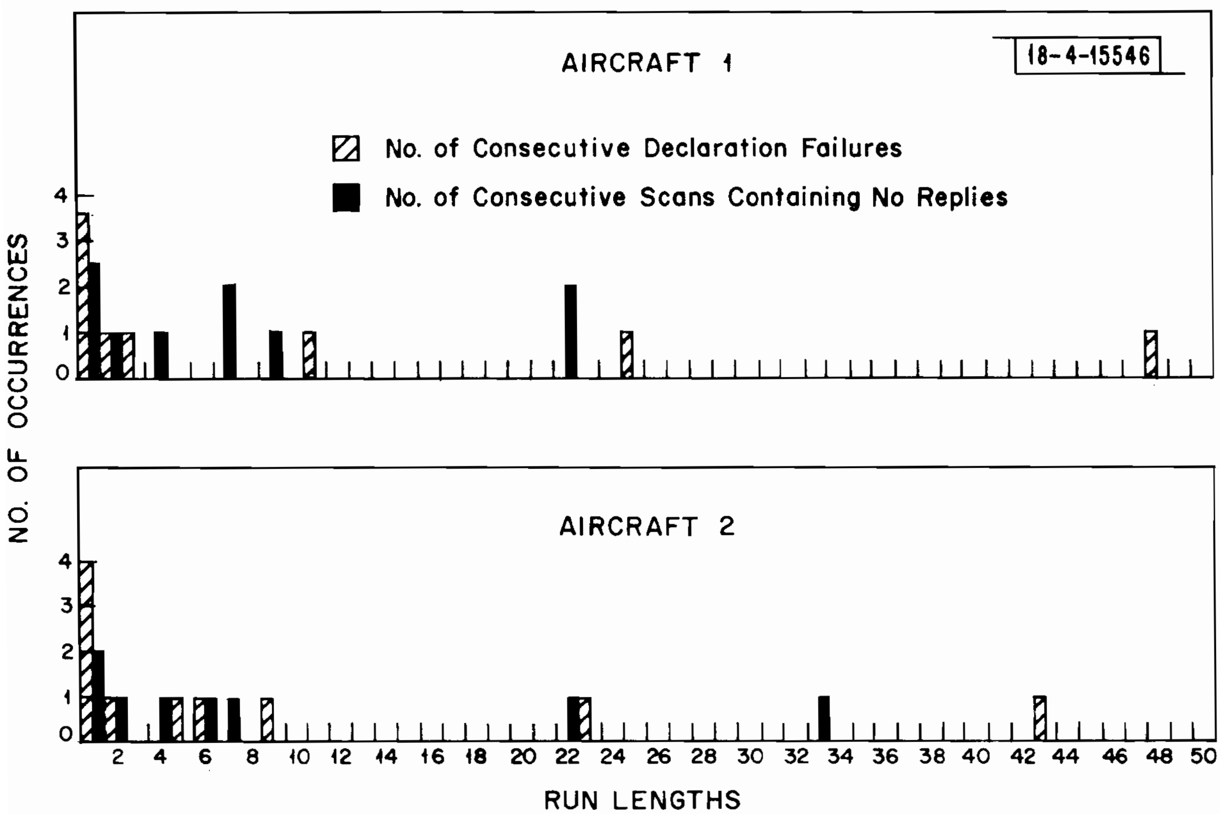


Fig. 24. Runlength Histograms - VFR Aircraft to East.

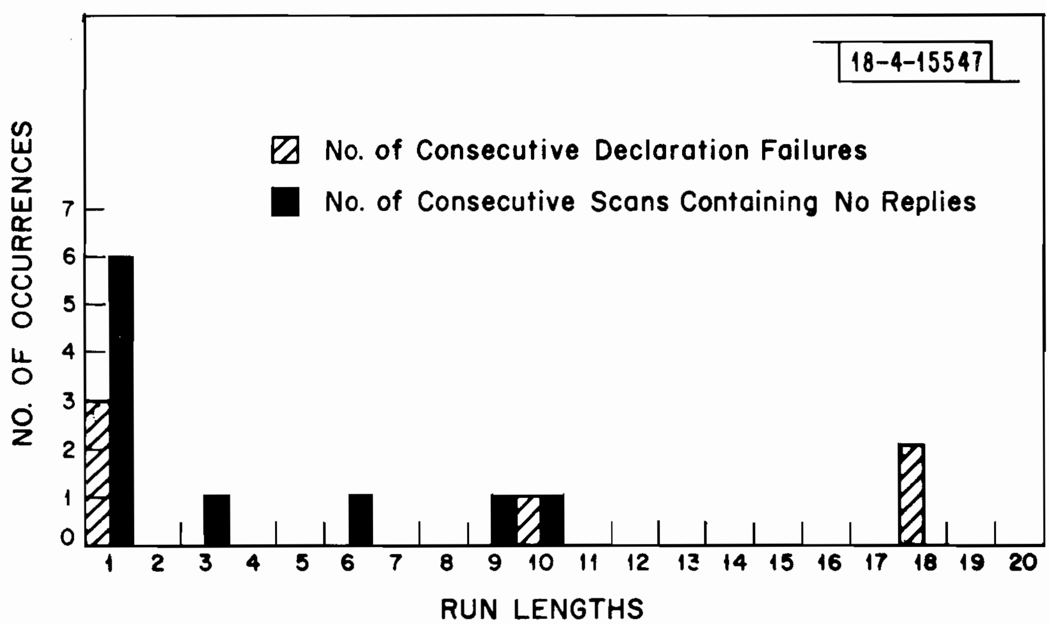


Fig. 25. Runlength Histograms - VFR Aircraft to North.

approach is to selectively lower thresholds for targets in track. Before the extent to which these avenues should be pursued can be decided, it is necessary to determine what future requirements will be for tracking the classes of targets (at Andrews, primarily VFR and distant military aircraft) which exhibit frequent weakness and declaration loss.

B. False Targets

The ATCRBS system frequently displays targets that do not correspond to actual aircraft locations. These are often weak, and of short runlength, but can frequently be of sufficient strength and runlength to be completely indistinguishable from legitimate targets. False targets do not occur at random locations at a particular site, but rather (as will be evident from the data which follows) are clustered within completely deterministic and relatively small volumes of airspace. Usually these volumes do not overlap busy airways, and, hence, the false target problem is of little operational concern. Occasionally, however, the geometry of a particular ATCRBS installation is such that false targets regularly appear in areas of heavy IFR traffic and materially affect the operational performance of the ATC System. The Trevose, Pa., ARSR site is a notable example of just such a situation. With the advent of extended radar advisory service, and similar concepts leading to a fully implemented system for Intermittent Positive Control of VFR aircraft throughout the surveillance coverage area, the effect of the false target problem can be expected to become far more noticeable, and to cause far greater degradation of the ATC system.

1. The Mechanism

The mechanism which causes false targets to occur is well-understood, and has been successfully corrected in several instances. As additional ARTS and NAS Stage A installations become operational, and greater use is made of discrete (4096-code) transponder replies, other fixes to the problem will become available. False targets are usually caused by reflection of the ATCRBS interrogation and response signals from buildings located nearby the interrogator* (see Figure 26). In order to intercept and reflect a large amount of signal energy, the reflecting surface must subtend a fairly large portion of the ATCRBS mainbeam. This implies either that the reflecting surface is very large or very close to the ATCRBS site. Unfortunately, quite often both conditions are found. In some situations, especially at close range to the interrogator where large reflection losses can be tolerated, surprisingly small reflectors can produce false replies. In all cases noted to date, reflections are highly specular (implying that reflecting surfaces are flat relative to a wavelength over an area several wavelengths wide). The result is that the region of airspace illuminated by each reflector is quite narrow and well-defined.

From Figure 26, it can be seen that aircraft within the solid angle illuminated by the reflecting surface will cause false targets whose apparent

*A notable exception to this situation occurs at the N. Platte, Neb., ARSR site, where severe false targets are caused by reflections from nearby ground which is not level, but rather "twists" the signals out of the vertical plane containing the mainbeam. This results usually in the creation of a false target at essentially the same range as the actual target, but slightly to the right or left of it; occasionally the two are merged, and a single wide target results whose center does not correspond to the actual aircraft azimuth.

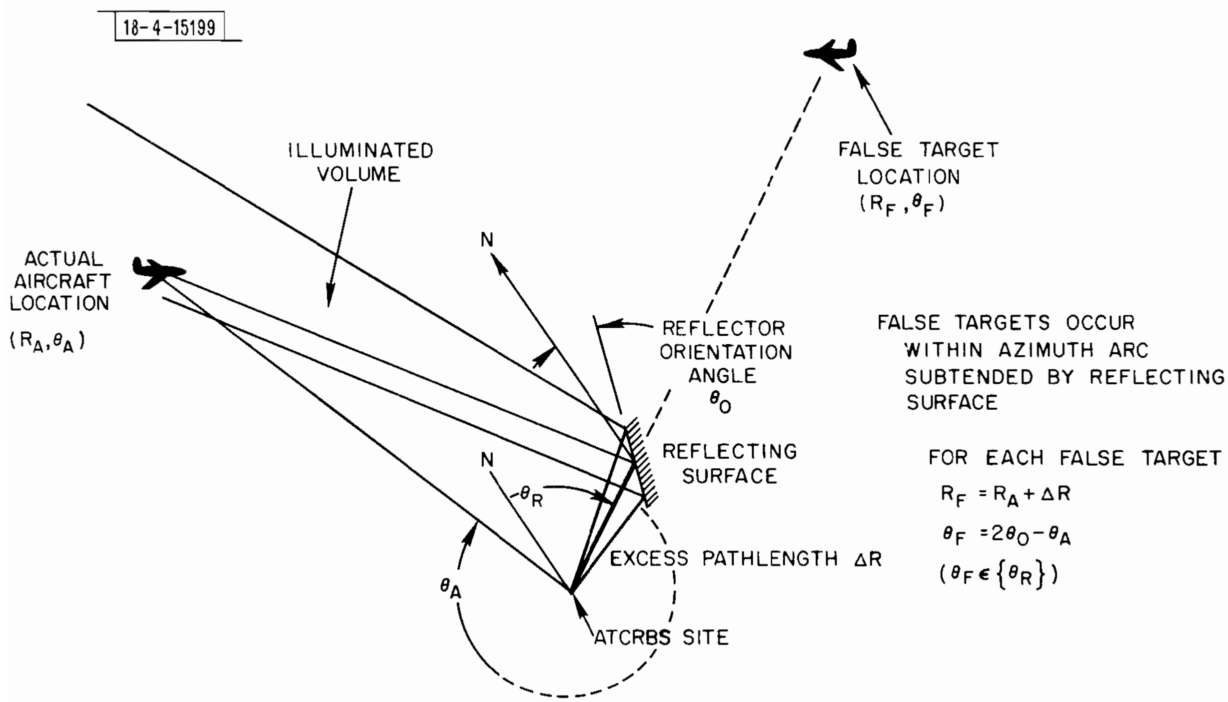


Fig. 26. Reflection Geometry.

azimuth is that of the reflecting surface, and whose range is greater than that of the actual aircraft by an amount equal to the excess distance traveled by the signal (typically less than a mile, although range differences of up to five miles have been observed). The particular volume of airspace illuminated by the reflector depends upon its orientation relative to the ATCRBS site, as shown in Figure 26.

Reflectors subtending fairly wide azimuths can cause such large volumes of airspace to be illuminated that on some headings aircraft can remain illuminated for many scans; this causes not only a false target, but a false track, based on many individual target reports. As would be expected, when a single large reflector is involved the false track appears as the "mirror image" of the track of the actual aircraft, at a small, fixed additional distance from the sensor (Figure 27).

2. Early Test Data

False targets have been noted since the inception of the IFF system, but their first comprehensive treatment within FAA appears to have been by Spingler [6, 7]. He employed or suggested several techniques to eliminate the problem at various sites, including use of absorbing or shielding material, and extension of "improved" SLS in the direction of the offending aircraft during that portion of the scan when the interrogator was facing the reflector. (The so-called "improved" SLS concept was itself developed to combat false targets.)

False targets were also noted in the 1968 FAA/DOD Beacon Flight Test in New York [3]. Eight false target producing mechanisms were observed (four at JFK, two at Newark, two at Elwood). The locations of reflectors

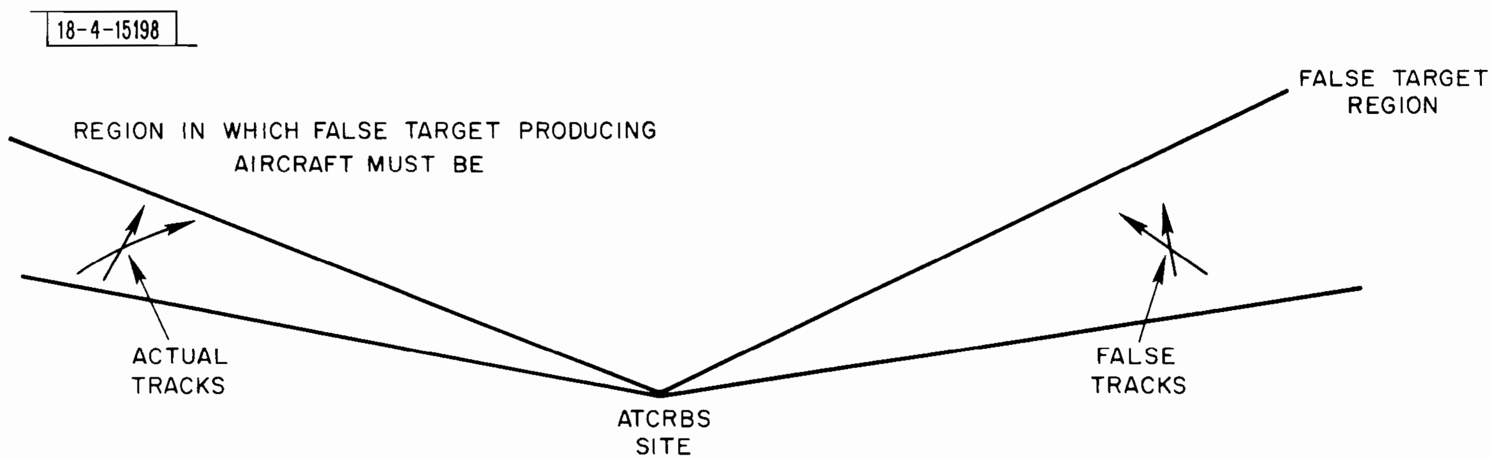


Fig. 27. False Target Track Geometry.

which would lead to the observed results were calculated and found to agree completely with locations of buildings (one of the EWR reflectors appears to have been a truck on the nearby New Jersey Turnpike!). It was apparently not recognized that the geometry allowed estimation of the reflector orientation as well as location; no data on orientation was given in that report.

3. MITRE Test Results

MITRE [2] observed false targets at Newark and Chicago, and calculated some gross occurrence factors. MITRE assumed a simple model for false target occurrence, which related the number of false targets observed per scan to the total number of actual targets through an "average synchronous fruit generation factor." That portion of the factor attributable to the reflection mechanism was determined to be of the order of 5-10%. That is, given 100 aircraft, one would expect on the average to see five to ten false targets per scan. The peak value of this factor was observed to be approximately twice the average.

Runlength distributions of the false targets were determined and compared with those of the actual targets. This data is shown in Figure 28. MITRE made the pertinent point that while the distributions are indeed recognizably different, the procedure employed in ARTS III whereby an attempt is made to separate false targets from actual ones on the basis of runlength discrimination is not especially effective, since, as is apparent from Figure 28, "a high degree of filtering of the false targets requires an unacceptable sacrifice of target detection." [8] In order to maintain a sufficiently low miss probability, "several false targets per scan must be expected and accommodated by the ARTS processor. Complete removal of these false reports will require additional signature analysis by the processor." [8]

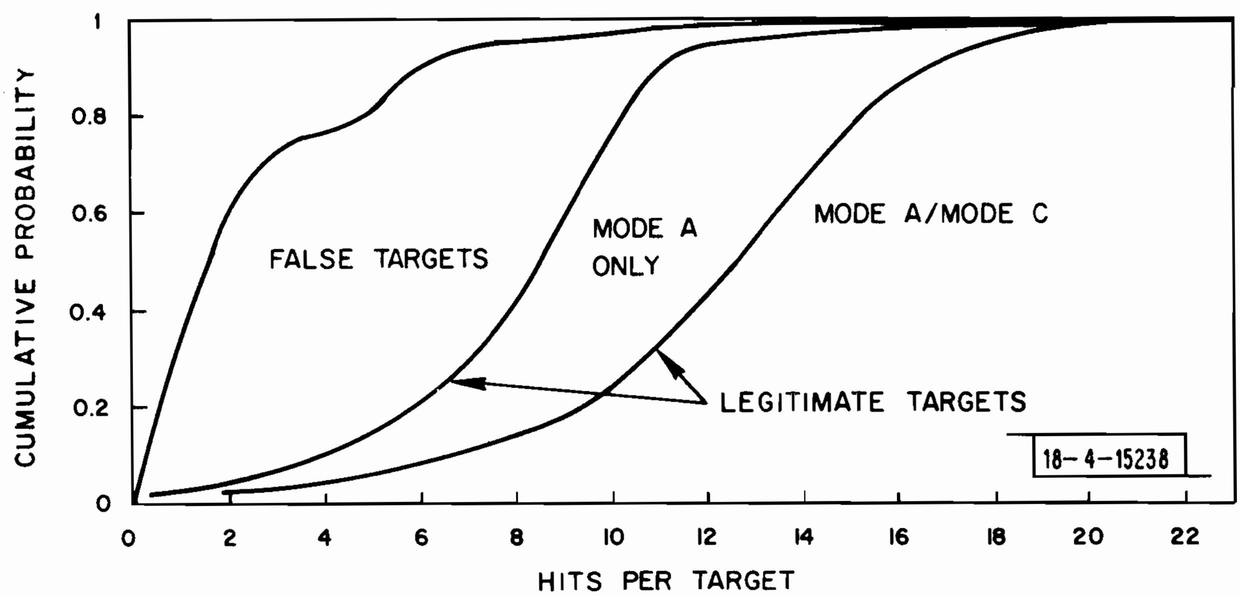


Fig. 28. False Target Runlength Distributions.

While MITRE recognized the deterministic nature of the false target generation process, and the possibility of eliminating the problem through "signature analysis," no analysis of the data was performed to determine how this might be accomplished. Indeed, the probabilistic treatment of the false target data seems contradictory to the nonrandomness of the false target generation process.

4. Our Data - Andrews AFB

Pairs of targets with the same discrete codes were observed in the Andrews AFB data (42 scans taken 28 July 1972), with behavior typical of a false target mechanism (Table 4). This data strongly suggests the presence of a large reflecting surface approximately 2750 ft from the ASR, subtending an angle from 94° to 101° (magnetic), oriented so as to be broadside to the ASR at 98°. The reflector appeared to end at 94°, since reflection stopped at that point; no measure was available of the extent of the surface in the other direction (i.e., at bearings greater than 101°), since the data began at that point.

Cursory examination of the Andrews ATCRBS parameters (Table 5) reveals that sufficient excess RF link power was available to support the reflection process, with loss in the reflection process of as much as 16 dB on the uplink, and 31 dB on the downlink. The fact that the angular width of the false target was substantially equal to that of the real one suggests that the actual reflection loss was quite a bit less.

Since it was known that there were several large buildings located along (parallel to) and east of runway 1R-19L (although no obstruction chart was available at the time, and as a result the location of the ASR was not

Table 4. A False Target Seen at Andrews Air Force Base.

Target Squawking 0350 - On Final to Dulles

Scan #	False Target Range	False Target Azimuth	False Target Runlength	Actual Target Range	Actual Target Azimuth	Δ R	θ_o
1	29.44	1151	9	28.50	3127	.94	91
2	29.31	1137	11	28.44	3130	.87	96.5
3	29.19	1144W	8	28.31	3138	.88	93
4	29.13	1151	11	28.25	3137	.88	96
5	29.06	1140	11	28.13	3140	.93	92
6	28.94	1133	10	28.00	3146G	.94	91.5
7	28.88	1134	11	27.94	3159	.94	98.5
8	28.75	1122	9	27.81	3154N	.94	90
9	28.69	1125N	9	27.75	3155G	.94	92
10	28.56	1117N	4	27.69	3164	.87	92.5
11	28.50	1100N	6	27.63	3168	.87	86
12	28.44	1112W	7	27.50	3168	.94	92
13	-----	-----	0	27.44	3170W	---	---
14	28.25	1097W	8	27.38	3179	.87	90
15	28.19	1100	11	27.25	3182	.94	93
16	28.13	1098	12	27.19	3187	.94	94.5
17	28.06	1096	12	27.13	3185	.93	92.5
18	-----	-----	0	27.13	3179W	---	---
19	-----	-----	0	27.06	3194	---	---
20	27.88	1115W	7	27.00	3204	.88	111.5
21	27.81	1094N		26.94	3201	.87	99.5
22	27.81	1079		26.94	3209	.87	86
23	27.81	1071W		26.94	3203	.87	89
24	27.81	1077W		26.94	3209	.87	95
25	27.81	1067W		26.94	3222	.87	96.5
26	27.81	Broken, N		26.88	3217	.94	---
27	-----	-----		.	.	---	---
.	.	.		(remained solid)		.	.
.	.	.		.	.	.	.
36				27.00	3248		

Notes: 1. Ranges in nmi quantized to sixteenths of a nmi.
2. Azimuths in ACP (4096 ACP = 360°) magnetic.
3. Runlength in consecutive mode 3/A hits.
4. Letters following azimuth represent ARTS reply signal strength:
Codes: blank = strong
W = weak
N = not declared
G = garbled

$\{\theta_R\}$ Lower bounded at ACP 1070. No upper bound. At least as great as 1151.

$\langle\theta_o\rangle_{Ave.}$ = 94 ACP ~ 8° magnetic

$\langle\Delta R\rangle$ = 29/32 nmi ≈ 5500'; d = $\langle\Delta R\rangle$ /2 = 2750'

(See Figure 2 for an explanation of symbols.)

Table 5. Andrews Air Force Base ATCRBS Parameters and Link Analysis.

System Parameters

Type	:	ATCBI-4
Defruiter	:	Storage tube*
PRF	:	385
Scan Rate	:	15 rpm
SLS	:	Improved

Link Parameters at R = 30 nmi:

Uplink

	(P_1)	(P_2) (omni)
Output power (200 w)	53 dBm	53 dBm
Power splitter loss	- 3 dB	- 3 dB
Cable, diplexer loss	- 2 dB	- 2 dB
Antenna gain	22 dB	6 dB
Pathloss (30 nmi)	-127 dB	-127 dB
Airborne Antenna gain	0 dB	0 dB
Received signal power	= - 57 dBm	= - 73 dBm
Nominal aircraft MTL	- 73 dBm	

Downlink

Output power (250 w)	54 dBm
Cable loss	- 2 dB
Antenna gain	0 dB
Pathloss	-127 dB
Receiver antenna gain	22 dB
I/R cable losses	- 2 dB
Received signal power	= - 55 dBm
Nominal tangential sensitivity	- 86 dBm

*Not typically found with ATCBI-4, but present at ADW.

known precisely), several other aircraft flying to the west of the site were tracked over approximately 40 scans, and a search was made for false targets to the east resulting from these aircraft, and consistent with the existence of other reflectors located parallel to the one noted above. Several were found (Table 6); unfortunately, none were found in the sector immediately above 101° magnetic (adjacent to where the first false target was noted), since there were no aircraft flying in that volume of airspace which would be illuminated by buildings in that sector.

Figure 29 shows the location and orientation of these reflecting surfaces to the east as deduced from the data; it can be seen that the results are in close agreement with actual building locations, with the exception of the reflectors labeled B and D. Since false replies from several aircraft indicated the presence of reflector D, it appears likely that a building is in fact presently located at that point.* Reflector B was likely a vertical fin of an aircraft on the taxiway. It appears that the building responsible for reflector A was acting as a corner reflector. Reflecting surfaces are clearly visible on the ADW panoramic photograph (Figure 32a).

Further examination of various other data (Table 7) reduced and plotted for the antenna switching tests, taken while the test aircraft was to the north, east, and south, revealed many of the remainder of the reflecting surfaces shown in Figure 29. While the accuracy of measurement of range to the reflector is generally commensurate or slightly better than the range quantization of the system (since motion of the target "dithers" the reflector location process,

*The Andrews AFB visitors guide (4 Feb. 1965) shows the Navy Operations building in that location.

Table 6. Other False Targets Observed at Andrews Air Force Base.

CODE 3613

Scan 1:	Actual Position	27.56 nmi,	3526 ACP	Reflector B;
	False Target	28.25 nmi,	0749 - 5 replies	$R_R \approx 2000'$; θ_o = 89.5 ACP
Scan 21:	Actual Position	25.88 nmi,	3441 ACP	Reflector C;
	False Target	26.56 nmi,	0852 - 3 replies	$R_R \approx 2000'$; θ_o = 98 ACP
Scan 40:	Actual Position	24.56 nmi,	3331 ACP	Reflector D;
	False Target	25.50 nmi,	0950 ACP - 10 replies	$2R_R = \frac{15}{16}$ nmi; $R_R \approx 2900'$;
Scan 41:	Actual Position	24.50 nmi,	3326 ACP	
	False Target	25.44 nmi,	0956 ACP - 3 replies	θ_o = 93 ACP
				$\langle \theta_R \rangle \in$ 0930-0965
				Bldg 60-100' long

CODE 0400

Scan 4:	Actual Position	16.38 nmi,	2633 ACP	Reflector A;
	False Target	17.44 nmi,	0581 ACP - 5 replies	$R_R = \frac{17}{32}$ nmi = 3100' ;
				θ_o = 1607 $\approx \perp$ To Incident Beam
Scan 25:	Actual Position	14.50 nmi,	2719 ACP	
	False Target	15.18 nmi,	1547 ACP - 3 replies	Reflector F;
Scan 27:	Actual Position	14.56 nmi,	2731 ACP	$R_R \approx 3620'$;
	False Target	15.25 nmi,	1520 ACP - 4 replies	θ_R = 1519-1547
Scan 28:	Actual Position	14.63 nmi,	2733 ACP	
	False Target	15.31 nmi,	1519 ACP - 1 reply	θ_o = 82 ACP

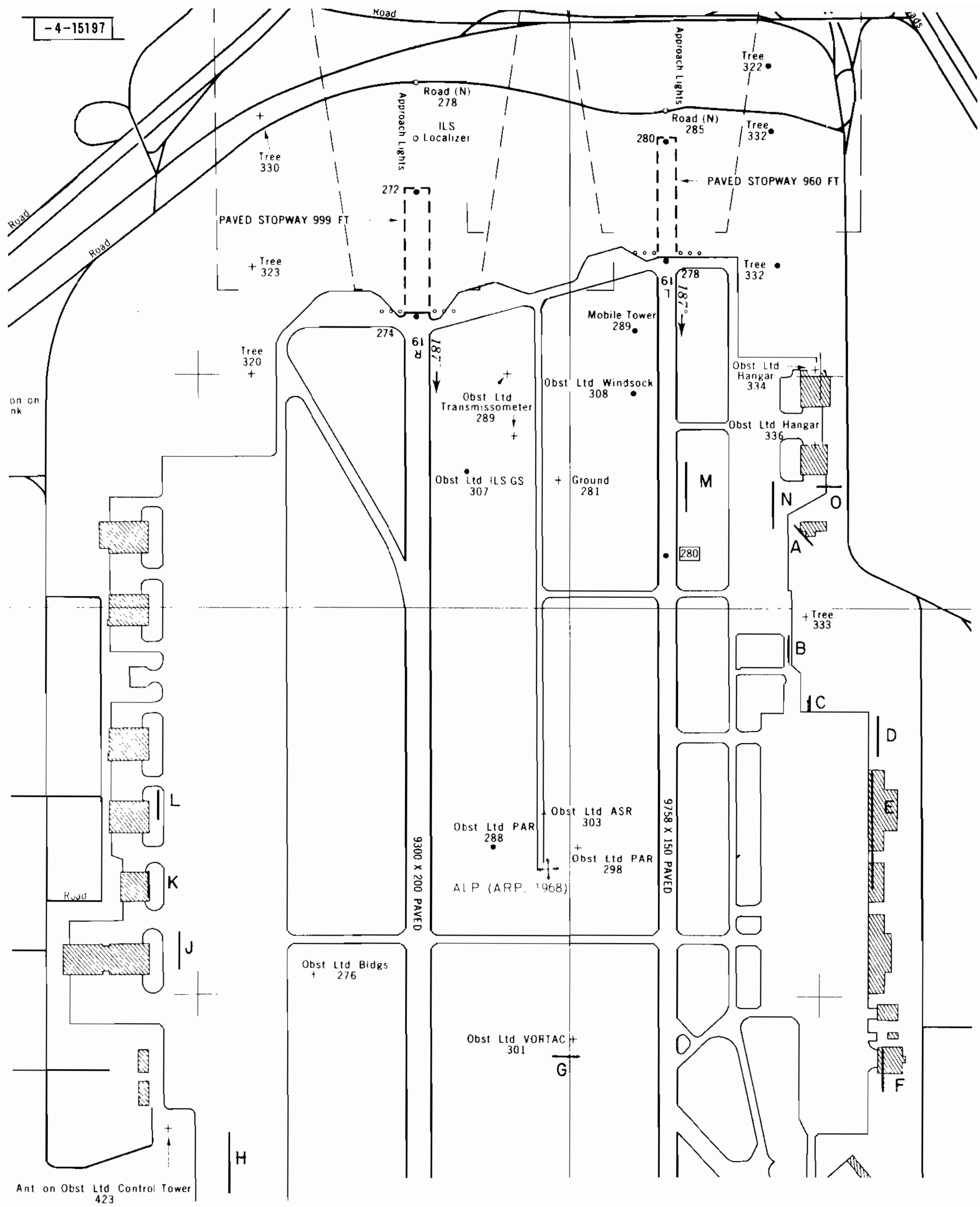


Fig. 29. Reflecting Surface Location and Orientation - Andrews AFB.

Table 7. False Targets Caused by Reflectors to the South, West, and Northeast at Andrews Air Force Base.

Data taken from Tape "F-106 Tests, Vol. 1 and Vol 2."
All false targets generated by aircraft under test (discrete code)

VOL. 1

Scan #	Real Target Range	Real Target Azimuth	Real Target Alt.	False Target Range	False Target Azimuth	# Hits
203	47.94	94.13°	6.4	48.81	279.18°	2A
204	47.625	94.22°	6.5	Reflector R = 3130' ; θ_o = 6.675° Reflector "L"		
210	46.25	96.33°	9.7	47.18	279.14°	AAC
211	46.00	96.68°	9.8	Reflector R = 3060' ; θ_o = 7.5° Reflector "L"		
231	41.68	107.31°	16.0	42.65	268.11°	2A
232	41.5	107.58°	16.0	42.3	268.85°	6 (decl.)
233	41.3	108.46°		Reflector R = 3270' ; θ_o = 8.0° Reflector "K"		
252	38.63	119.88°	16.0	39.56	256.3°	3A
253	38.5	120.59°	16.0	Reflector R = 3000' ; θ_o = 8.25° Reflector "J"		
292	37.06	142.26°	16.0			
293	37.12	143.7 °	16.0	37.69	51.86°	9 (decl.)
294	37.18	144.05°	16.0	37.75	51.06°	5
295	37.3	144.76°	16.0	37.81	51.15°	3
				Reflector R = 3700' ; θ_o = 97.57° Reflector "O"		
448	32.00	175.96°	15.9	32.68	229.2 °	2
	31.88	176.92°	15.9	Reflector R = 10,500' ; θ_o = 22.6° Reflector off scale		

(continued)

Table 7. (Continued)

VOL. 2

Scan #	Real Target Range	Real Target Azimuth	Real Target Alt.	False Target Range	False Target Azimuth	# Hits
488	1.06	199.4°	0.0	(on airport surface)		
489	1.06	200.2°				
490	1.06	200.4°		1.12	226.6°	1
491	1.06	200.4°		1.25	226.4°	1
492	1.06	199.5°				
493	1.06	199.5°				
494	1.06	199.6°				
495	1.06	199.5°		1.18	225.9°	2
496	1.06	199.4°		1.25	226.0°	3
497	1.06	199.5°		1.12	226.2°	7 (decl.)
498	1.06	199.5°		1.18	226.2°	7 (decl.)
499	1.06	199.6°		1.12	225.3	2
500	1.06	199.8°		Reflector R = 3620' ; θ_o = 19.4° Reflector "H"		
515	1.30	1.85°	0.0	1.43	34.1°	2
516	1.56	7.03°		Reflector R = 2680' ; θ_o = 11.4° Reflector "M"		
515	1.30	1.85°	0.0	1.56	42.98°	7 (decl.)
516	1.56	7.03°		Reflector R = 3060' ; θ_o = 15.1° Reflector "N"		
515	1.30	1.85°	0.0	2.00	185.6°	
516	1.56	7.03°		Reflector R = 2000' ; θ_o = 91.65°		

allowing effective averaging of redundant data), note that there is some significant error in determination of the range of some surfaces. This is because of the oblique reflection geometry, which dilutes the precision with which the range to the reflector can be determined. Recall that the measured false target range equals the sum of the distances from the ASR to the reflector and from the reflector to the actual aircraft. In this case (Figure 30), it can be seen that small errors in this parameter can lead to large errors in reflector range.

It should be emphasized that all of the reflection mechanisms described above were derived from approximately five minutes' worth of data and that the precision with which their parameters were determined (especially reflector orientation) was generally quite high. This high precision suggests an intriguing fix to the problem, involving only software, which will be discussed in a later part of this section.

5. Our Data - Boston

Several similar false target mechanisms were noted (Table 8, Figure 31) from examination of approximately three minutes of Boston ARTS III data. Only eight aircraft were within the coverage area during the period in which this data was taken; thus, Table 8 is hardly a complete listing of all the reflectors affecting the performance of the Boston secondary radar at long range.

Discussion with controllers at Boston revealed that the more or less conventional false target mechanism described above was of relatively minor importance in comparison to a somewhat more peculiar false target problem. According to Boston personnel, the problem is not unique, having been

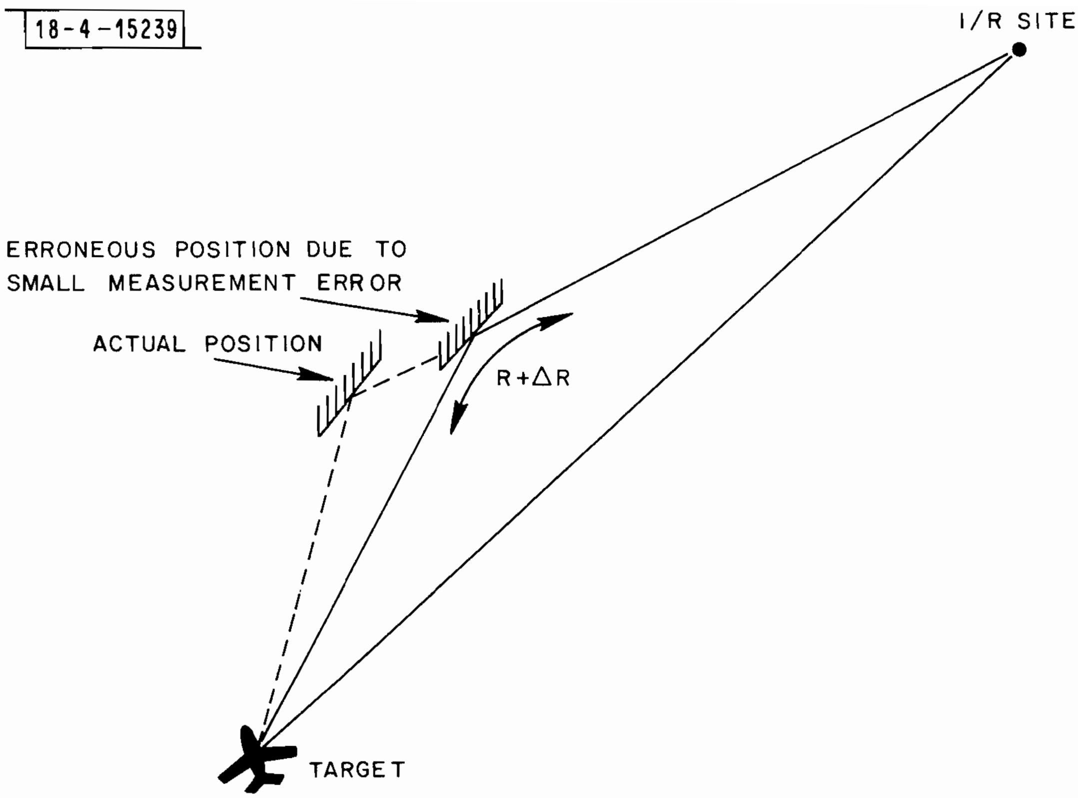


Fig. 30. Oblique Reflection Geometry.

Table 8. False Targets Due to Aircraft at Long Range Observed at Boston.

Boston Tape 2, Scans 1-48

Scan #	Code	Real Target Range	Real Target Azimuth	Real Target Alt.	False Target Range	False Target Azimuth	False Target # Hits
2	0300	36.12	4.6°	8.1	38.68	283.0°	4C
3	0300	36.06	4.66°	N.R.	38.62	283.9°	3C
4	0300	35.97	5.0°	N.R.	38.62	284.2°	5C
5	0300	35.90	6.68°	7.0	38.57	283.7°	4C
					Reflector R = 2.32 nmi; θ_o = -33.45° Reflector "5"		
7	1100	18.06	264.0°	-	18.25	215.9°	4
8	1100	18.25	263.9°	-	18.43	215.16°	1
9	1100	18.47	263.75°	-	18.69	215.77°	6 (decl.)
10	1100	18.69	263.9°	-	18.88	215.7°	6 (decl.)
					Reflector R = 0.38 nmi; θ_o = -30.0° Reflector "4"		
8	0300	35.62	7.9°	-	37.30	291.5°	2
					Reflector R = 1.6 nmi; θ_o = 69.5° Reflector "13"		
14	1201	11.15	335.3°	-	16.38	172.0°	4
15	1201	11.20	334.4°	-	Reflector R = 2.62 nmi; θ_o = -16.3° Reflector "3"		
20	0300	35.19	1.2°	3.1	37.00	276.7°	1
					Reflector R = 2.05 nmi; θ_o = -32.72° Reflector "5"		
23	0300	35.16	16.0°	2.5	37.12	300.7°	2
					Reflector R = 1.53 nmi; θ_o = -20.3° Reflector "8"		
30	0300	35.25	18.6°	2.0	38.93	141.7°	2
					Reflector R = 2.34 nmi; θ_o = -11.39° Reflector "2"		
31	0300	35.19	19.9°	2.0	37.00	100.3°	2
					Reflector R = 2.1 nmi; θ_o = -51.5° Reflector "1"		
33	1200	2.18	283.8°	-	3.65	282.2°	6
					Reflector R = 1.46 nmi; θ_o = -77.8° Reflector "6"		

(continued)

Table 8. (Continued)

Scan #	Code	Real Target			False Target		
		Range	Azimuth	Alt.	Range	Azimuth	# Hits
38	1200	2.00	293.0 °	-	2.18	293.6 °	4
39	1200	2.00	295.0 °	-	2.18	293.9 °	8 (decl.)
					Reflector R = 2.0 nmi; θ_o = 113.0° Reflector "7"		
40	1200	2.00	297.25°	-	2.12	296.0 °	8 (decl.)
					Reflector R = 2.08 nmi; θ_o = 116.0° Reflector "8"		
41	1200	2.00	299.36°	-	2.43	298.5 °	3
					Reflector R = 2.22 nmi; θ_o = 118.5° Reflector "9"		
42	1200	2.03	301.1 °	-	2.56	300.6 °	3
					Reflector R = 2.3 nmi; θ_o = 120.0° Reflector "10"		
45	1200	2.12	306.7 °	-	2.25	305.8 °	6 (decl.)
					Reflector R = 2.2 nmi; θ_o = 126.0° Reflector "12"		

Fig. 31. Reflector Location and Orientation - Boston.

observed at several other ARTS III installations. Due to the relatively high power and sensitivity of the Boston I/R, and the presence of a very large number of small reflectors on the horizon at relatively great distances (typically 2-3 nmi), a single aircraft frequently causes a large number of false targets at many azimuths within the timespan of a few scans. Since the reflecting surfaces are distant, and are fairly low on the horizon (Figure 32b), the volume of airspace they illuminate is restricted to within a few hundred feet of the ground. Thus only aircraft on takeoff or final approach (or on the airport surface) are involved.

Observation of the PPI while a single aircraft was on final approach to runway 4R (with no other aircraft in the vicinity) revealed several dozen false targets (many of which were declared by ARTS III), apparently all produced by that aircraft, occurring within about a minute of touchdown; the PPI screen, displaying only ATCRBS video (conventionally decoded) bore a marked resemblance to the electronic scoreboard at the Houston Astrodome when a home run has been hit! The false targets occurred at ranges between one mile and ten miles; actual aircraft slant range from the radar was less than one mile; for some reason,* the actual aircraft position was not displayed during this period. Frequent multiple replies were observed on individual sweeps; the effect of this is to generate radial lines (strobes) on the display.

Further discussion with radar maintenance personnel revealed that while most of the reflecting obstructions are low on the horizon, the one

*Probably overloading or STC operation; ARTS III is equipped with a minimum range filter, but this was not in use at the time.

azimuthal direction where relatively tall reflecting objects (the skyline of downtown Boston, see Figure 32b) are present is the direction where most arriving traffic appears. Blockage and shielding of distant aircraft due to these buildings has necessitated operation at fairly high power (typically 650 W peak) and high sensitivity (better than -92 dBm). Of course, the high power and sensitivity cause numerous false target mechanisms which would ordinarily be unnoticeable to become quite noticeable and objectionable.

Extractor - derived data was examined for this phenomenon during two departures on runway 22L. Both aircraft were squawking discrete codes, and were tracked from initial entry onto the runway to several miles beyond takeoff. All false replies were noted and recorded for each. Figures 33 and 34 are plots (one for each aircraft) of false reply locations (in range and azimuth) over approximately twenty scans centered on takeoff. No false replies were noted outside this interval. The dotted lines connect multiple replies occurring during single sweeps; phantom replies, which occur whenever pulses in the various false replies bear the proper time relationships to one another to be mistaken for legitimate brackets, were removed from the data prior to plotting.* Note that multiple replies at different ranges were frequently received on each sweep whenever a reflection mechanism was active. The reason for this can be seen from the geometry shown in Figure 35. The aircraft are so close to the interrogator that their replies to reflected interrogations are received over direct line-of-sight through the antenna sidelobes, as well as back over the reflecting path, and in through the mainbeam.

*ARTS III includes automatic phantom-elimination circuitry. However, this functions effectively only when both replies causing the phantom are successfully decoded. This was not always the case, since the reflected replies were apparently quite distorted.

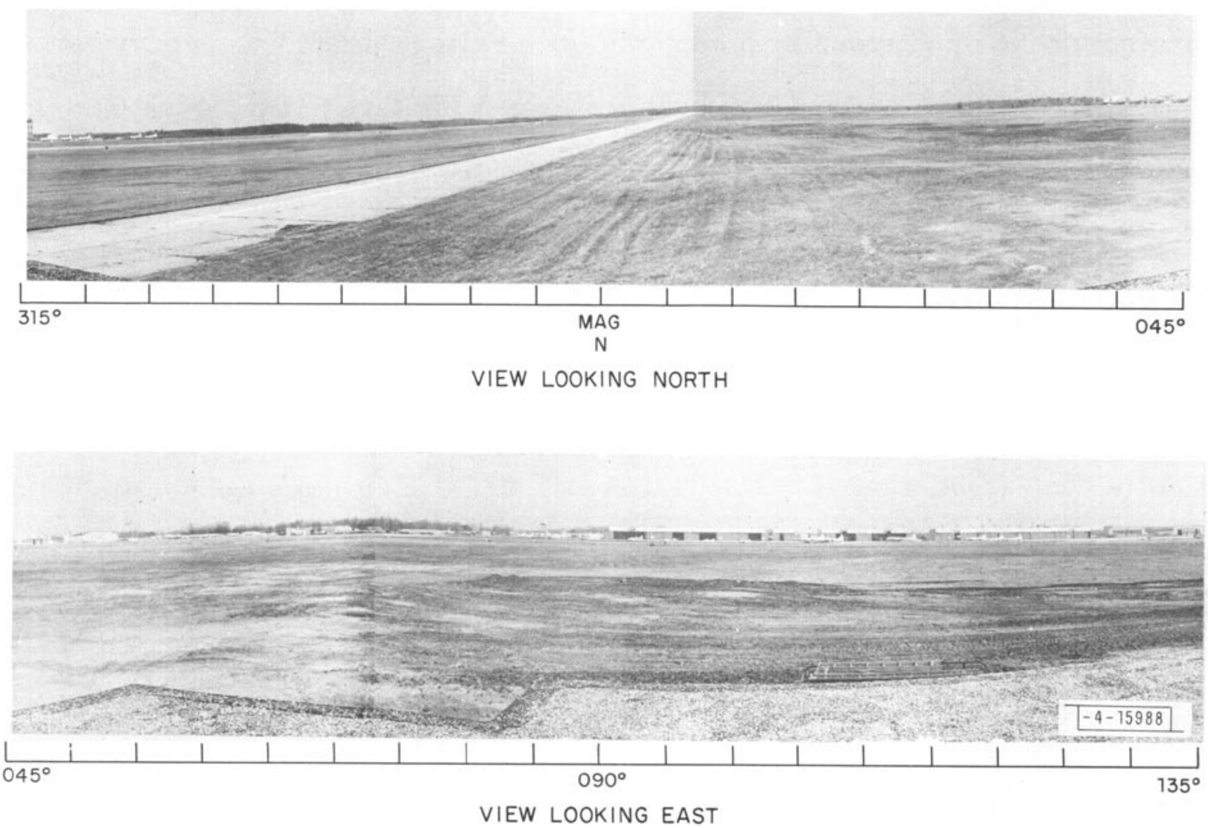
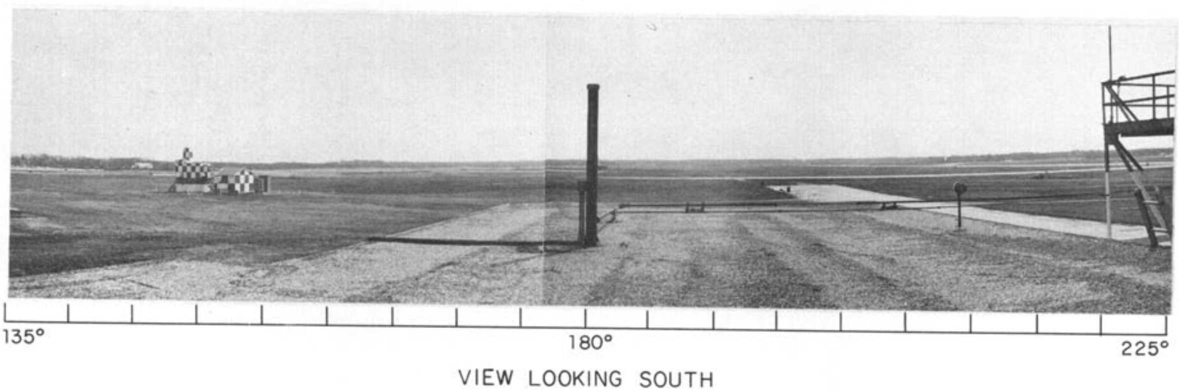


Fig. 32. Panoramic Photographs.
a. Andrews AFB (1).



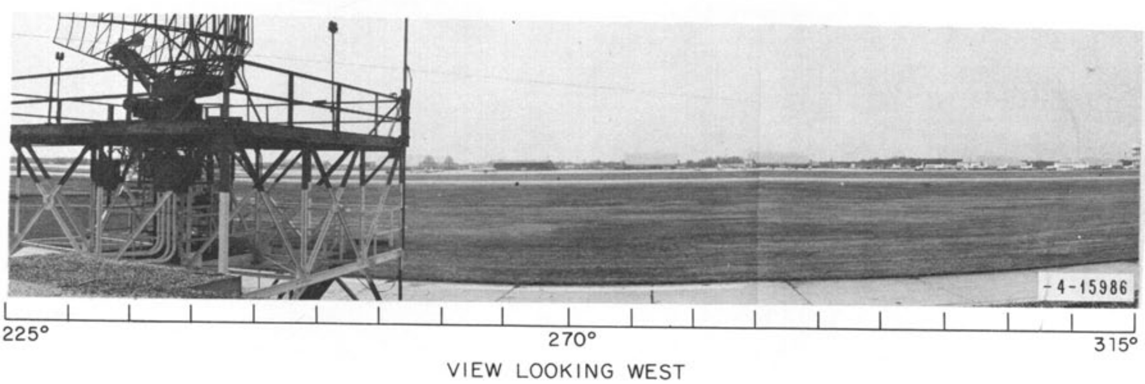
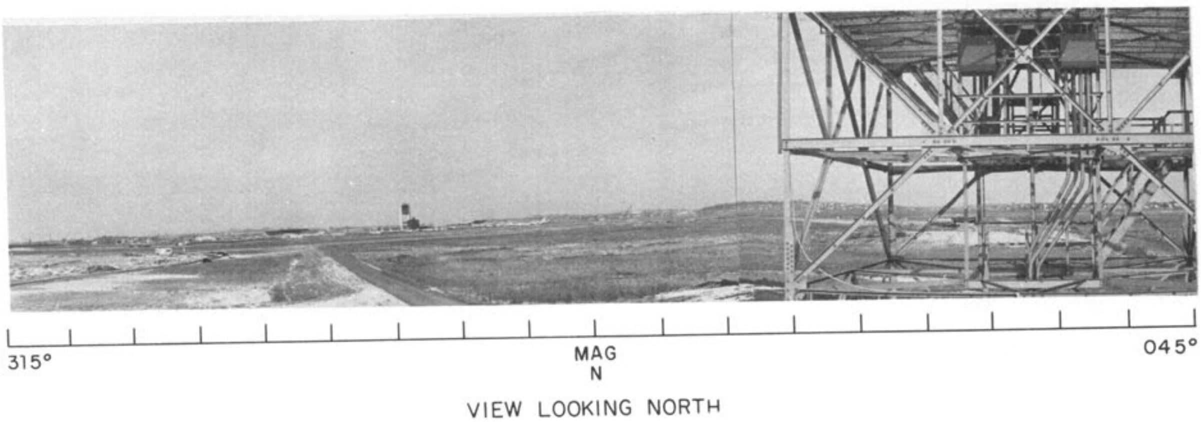


Fig. 32. Panoramic Photographs.
a. Andrews AFB (2).



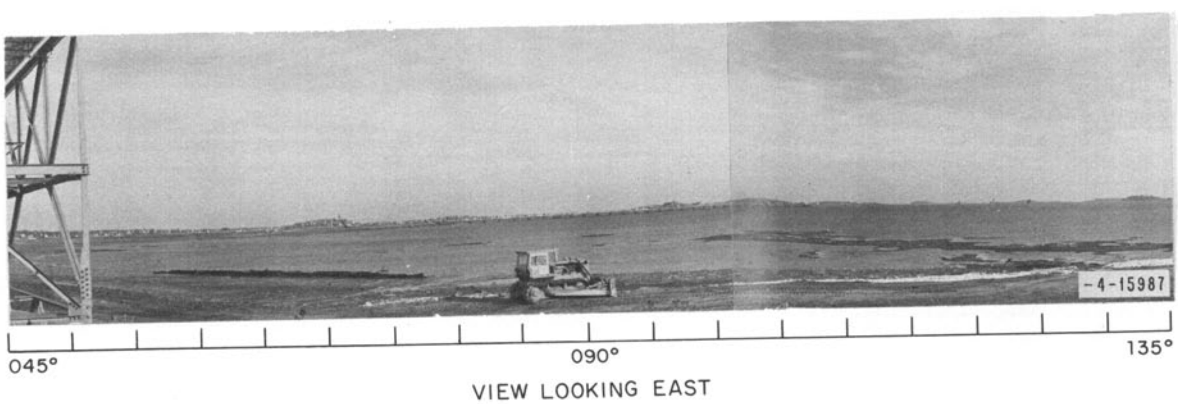


Fig. 32. Panoramic Photographs.
b. Boston (1).

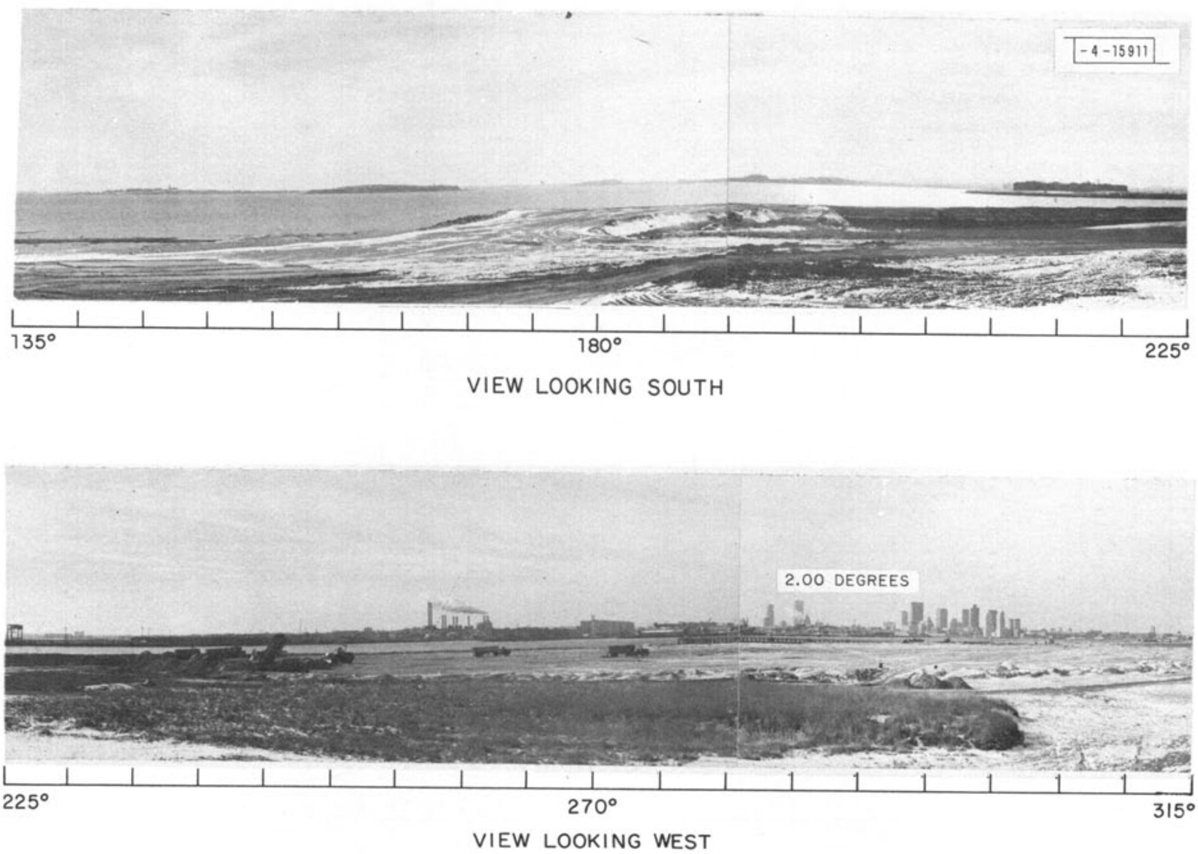


Fig. 32. Panoramic Photographs.
b. Boston (2).

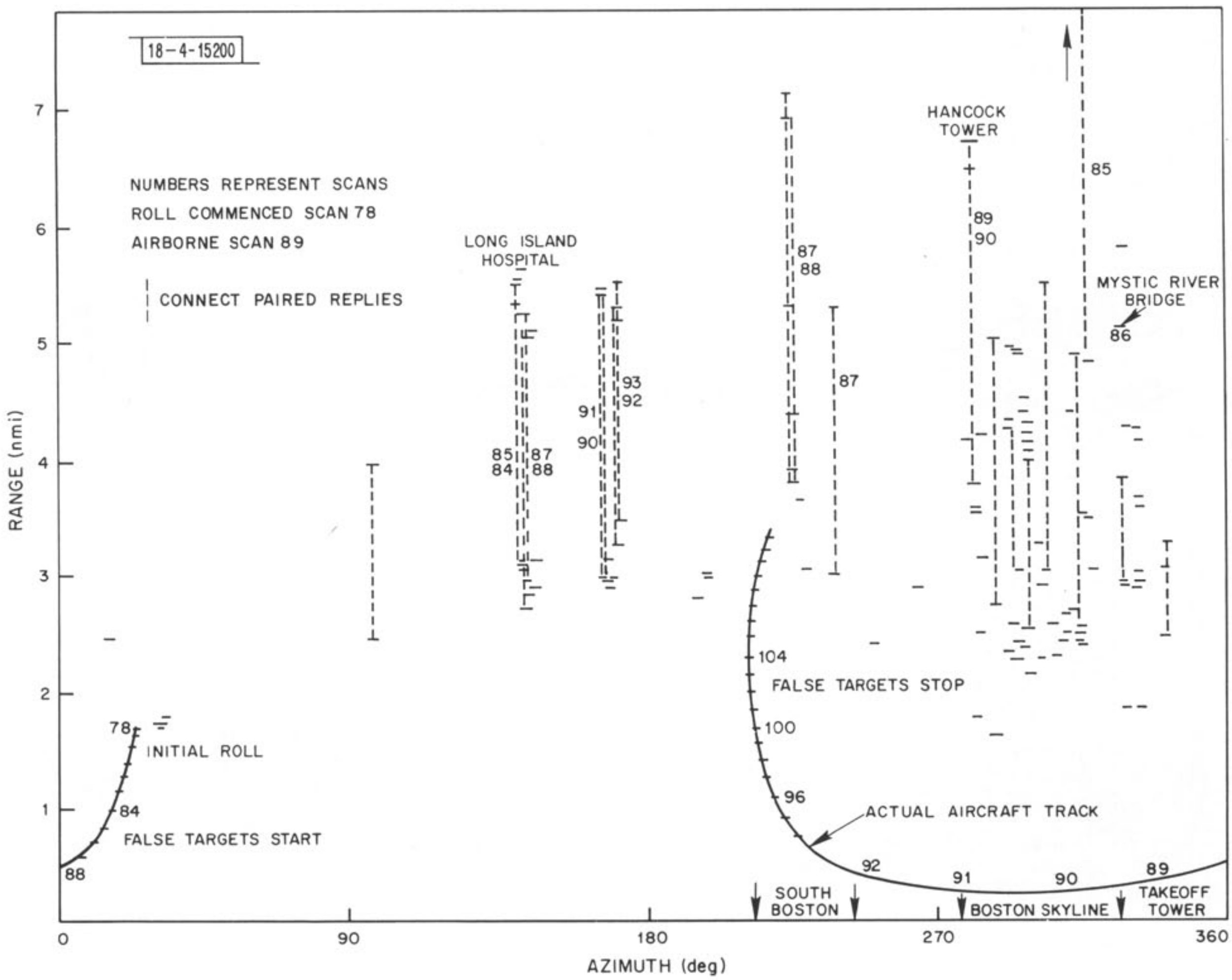


Fig. 33. False Targets Caused by Aircraft on Takeoff - Boston (Aircraft #1).

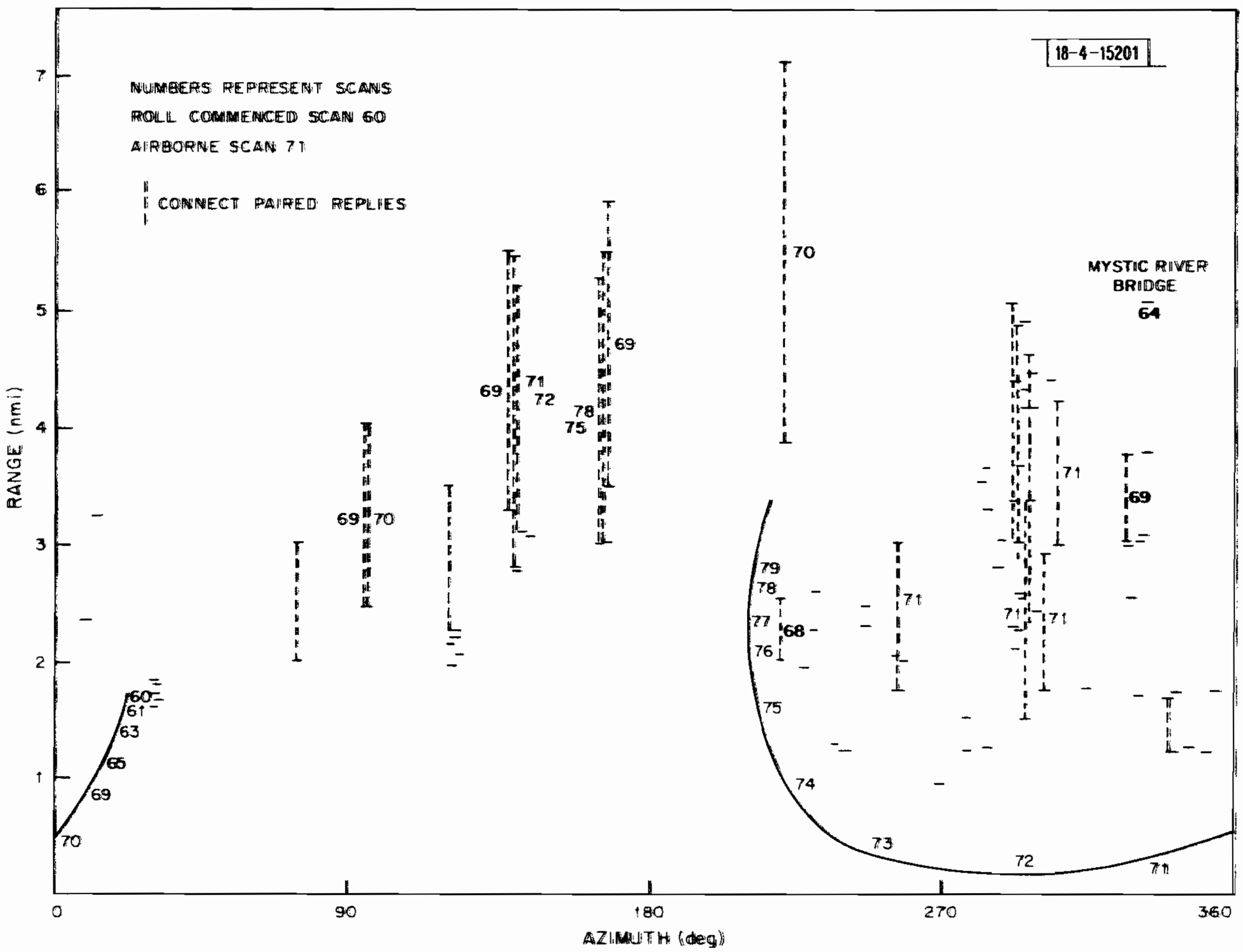


Fig. 34. False Targets Caused by Aircraft on Takeoff - Boston (Aircraft #2).

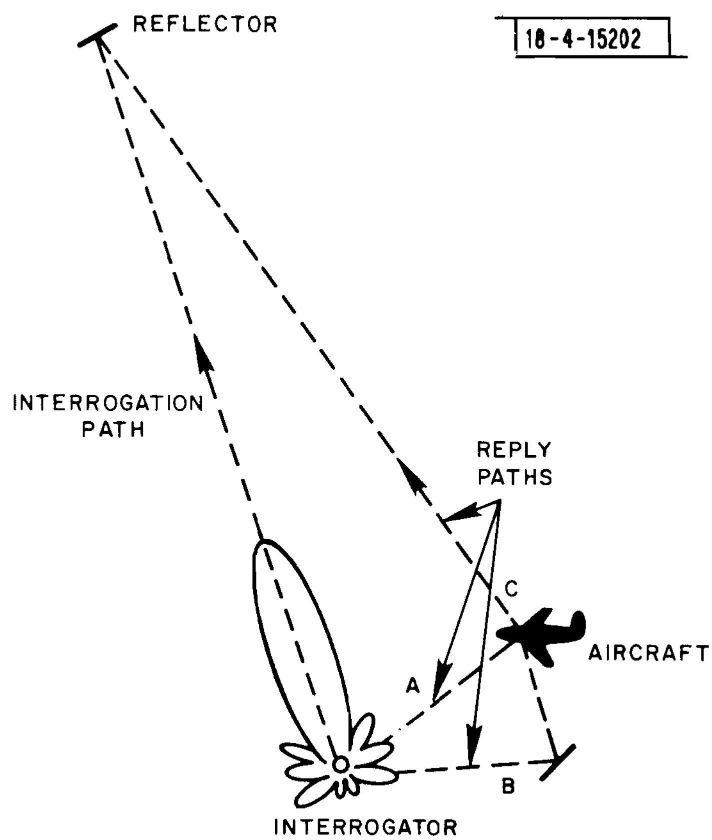


Fig. 35. Close-In Reflection Geometry.

In addition, in several cases, replies at ranges between the two corresponding to these mechanisms are present, suggesting that other reflection mechanisms provide sufficient signal levels on the reply path to penetrate the I/R antenna sidelobes. Examination of the RF power levels involved (Table 9) reveals that these mechanisms would require large reflecting surfaces to provide sufficient power to be detected.

As Table 9 suggests, the reply path through the antenna sidelobes is substantially stronger than the reflected reply path. This is borne out by the data, which shows in all cases that the sidelobe (shorter range) reply sequence is wider (of longer runlength) than the reply sequences occurring at the longer range, corresponding to the reflected reply path. This fact also suggests that the interrogation link is overpowered relative to the reply link, since it must be successfully interrogating the aircraft throughout the period in which synchronous sidelobe replies are being received. Note that Table 9 does not support this observation; it was prepared using "typical" transponder parameters. Apparently those on the two aircraft involved were atypical.

The fact that the sidelobe reply path is stronger than the reflecting reply path enabled us to interpret reply sequences occurring only at a single range over several sweeps as being the result of a reflected interrogation and a direct (sidelobe) reply, and to determine the reflector location accordingly.

Based upon the data, the actual aircraft positions, and the above considerations, the locations and orientations of several of the more severe false target producing reflectors were determined; these are plotted in Figure 36. They are generally in good agreement with locations of reflecting surfaces observed on the panoramic photograph (Figure 32b).

Table 9. RF Link Parameters at Boston.

Interrogation Path

(Range from interrogator to reflector...5 nmi)

(Range from reflector to aircraft...5 nmi)

(Assuming A 60' x 20' reflector)

Output Power (650W)	58 dBm
I/R Antenna Gain	22 dB
First Hop Pathloss (5 nmi)	-111 dB
Reflector Gain (x2)	77 dB
Second Hop Pathloss	-111 dB
Aircraft Antenna Gain	0 dB
Received Power	-65 dBm
Transponder MTL	-76 dB
Excess Signal Power	11 dB

REPLY PATHS

(Range From Aircraft to Interrogator...2 nmi)

	Direct Through Sidelobes (A)*	Reflected Through Sidelobes (B)	Reflected Through Main Beam (C)
Output Power (200W)	53 dBm	53 dBm	53 dBm
Antenna Gain	0 dB	0 dB	0 dB
First Hop Pathloss	-105 dB	(1nmi) -99 dB	(5nmi) -111 dB
Reflector Gain (x2)	------	77 dB	77 dB
Second Hop Pathloss	------	(2nmi) -105 dB	(5nmi) -111 dB
I/R Antenna Gain	-7 dB	-7 dB	+ 22 dB
Received Power	-59 dBm	-81 dBm	-70 dBm
STC Desensitization (nmi)	-15 dB	(7nmi) -14 dB	(10nmi) -10 dB
Tangential Sensitivity	-92 dBm	-92 dBm	-92 dBm
Excess Signal	18 dB	-3 dB	12 dB

* Note: letters refer to signal paths of Figure 35.

Fig. 36. Reflectors at Boston - Low-Altitude Aircraft.

While the same factors that were discussed in connection with the Andrews data limit the accuracy with which the reflectors at Boston can be located, several additional factors warrant consideration. As mentioned, although aircraft position was known upon initial takeoff roll and after departure, ARTS III did not declare actual target locations in between. This necessitated interpolation of the fourteen aircraft positions surrounding actual takeoff. Declared position (rather than tracker-derived position) was used exclusively, where available. Position was corrected to account for the time difference between the beginning of a scan and the instant when the aircraft was seen by ATCRBS; the positions shown in Figure 36 are those of the aircraft at the beginning of each scan. The interpolation procedure assumed uniform horizontal acceleration from the smoothed velocity observed immediately prior to loss of target up to the velocity observed on departure, when actual target reports resumed. (In both cases, targets were at essentially constant velocity when they were reacquired by ATCRBS.) In both cases, the point at which departure velocity was reached (where horizontal acceleration stopped) occurred one or two scans after takeoff.

Although horizontal position was not directly measured during the few scans around takeoff, altitude information was available, since both aircraft were Mode C equipped, and Mode C data came through successfully with the false replies. Thus, the takeoff point and altitude could be accurately determined. Corrections for slant range were made while the aircraft were in the vicinity of the radar. In the case of one aircraft, after position had been interpolated, it was discovered that the aircraft was replying to sidelobe interrogations (causing ring-around) throughout its takeoff. Range determined from ring-around replies agreed well with calculated positions.

Many potentially strong reflectors observed on the panoramic photograph (Figure 32b) (most of the Boston skyscrapers) were not found to contribute to the particular false target patterns observed. This is again consistent with the argument that reflections are highly specular; careful examination of an enlarged photograph of that sector reveals that the buildings are not oriented exactly broadside to the radar, which would be necessary to illuminate the airspace where the departing aircraft were. It appears that they would be more likely to affect operations at the opposite end of the runways (i.e., departures on rwy 4). Analysis of data taken during such operations would be helpful to confirm this; no such data has been analyzed to date. It appears that an almost entirely different set of reflectors would likely be involved in those cases. Since over three dozen false reply sequences were noted in the data on hand, taken during rwy 22L departures, the total number of reflectors affecting the site is likely to be very large.

Severe garbling was noted regularly on the downlink, indicating that multiple reflection mechanisms were often active simultaneously. This was apparently the case on the uplink also, for one aircraft was observed on several occasions replying to Mode A interrogations (8 μsec spacing) with its Mode C reply code; this indicates that it had not received a single reflected interrogation of sufficient strength, but rather the superposition of several, which somehow appeared consistent with a Mode C interrogation (21 μsec spacing).

The false targets at Boston are frequently declared; on several occasions during observation of incoming traffic, the ARTS III tracker actually correlated with (and attempted to track) false targets. One inbound was tracked by

ARTS III to the runway threshold, and then appeared to make an abrupt left turn and head rapidly to the west. ARTS III actually tracked all this (and coasted out to about 15 nmi).

6. Our Data - Las Vegas

The ATCRBS/ARTS III installation at McCarran International Airport (Las Vegas, Nev.) (LAS) has been cited frequently as having an unusual and severe multipath reflection problem. This problem leads to generation of false targets at the same azimuths and at ranges up to half a mile greater than those of the actual aircraft producing them. In order to determine the source of this problem, and thus suggest means to correct it, several ARTS III extractor tapes were obtained from the site and from Western Region headquarters. Analysis of the data on these tapes showed that false replies appeared to fall into two categories: those in adjacent range cells to the responsible aircraft, which were most likely caused by problems in the ATCRBS I/R, and those which fell further out, which appear to be caused by reflections in the surrounding environment.

The latter type of false replies, occurring at excess ranges of greater than one range cell, were observed in the first LAS data tape at several azimuths. Consistently strong false replies (frequently leading to false target declaration) were observed, in particular, in the azimuthal bands 041-042°, 132-138°, 170-173°, 194-198°, and 352-355°. Indicated excess ranges of up to 7/16 nmi were noted. Consideration of the transponder suppression mechanism leads to the conclusion that the two (real and false) replies are both due to a single reply transmission from the aircraft, received directly in the case of the real reply, and over a reflecting path in the case of the false reply. Since ARTS III equates range to round-trip time, difference in (one-way) direct and reflected path distances is twice what is indicated, or up to 7/8 nmi.

The same reflecting mechanism is undoubtedly present on the uplink; however, transponder suppression caused by receipt of the first interrogation causes the transponder to ignore the second one. Such "echo suppression" was recognized as desirable early in the development of air-to-air IFF, and is a principal reason for requiring transponder dead times; however, it is rarely observed in ground installations, where reflections from nearby ground more frequently cause vertical lobing, due to the extremely small pathlength differences usually observed.

That uplink reflections were occurring was confirmed to some degree by the observation that one aircraft, which was generating long - ΔR false replies, occasionally replied to mode C interrogations with its mode A code, causing completely spurious altitude reports. It apparently read P_1 and a reflected replica of P_1 as a legitimate mode A interrogation. A similar phenomenon, also caused by severe multipath reflections, was observed in the Boston data of the previous section; in that case, reflections were caused by buildings.

Whenever a long-ΔR reflection process was active at LAS, garbling or G-flag setting was noted far more frequently than actual garbling, suggesting that there were significant differences in direct and reflected signal levels. Occasionally, pulses were garbled in the direct or reflected replies which could not have resulted from one of them garbling the other, but rather appeared due to a third replica of the reply, appearing at an intermediate range; these replies were never bracket detected. This is consistent with ARTS III BDAS performance which is such that replies of that sort (the middle ones in a triple garble) cannot be detected, due to overloading of the decoding registers.

The result of all of this on operational performance at LAS is regular and severe problems associated with tracking aircraft through regions illuminated by reflectors; although we did not examine our data for tracking performance, we understand from LAS personnel that trackdrops occur frequently because of this. Erroneous altitude decoding is also freqı ently noted. Both phenomena are consistent with the poor target declaration and decoding performance we observed.

False replies occurring in two sectors (170-173° and 194-198°) were analyzed in detail. On the assumption that each resulted from a single reflection of the legitimate aircraft reply which was received directly, the following parameters were calculated for each reply sequence noted: (See Figure 37)

R_R - range from the I/R to the reflecting surface.

θ_R - center azimuth of the reflecting surface.

θ_I - inclination angle (horizontal ground = 0°) of the reflector, measured in the plane of the I/R and aircraft.

θ_S - "Skew" angle, the angle at which the reflecting surface is tilted to the right or left, as measured in the plane normal to the line from the I/R to the reflector. A tilt downwards to the left (such that the center azimuth of the false target is <u>greater</u> than that of the aircraft) is defined as negative; a tilt to the right is defined as positive.

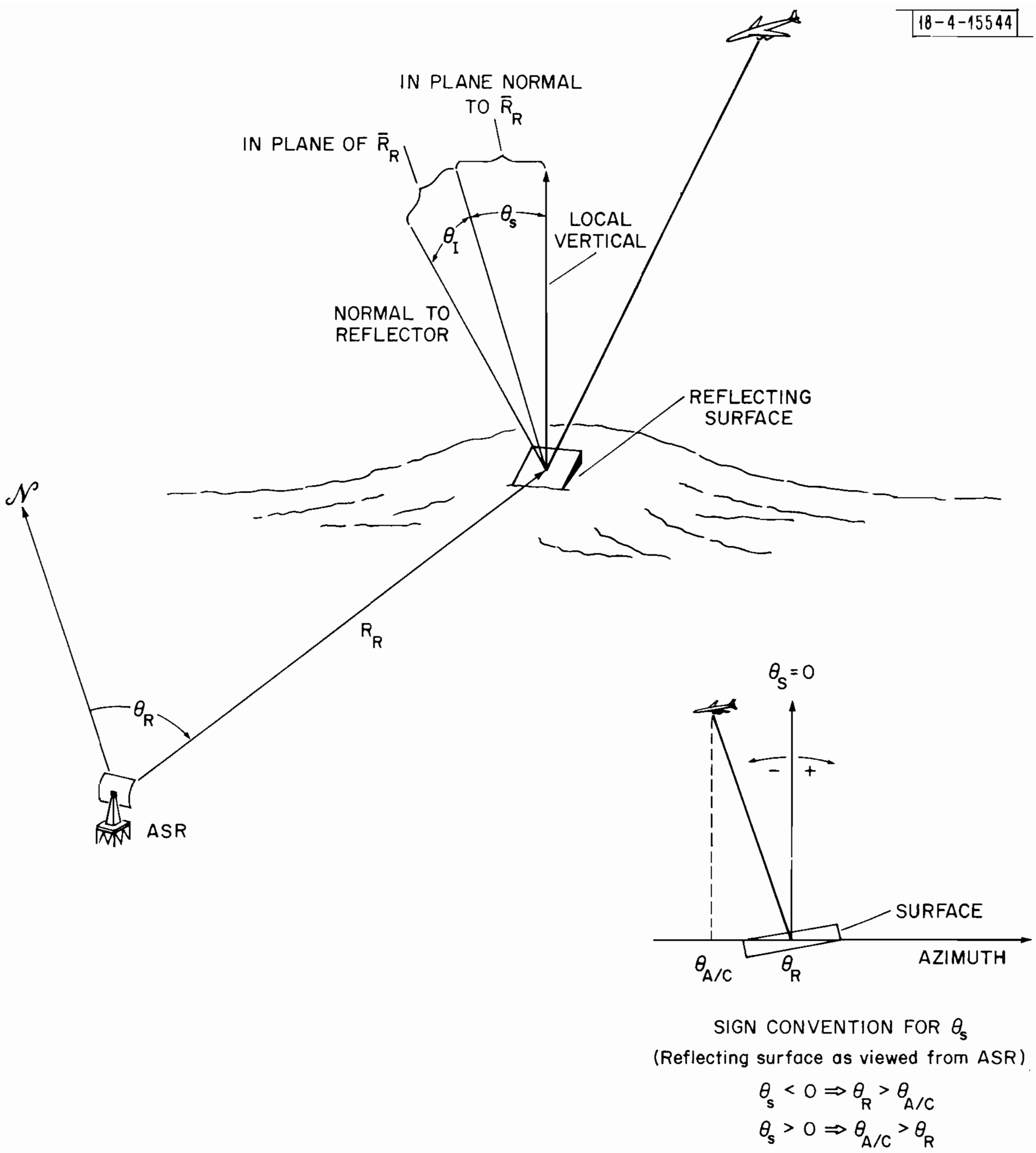


Fig. 37. Las Vegas Reflection Path Geometry.

Table 10a presents these four parameters for the false replies around 172°, listed in order of increasing θ_R; Table 10b presents similar data for the 193° sector. Figure 38 is a topo map of the areas of interest.

It is evident that the data in Table 10 are quite noisy; from the nature of the area in which the reflections were occurring, one would expect them to be. Due to the continuously changing terrain angles and aircraft positions, it would be expected that each reflection would be centered at a slightly different point on the ground. Other sources of error include range quantization and uncertainty in actual aircraft height above terrain; these would affect R_R severely, so little faith in the precision of that parameter is warranted. Effects of refraction and earth curvature, as well as sloping ground, were included, but found to be quite small relative to the error sources noted above.

Another difficulty resulted from the fact that reflected replies were observed only on those sweeps where direct replies were also received, in spite of the fact that the reflection mechanism could conceiviably have continued past (or commenced before) the edges of the direct reply sequences. That this was not noted was probably due to the inability of the reflecting path to sustain interrogations of sufficient power to elicit replies, or to successful I SLS operation, or both, (Typical aircraft range was 30 nmi.) The effect of this is to reduce the difference between the aircraft and false target azimuths (already small compared to a beamwidth), and thus lead to an overly conservative estimate of θ_S.

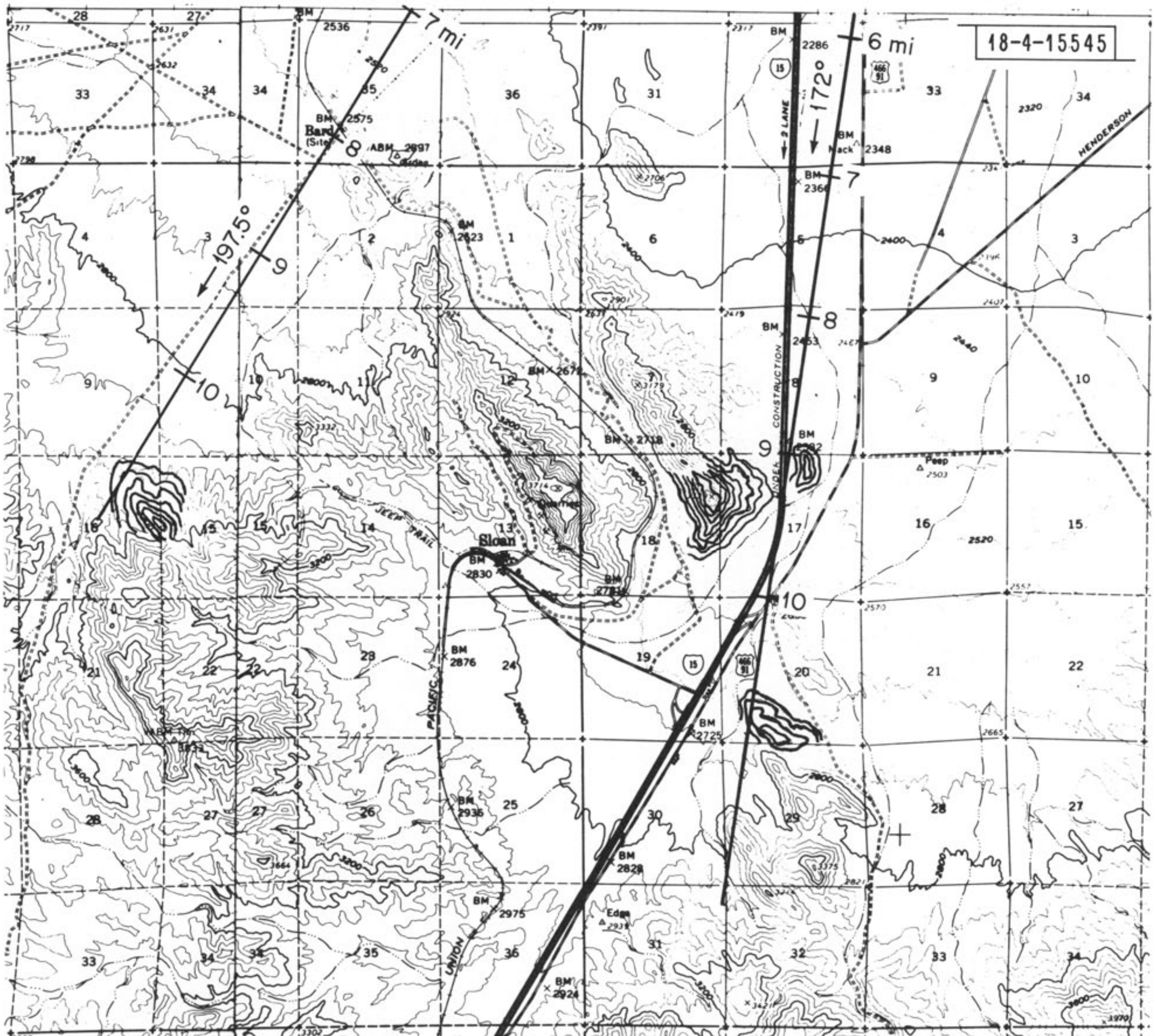


Fig. 38. Topographical Map of Reflecting Area - Las Vegas.

Table 10a. Parameters of Reflectors Observed Around 172°. (In order of increasing θ_R.)

θ_R (degrees)	R_R (nmi)	θ_I (degrees)	θ_S (degrees)
169.45	8.8	14	+ 1.8
170.5	8.8	11.5	+ 6.3
170.5	10.5	13	+ 4.8
170.9	9.2	13.7	- 2.1
171.2	9.4	13.5	+ 3.8
171.21	10.1	13.2	0
171.5	10.0	11.5	+ 5.1
171.	9.0	10.	+ 2.6
171.9	8.0	11.6	+ 3.33
172.1	8.5	12.3	0
172.3	6.5	11.3	- 6.8
172.3	6.8	11.4	- 3.1
172.3	9.0	12.	+ 5.2
172.7	6.1	9.5	- 0.9
173.1	5.2	10.1	- 3.9
174.0	7.1	9	- 3.2

Table 10b. Parameters of Reflectors Observed Around 193°.

θ_R (degrees)	R_R (nmi)	θ_I (degrees)	θ_S (degrees)
194.	9.3	14.5	+ 3.8
196.3	9.1	8.3	+ 2.45
196.9	8.9	8.4	- 3.9
197.2	10.9	7.6	+ 9
197.6	10.1	8.	0
197.6	9.9	8.	- 0.84
198.5	9.8	12.2	+ 3.72

Note: Parameters defined in test and depicted in Figure 37.

In spite of the noise in the data, observe that some parameters agree fairly well with the terrain on the topo chart. In the 172° data, the variations of range and especially θ_S with azimuth appear consistent with the topography. (The change of θ_S from positive to negative with increasing azimuth suggests a slightly concave surface, which is seen on the chart.) Examination of elevations on topographic charts reveals that the two hills causing this concavity are within line-of-sight of the ASR, and that they are the first significant inclinations seen by the I/R site. Similarly, the generally positive skew angle in the 193° data is consistent with the slope of the hill there. In the same manner, calculated inclination angles are consistent with the slopes of hills observed on the charts.

The areas of reflecting surfaces observed on the chart appear sufficient to sustain a reflection mechanism of the sort noted, provided their reflectivities are fairly high (Table 11). Note that calculated reflectivities of various types of soil exhibit nulls at angles of incidence between 10 and 20° (the Brewster angle); the angles of incidence in this case are in that range. Since we have not seen the reflecting surfaces and have no idea of their composition (except to note from the topo map that they have little vegetation), it can only be speculated that their Brewster angles are sufficiently different from the actual angles of incidence to support the reflection process.

Reflection from (sandy ?) hills on the reply path appears to be the only plausible explanation of the peculiar LAS false target problem consistent with the data on the first LAS tape. An instrumented measurement program appears necessary to completely confirm (or refute) this conclusion. Other possible sources of the problem which have been suggested in the past include improper

Table 11. RF Link Parameters Associated with Downlink Reflection Process.

P_T	(400W)	56 dBm
G_A	(aircraft)	0 dB
ℓ_1	(20 nmi)	-124 dB
G_R^{2*}		74 dB
ℓ_2	(10 nmi)	-118 dB
$G_{I/R}$		22 dB
I/R tangential sensitivity		-90 dBm

*Selected to make received power equal tangential sensitivity.

G_R^2 = 74 dB.

This could result from a sloping surface inclined 8° with reflectivity = 0.5 and area 300 x 300 feet.

line termination within the ATCRBS I/R, and temperature inversions. The strong dependence on azimuth (and correlation of the data points to the extent that they do) would tend to rule out the former; the fact that the phenomena are seen at various times of day and under various weather conditions would appear to rule out the latter. That the phenomenon should be peculiar to LAS can only be ascribed to the peculiar terrain, lack of vegetation, and so forth.

7. Fixes

As noted previously, the usual false target mechanism (involving relatively small numbers of vertical reflectors subtending relatively large solid angles as viewed from the I/R antenna) is highly deterministic, regular, and predictable. It therefore appears particularly amenable to a software fix which could be accommodated in ARTS III (perhaps with some addition of memory or processing equipment in some instances). Just as autoacquire and automatic track drop areas are defined within the ARTS III memory presently, so too could "suspect false target" regions be included. Generally, each of these would be simply an azimuthal sector a few degrees wide. Along with each would be stored the two parameters, ΔR and θ_o, corresponding to the particular reflector, which relate false and actual target positions (Figure 26). Whenever a target was observed within a "suspect false target" region which was not tracked in from outside, a special subroutine would be entered, which would:

- Determine the actual target position corresponding to the suspected false target.
- Search the trackfile or observe the target declarations on the next scan to determine whether there is a target near that position, squawking the same code and altitude as the "suspect."
- Repeat the process for a number of scans, and discard (or at least flag) the false target if correlation continues.

The various parameters involved (e.g., number of scans prior to making a decision, allowable variation between predicted and actual position, etc.) would necessarily be determined by experimentation; in addition, the relative penalties for inadvertently dropping a real aircraft and failing to identify a false one would influence the setting of these parameters. Further pursuit of this concept has not been possible in the present study, but it appears to be an area of extremely high payoff, involving a relatively small amount of research, experimentation, and development.

Another similar concept which has been employed to a limited extent at sites where the false target problem is severe involves attempting to correlate target reply declarations with primary radar replies. When beacon replies are observed consistently with no primary radar reinforcement, they can be flagged as suspect or dropped. This concept will be simple to implement when the radar data acquisition system (RDAS) being developed by UNIVAC under the ARTS III enhancement program becomes operational, but is limited today to those very few terminal sites (e.g., New York, Los Angeles) which are equipped to process radar data.

This process could be accomplished manually simply by readjusting display brightness controls to eliminate ATCRBS video, activate primary radar video, and continue to display ARTS III symbols. Any symbol not accompanied by video for several scans could be considered false. Operation in this fashion appeared to be quite effective when tried on a spare display at Boston.

These relatively simple fixes could eliminate a large fraction of the false targets declared by ARTS III. Exact numbers pertinent to the entire country are not known, since only a few sites were examined; however, they could be expected to successfully eliminate virtually all "conventional" false targets, leaving only those caused by unconventional geometries, such as that observed at Boston and Las Vegas. Sites such as these would require some detailed engineering analysis in order to select the right combinations of fixes to employ to remove the residual false targets. Many fixes are available to do this; for each site, some combination of the following fixes could be expected to eliminate virtually all false targets not caught by the software procedures described above.

a. Procedural changes: Since the Boston problem is severe only during takeoff and initial climb, or final approach, it certainly appears possible to request aircraft to squawk standby during these phases of flight, and to activate transponders only upon handoff to departure control in the departure case; in the approach and landing situation, this action would occur upon handoff to the local controller. Of course, these are the most critical phases of flight, and nontechnical problems associated with forcing an additional work item on pilots are likely to be severe. In addition, the trend toward improved surveillance in the immediate vicinity of the airport (as exemplified by the ATCRBS - based ground surveillance study being conducted presently) is completely contrary to this approach.

b. Shielding: Since most reflectors are low on the horizon, it appears that an earthwork dike, built the proper distance from the interrogators, with properly sloping walls (as described in Ref. 7) might be fairly effective, at least in some sectors. Unfortunately, in the case of Boston, in many critical directions, proper siting of a shield of this sort would be hazardous to flight, or would interfere with shipping.

c. Adjustment of parameters: Based on the brief analysis made to date, it appears that the interrogator at Boston is very overpowered; this is done to mitigate the problem of weak targets. New fixes to that problem could allow some power and sensitivity reduction. Assuming that a reflector has equal effects on both the interrogation link and the reply link, the fact that sidelobe (direct) replies are observed at azimuths beyond those where the replies reflected over the mainbeam path stop suggests that power could be reduced to the level when the lengths of these two reply sequences (i.e., mainbeam/reflected and sidelobe/direct) are equal. At that point, the uplink and downlink would be equally powered if the assumption regarding reflector effects is valid.

Since the ranges at which the Boston false targets occur are known precisely it appears that a programmed STC curve a bit more complex than the usual exponential, perhaps varying as a function of azimuth, could be used to advantage. Whether this would provide sufficient margin to block direct sidelobe replies is not known, and would require extensive RF measurements to determine.

Sensitivity adjustments have been attempted as a means of eliminating the LAS false replies; however, it appeared to site personnel that the level of these replies was within about 5 dB of the direct replies. This does not allow a sufficient margin to eliminate false replies on the basis of signal level in the LAS case.

d. Employ a delayed repeater for P_1-P_2 pulses: This appears to be by far the most desirable fix in the Boston situation. Apparently, for the most part the false targets there are multiple returns from multiple reflectors of a single aircraft reply per sweep, elicited by a reflected interrogation which arrives at the aircraft after ISLS suppression is completed. The times during which these interrogations arrive at the aircraft are well-bounded and well known as a function of mainbeam orientation and aircraft position on the airport surface. A relatively low-powered source of omnidirectional P_1-P_2 pulse pairs, appropriately delayed, might be used effectively to silence transponders in the immediate vicinity of the airport (by SLS inhibiting) at the instants the reflected interrogations are heard. This is nothing more than a generalized form of "improved SLS." In principle, this silences transponders for a suppression interval (typically 30-40 μsec according to Ref. [9]), thus preventing their response to interrogations arriving within that period after the main interrogation (which is usually the case when reflectors are close to the interrogator).

Since virtually all major reflectors are distant at Boston, reflected interrogations arrive after transponder suppression is complete; thus, "improved SLS" would not appear to improve the situation at all. Boston radar maintenance personnel stated that this was indeed the case.

A properly delayed P_1-P_2 interrogation, however, could be timed to suppress transponders at the correct moment (ranging from 20 to 50 μsec after the main interrogation, depending on the azimuth). Since this signal would always follow the main interrogation, it would have no effect on the legitimate operation of the site, and, if limited to low power, would not appreciably reduce the reply probability of other nearby radars. Because the signals would be broadcast while the ATCRBS receiver is in operation, substantial isolation would appear necessary. Whether they could be broadcast from an auxiliary horn at the ATCRBS site, or would require further isolation by locating the "ISLS repeater" at a different point on the airport surface, remains to be determined, as do the detailed timing characteristics involved for each installation, including whether or not the delay would have to be programmed to vary with interrogation azimuth. In addition, if the "ISLS repeater" were separately located from the ATCRBS site, study would be required to determine the most effective location in each case, and whether it could cause erroneous triggering of transponders at certain positions, when received in conjunction with the main interrogation. This is not anticipated to be a severe problem, since power levels would be disparate, and ISLS would be expected to silence transponders in this situation. Another area requiring study concerns how to time these inhibiting signals in such a way that they are not ignored by transponders already suppressed by the initial ISLS interrogation. One way to accomplish this might be to turn off the "improved SLS" system. Whether the benefits gained by this outweigh the disadvantages, if any, also remains to be determined.

e. Re-site the surveillance system: Presently, ATCRBS sites are selected mainly in accordance with primary radar considerations. In order to minimize clutter, FAA policy requires siting close to the ground. ATCRBS performance would be substantially improved if the interrogator antenna were sited at a higher elevation (for example, on top of the new control tower at Boston or at the LAS ARSR site, which is located 28 nmi WNW of LAS airport, at an elevation several thousand feet higher.) Weak target problems due to blockage would be reduced, since fewer obstacles would appear on the horizon if the sensor were elevated; this would allow operation at reduced power and sensitivity. In addition, false-target causing reflectors would tend to reflect interrogations down into the ground rather than into the air. New clutter elimination techniques would appear to allow the primary radar to be sited in such a location.

f. Employ an antenna with a sharp vertical cutoff at the horizon: This direction is presently being pursued as a means of reducing the effects of vertical lobing due to reflections from ground at slightly negative angles. In the case of the reflections seen at Las Vegas, however, it was noted that the reflecting surfaces were usually at positive elevation angles, up to 1 $1/2^{\circ}$; actual targets were seen with 3° or lower elevations. The vertical cutoff would of necessity be extremely sharp to eliminate the former and not the latter. Because of changes in elevation angle as a function of azimuth, programmed switching of cutoff angle could be necessary.

g. Employ NADIF: The fix used by Spingler at No. Platte and other sites, which employs AN/CPN-19 dipoles mounted outboard of the radar feed horn, illuminating the radar sail, might be effective at these sites; this fix has recently been given its own acronym: the NAFEC DI pole Fix (NADIF). Appropriate placement and phasing of the dipoles can result apparently in variations in gain with elevation angle which might suffice to attenuate the false replies sufficiently. It should be noted that in the past this procedure has been used by FAA only on ARSR's; pattern degradation due to the smaller size of the ASR sail might reduce its effectiveness in terminal installations.

Several variations in this basic concept come to mind: use of the conventional "hog-trough" directional antenna could be continued along with the NADIF, perhaps tilted upward. Relative amplitudes and phases could be adjusted to place a null at the elevation angle of the reflectors. Alternatively, the "hog-trough" could be used in a difference mode for transmission of P_2 pulses in an "uplink monopulse" scheme, to compensate for the increased beamwidth resulting from the smaller radar reflector.

h. Remove False Target Declarations in Software: Currently, LAS personnel are inhibiting the generation of "piggyback" target reports by means of a modification to the DAS, which prevents a reply word from being generated within 6 μsec of another one. (This modification was, of course, not in operation during the time our data was taken.) An undesirable consequence is that when two legitimate targets are within 1/2 nmi of one another in range, the more distant target will either be lost or will be declared with excessive azimuth error. Performing a similar function further downstream in the ARTS III target detection and reply correlation process could perhaps eliminate the false targets more effectively with a lower likelihood of missing legitimate targets, by varying the ΔR for which suppression would occur as a function of azimuth, based on a knowledge of what reflecting mechanisms are active at what azimuths. Either solution would suppress the generation of double target reports, but would do nothing to improve the garbling (real or apparent) caused by the reflected replies; thus, these techniques would not provide substantial improvements in tracking performance.

8. The Role of "Improved Sidelobe Suppression"

FAA has widely implemented a system known as "improved SLS," in order to reduce the incidence of false targets. In this system, a portion of the P_1 signal energy is intentionally radiated along with P_2 over the omni antenna. The intent of this is to suppress all transponders within the omni coverage volume not in the mainbeam during the time interval when reflected interrogations from close-in reflectors would be expected. This technique has the admitted deficiency of being unable to suppress false targets due to reflectors whose locations are such that reflected interrogations reach the aircraft transponder either before it goes into suppression or after it comes out. In addition, the large number of suppressions could be expected to reduce reply probabilities associated with other nearby interrogators, although this effect appears to be negligible.

Because of the distances from the Boston I/R site to the reflectors of interest, "improved SLS" would not be expected to be effective there; indeed, tower personnel, when observing ATCRBS video displays, have been unable to discern any improvements (or, indeed, any changes at all) resulting when "improved SLS" is switched in and out by maintenance personnel.

Arrival time differences associated with virtually all the false-target producing mechanisms at Andrews, however, were such that "improved SLS" would be expected to eliminate the false targets observed. "Improved SLS" was operating when the Andrews data was gathered; there is no evidence in that data that it suppressed any false targets. This could be the result of several shortcomings, none of which can be verified from the data on hand. The most plausible reason why "improved SLS" was not effectively suppressing false targets is that the omni transmission RF power level is insufficient to cause suppression except at some minimal range. This was suspected at first, but examination of data taken with an aircraft employed for the switched antenna test revealed false targets (those labeled H and I) resulting from that aircraft while it was on the taxiway. Differences in arrival time were appropriate for proper operation of "improved SLS," the transponder was suppressing properly, and the observed data was consistent in every way with the geometry. In short, there is no obvious explanation derivable from the data on hand as to why the Andrews "improved SLS" is not operating effectively. Similar performance was observed at other sites.

Whether the problem is peculiar to a few sites or widespread is not known; nothing in the Boston data suggests that the Boston "improved SLS" is functioning properly (but, on the other hand, one would not expect "improved SLS" to change the situation appreciably at Boston).

A fairly straightforward way to attack this dilemma would involve a single test flight employing a simple straight-line low-altitude approach to Andrews along the 277^{o} radial of the Andrews VORTAC (the center of the area illuminated by the large reflecting hangar, labeled E in Figure 29). Determination of the range at which false targets caused by the test aircraft cease would yield a direct measure of the effective range of the "improved SLS." Our data suggests that this is likely to be exceedingly small.

9. Conclusions

It appears that several simple and straightforward improvements to ARTS III software could effect a substantial reduction in the incidence of false targets due to reflections. These improvements could be developed, implemented on a limited basis, and tested, with little difficulty. Once these are effected, many other practical techniques are available to eliminate any residual problems. Thus, it appears that a properly directed research and development program could reduce the false target problem to the level where it is no longer troublesome. The false target problem is pivotal in the sense that its correction would allow the necessary modifications to ARTS III target detection logic to be made in order to reduce other problems such as the weak target problem (Section III.A).

A program of this nature should start with the necessary data-gathering, to determine the false target environments at <u>all</u> sites, in order to provide a rational basis for deciding what mechanisms are most in need of elimination.

In addition, at an early stage of the investigation, a more detailed determination should be made regarding the effectiveness of "improved SLS," and if the results are consistent with those seen in our data, proper steps should be taken to determine how the technique could be made more effective.

C. Synchronous Garble

The synchronous garble problem was suggested by ATCAC to be the principal surveillance problem not amenable to straightforward solution which would become so severe in the next several decades to warrant major changes in the active surveillance system. Although it is not presently considered to be a problem, it is apparent that when the densities of aircraft forecast by ATCAC come about, the effects of synchronous garble on the system could become severe.

1. Discussion

Since many different phenomena are involved in the synchronous garble situation, and all are generally given the generic term "synchronous garble," it is appropriate at the outset to define these several phenomena more precisely. MITRE [10] has defined the event "two aircraft sufficiently close in range and azimuth such that any replies are overlapped in any way"* as the synchronous garble event. Use of this definition leads to straightforward analysis from which the conclusion results that when the ATCAC-forecasted traffic density levels are reached (1995), the probability of a synchronous garble for any arbitrary aircraft on any arbitrary scan will be very high (around 50% or so).

It must be emphasized that the synchronous garble event defined above is quite different from the event "something deleterious to system perform-

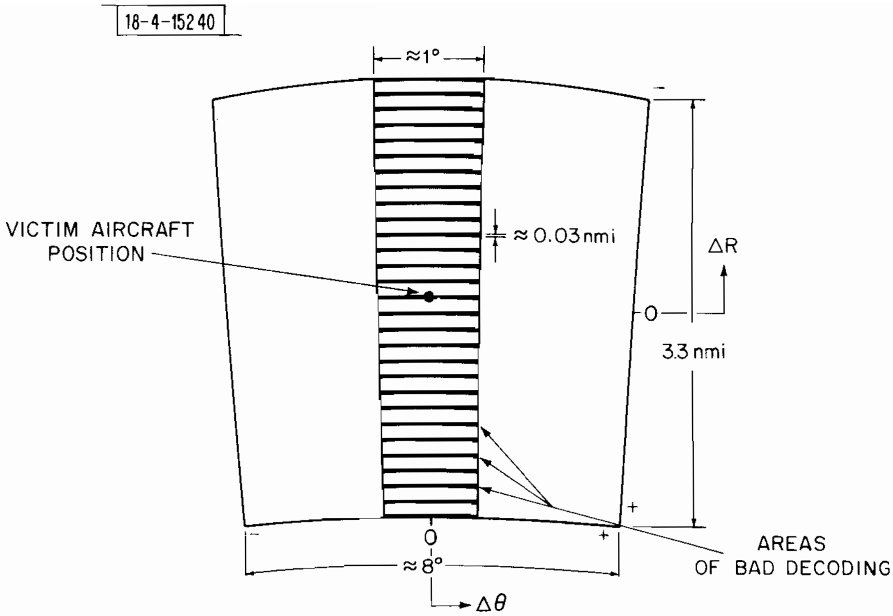
* Nominally, within 4^o and 1.65 nmi of one another.

ance occurs due to synchronous garble." The latter event comprises only a subset of the former. Our analysis of ARTS III performance data suggests that this subset is exceedingly small.

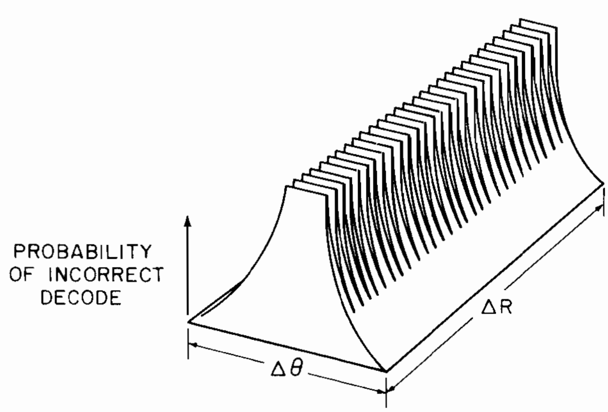
Given the synchronous garble event as defined by MITRE, some individual replies from each aircraft will be overlapped by replies from the other, and some will not. The numbers, of course, depend on the difference in target azimuths, and the target angular widths (see Section III.A for a discussion of target width statistics). Also, given an overlap of replies on a particular sweep the code pulses can either interfere with one another (overlap), or be time-separable by the decoding device (interleaved). The ARTS III Data Acquisition System (DAS) recognizes when individual replies are overlapped with sufficiently close spacing that erroneous decoding could result, and flags the replies. In the process of code determination, ARTS III searches through each reply set for ungarbled replies. If two ungarbled replies of the same code in a row agree, then that code is declared. Thus, in principle, correct decoding will occur in the synchronous garble situation whenever either a) reply sequences do not overlap exactly in azimuth, but rather a few replies (two is enough) extend beyond the azimuths where garbling occurs, or b) on individual sweeps, the difference between the arrival times of individual reply sequences is such that the DAS can separate and individually decode them. For a single interfering aircraft, and assuming that transponder reply parameters are within specifications (with regard to pulsewidth and timing), it is a relatively straightforward exercise to show that, given uniform probability distribution in range difference, the probability of incorrect decoding on a single sweep is roughly one-third. Likewise, assuming a single interfering aircraft, equal runlengths of sixteen mode A replies, and uniform distribution of azimuth difference, the probability that less than two replies in a scan will be garble-free is roughly one in sixteen. Thus, we would expect that, given the synchronous garble situation, an incorrect code declaration would occur only roughly one time in fifty. (Figure 39.)

Incorrect decoding on a single scan is not necessarily deleterious to ARTS III performance. Target reports are frequently lost for other reasons for brief periods, and the ARTS III tracker successfully "dead-reckons" until new data arrives. From Figure 39 we would expect, given the presence of the synchronous garble event over several scans, that the probability of incorrect decoding over several consecutive scans would be quite low, since decoding errors do not appear to be highly correlated from scan to scan. That is, given that range and azimuth differences are such that a decoding error occurs on one scan, it is far from certain that the same result will be present on the following scan. From Figure 39, it can be seen that changes in range difference of only a few hundred feet are sufficient to effect the transition from a "bad decode" area to a "good decode" area.

Finally, it should be noted that incorrect decoding does not necessarily imply loss of target. ARTS III will successfully perform bracket detection even when a framing pulse is completely overlapped by a garbling code pulse. The only cases when bracket detection would be expected to fail are a) when two reply trains are almost exactly overlapped ($|\Delta R| < 150$ nanoseconds), such that the composite reply has essentially the same length as a single reply, and b) in the case of a triple garble, when all three aircraft reply trains are overlapped such that the ARTS III DAS overloads, and thus eliminates the reply from the middle aircraft.



(a) Deterministic Model



(b.) Probabilistic Model

Fig. 39. Garble Cell Geometry for a Single Interfacing Aircraft.

2. New York 1968 Data

Lella [3] counted seventy erroneous code declarations of a particular discrete code in slightly less than two hours of flight testing in the New York area; fourteen of these were attributed to synchronous garble. All but one of these resulted in addition of incorrect pulses (in that one, the lost pulse was garbled by a framing pulse). In all but two cases, the decoder recognized that there was a potential error, and set the validity low.

Since the New York study was aimed primarily in other directions, no attempt was made to determine how many decoding successes occurred during synchronous garble. This quantity is, of course, essential in determining overall decoding performance. The data that was observed, however, (e.g., garble patterns, scan-to-scan correlations, validation performance, etc.) agreed quite closely with our data.

3. MITRE Data

Freedman [2] discussed the various mechanisms involved in synchronous garbling, coming to conclusions which agree in principle with those reached above but differing somewhat in numerical results due to different initial assumptions about DAS performance. He also recognized (and calculated the relative incidence) of subtractive code errors due to RF phase cancellation. These were predicted to be relatively infrequent; our data supports this.

As in the false target case, MITRE experimental data on synchronous garble was limited, and analyzed on a probabilistic basis. "The probability of synchronous garbling... was estimated from the Chicago videotape data by counting the total number of targets which had one or more of their replies synchronously garbled (as indicated by the garble bit* of the reply word), and dividing by the total number of targets present. Over a sample size consisting of 50 scans (with a traffic density of about 70 targets per scan), [the probability of synchronous garbling] was estimated to be 0.1. That is, 10% of all target sequences contained at least one synchronously garbled reply." [11]

Rather than going through these potentially garbled reply sequences and determing how many actually resulted in improper target code declaration, MITRE exercised the "MITRE Beacon Detection Model" [12] to estimate this parameter. Results are shown in Figure 40.

In addition, MITRE tabulated the results of field measurements of the percentage of targets having no ungarbled replies available for identity code validation (i.e., the number of target reports with mode A validity equal to 0). On the average, this percentage was found to be roughly one percent of the total target reports. It was recognized that this frequency of erroneous data had little effect on general tracking performance.

4. Our Data

Fifty scans of Andrews AFB data were examined for the presence of garbles by searching for replies with the G-flag set. Whenever one or more G-flags were observed in a sequence, the situation was examined to determine whether an actual synchronous garble was occurring, and whether ARTS III decoded correctly. Two points are worthy of comment at this point:

- G-flags were frequently set in connection with several VFR aircraft (code 1200); frequently two replies would be detected in each sweep, in adjacent range bins, with idential codes. This occurred with a small portion of the population, and tracking these aircraft over several scans made it apparent

*The same situation as "G-flag set" in the following section.

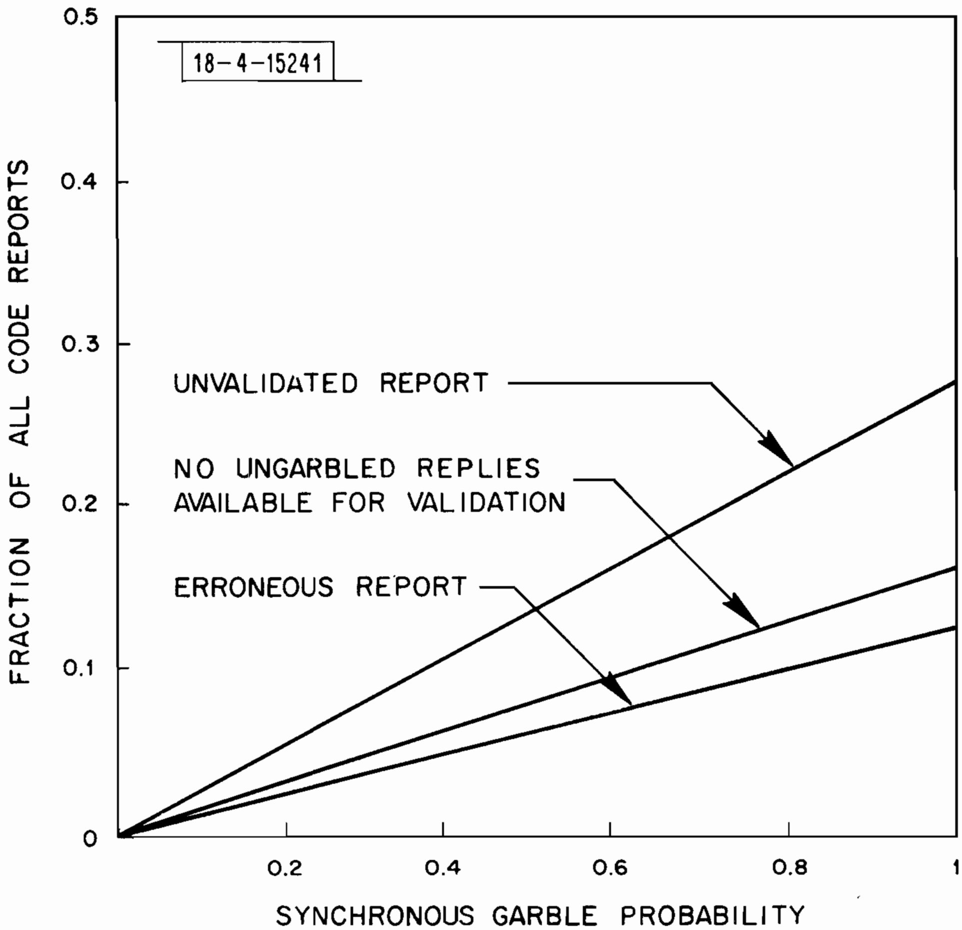


Fig. 40. Code Detection Performance.

that, rather than being the result of actual synchronous garbling, the G-flag setting and dual reply declaration were actually due to transponders whose pulsewidths were out of specification. All of these targets were decoded properly all the time; they are not included in the synchronous garble data which follows.*

- Recall that in theory two-thirds of the time ARTS III can properly decode reply codes which overlap one another (when these codes are "interlaced"). Under this circumstance, the G-flag is not set, since ARTS III has high confidence in decoding quality. Due to the manual nature of the data reduction, the only practical procedure to follow in this study was to search out garbles by looking for set G-flags. Thus, many instances in which ARTS III performed properly, which meet the definition of "synchronous garble," were not discovered, and are not included in the analysis, whose conclusions, therefore, are quite pessimistic.**

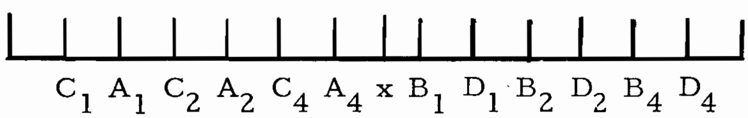
During the fifty scans of data, eighty-eight actual synchronous garbles were observed. Of these, eighty were decoded correctly. ARTS III incorrectly decoded one code in each of the remaining eight (Table 12). In all eight, the code of the other aircraft was declared correctly. Thus, ARTS III declared the code for the target correctly in the presence of synchronous garble approximately 95% of the time. In most cases of incorrect decoding (five out of eight), ARTS III had little confidence in its decoding performance, and set mode A validity low.

*If such behavior were present in the data analyzed by MITRE (above), this would tend to greatly increase the apparent probability of synchronous garble. (In the case of the Andrews data, that parameter would be more than doubled.)

**This fact would affect the MITRE data by making their apparent probability of synchronous garble low, since these events, which are certainly synchronous garble, are not counted in their analysis either.

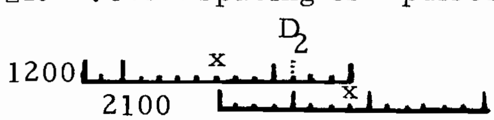
Table 12. Decoding Errors Due to Synchronous Garble (Andrews Air Force Base Data).

Scan #	Actual Code	Declared Code	Validity	Other air-craft code	ΔR	Predicted Error
2	1200	1202	1	2100	.875 nmi	1202 x
8	0500	0522	3	2100	.30 nmi	0522 x
9	0350	6750	0	1100	.43 nmi	6750
17	1300	0300	3	2100	.25 nmi	5300
22	1200	1602	0	0350	1.3 nmi	1602
24	1100	1500	0	2100	.93 nmi	1500
29	2100	3100	3	1100	.75 nmi	3100
43	1200	3230	0	1717	1.12 nmi	3230

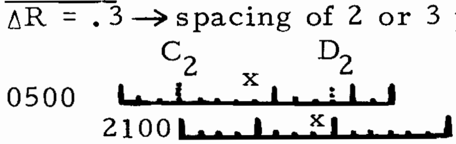


Pulse separation interval = 0.118 nmi

Scan 2
ΔR = .875 → spacing of 7 pulses:

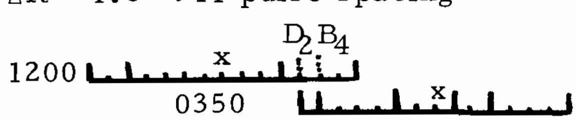


Scan 8
ΔR = .3 → spacing of 2 or 3 pulses

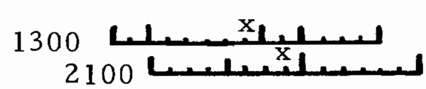


Scan 9: See Figs. 16 and 17

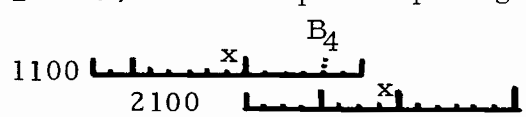
Scan 22
ΔR = 1.3 → 11 pulse spacing



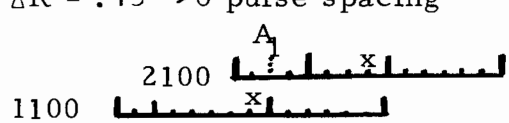
Scan 17
ΔR = .25 → 2 pulse spacing



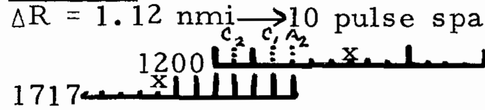
Scan 24
ΔR = .92 nmi → 8 pulse spacing



Scan 29
ΔR = .75 → 6 pulse spacing



Scan 43
ΔR = 1.12 nmi → 10 pulse spacing



Two phenomena were observed in the data which are not generally included in system modeling and analysis:

- Frequently at target edges, incorrect reply decoding occurred which was attributable to low RF link signal level rather than garbling. This caused missed bits, and in one of the eight cases (see Figure 43) was responsible for the incorrect code declaration. Two leading-edge replies were in the clear and recognized as such; however, these differed in one pulse, and therefore ARTS III chose to select the incorrect (garbled) but more consistent code. This phenomenon was recognized by Freedman, [2] and apparently by the ARTS III designers; ARTS III is inhibited from code determination until after T_L is declared (several sweeps into the sequence).

- The garble pattern imposed on a reply by another reply would frequently remain present for several sweeps after the point where that second reply ceased to be detected. (A similar phenomenon occurred on leading edges.) In these situations, frequently a code was obviously garbled but the DAS did not sense the garbling; thus, two bad codes in a row, not recognized as bad, could be detected, ARTS III could "make up its mind" that these represented the proper code, and all subsequent codes would be ignored, even though many might be the actual code. This phenomenon was responsible for two of the bad decodes (Table 12) which were declared with high validity.

In an attempt to determine empirically the validity of the analysis which led to Figure 39, the target range and azimuth differences corresponding to all seventy-six synchronous garble incidents are plotted in Figure 41. In this plot, no distinction is made among the four quadrants (corresponding to the four combinations of negative or positive ΔR and $\Delta \theta$ of the garbling aircraft relative to the garbled aircraft); symmetry is assumed, and was observed among the eight incidents resulting in decoding errors. The results

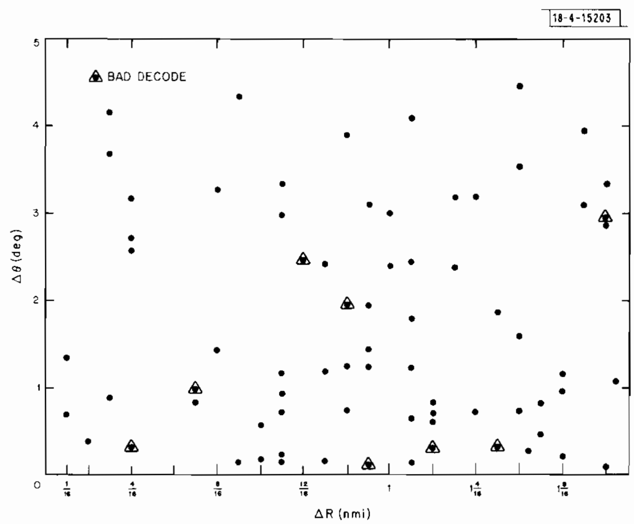


Fig. 41. Range and Azimuth Differences Synchronous Garble Events.

illustrate the probabilistic nature of the mechanisms leading to Figure 39; the bunching of erroneous decode points around $\Delta\theta = 0$ is consistent with the notion that fewer good replies are likely to be present as $\Delta\theta$ approaches zero. The number of data points is insufficient to show the "lattice" behavior exhibited in Figure 39; in addition, range accuracy is limited by quantization to 1/16 nmi; this is comparable to the distance between adjacent "bars" in the lattice, which is almost twice as large.

Scan-to-scan correlation of decoding errors was also analyzed. In no case observed were two decoding errors made on the same aircraft on adjacent scans. In fact, several of the eight bad decodes were surrounded on adjacent scans by valid target reports of both aircraft with no garble flags set. Those garble interactions which lasted for several scans are plotted in Figure 42. This behavior is again compatible with the model of Figure 39; when range difference is changing slowly, that figure suggests that the garble flag might alternately be set and not set over a sequence of scans.

5. Microscopic Analysis of Our Data

In almost every case where garbling was noted on an individual sweep, it was possible, given the actual codes and range difference, to predict the garbling patterns observed. As an example, the incident in which the aircraft squawking 0350 was incorrectly decoded at 6750 (scan 9) is now discussed in detail.

Figure 43 shows the data surrounding that event. The garbling aircraft, squawking 1100, was at range 28.25 nmi and azimuth 278.26 degrees; the garbled aircraft was at 27.75 nmi and 277.29 degrees. Thus, the two differed in azimuth by roughly one degree and in range by 1/2 nmi. Note that the aircraft squawking 0350 was received in the clear for two returns initially, but one of those was improperly decoded as 0340, probably due to marginal RF

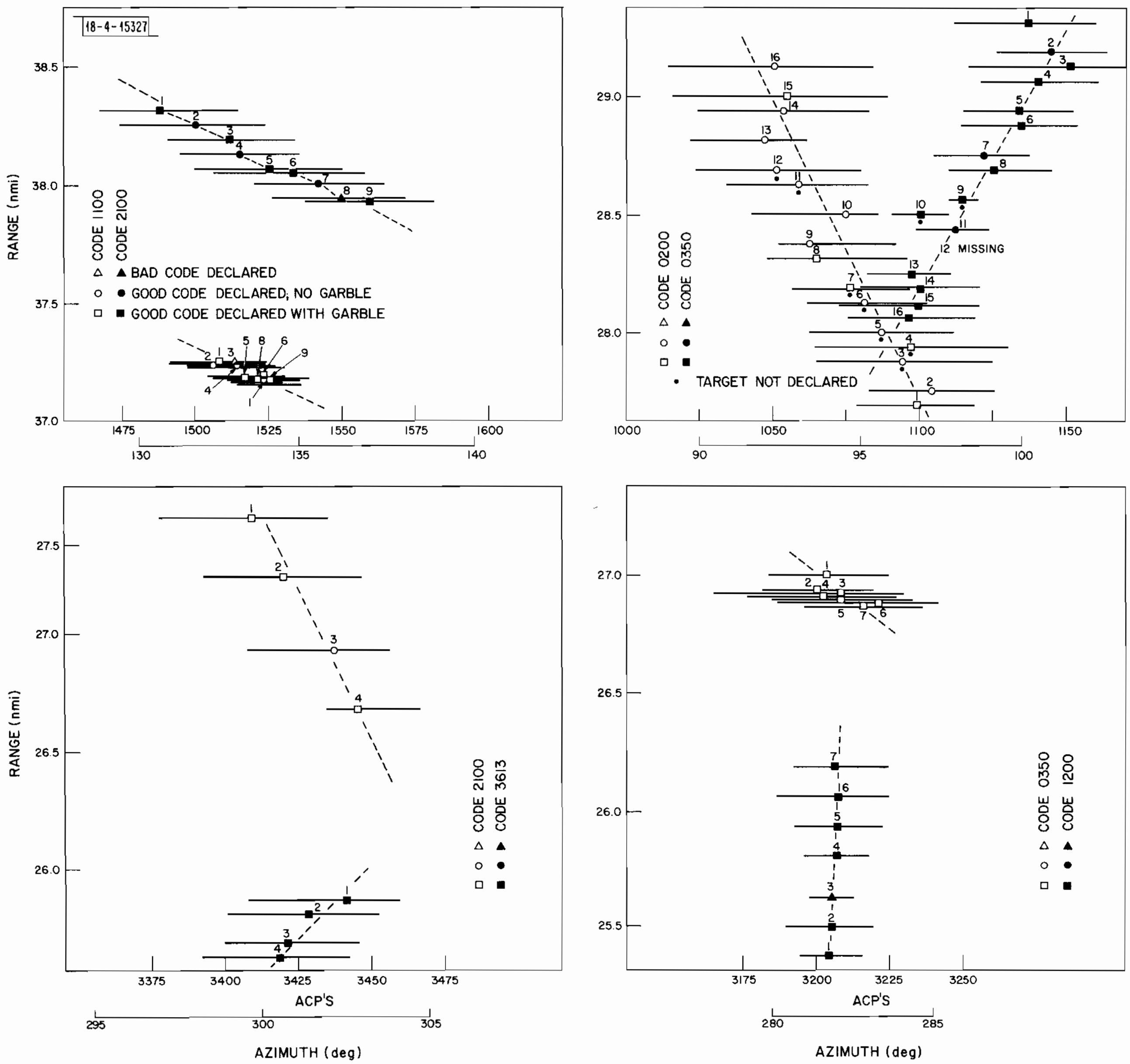


Fig. 42a. Several Synchronous Garble Interactions.

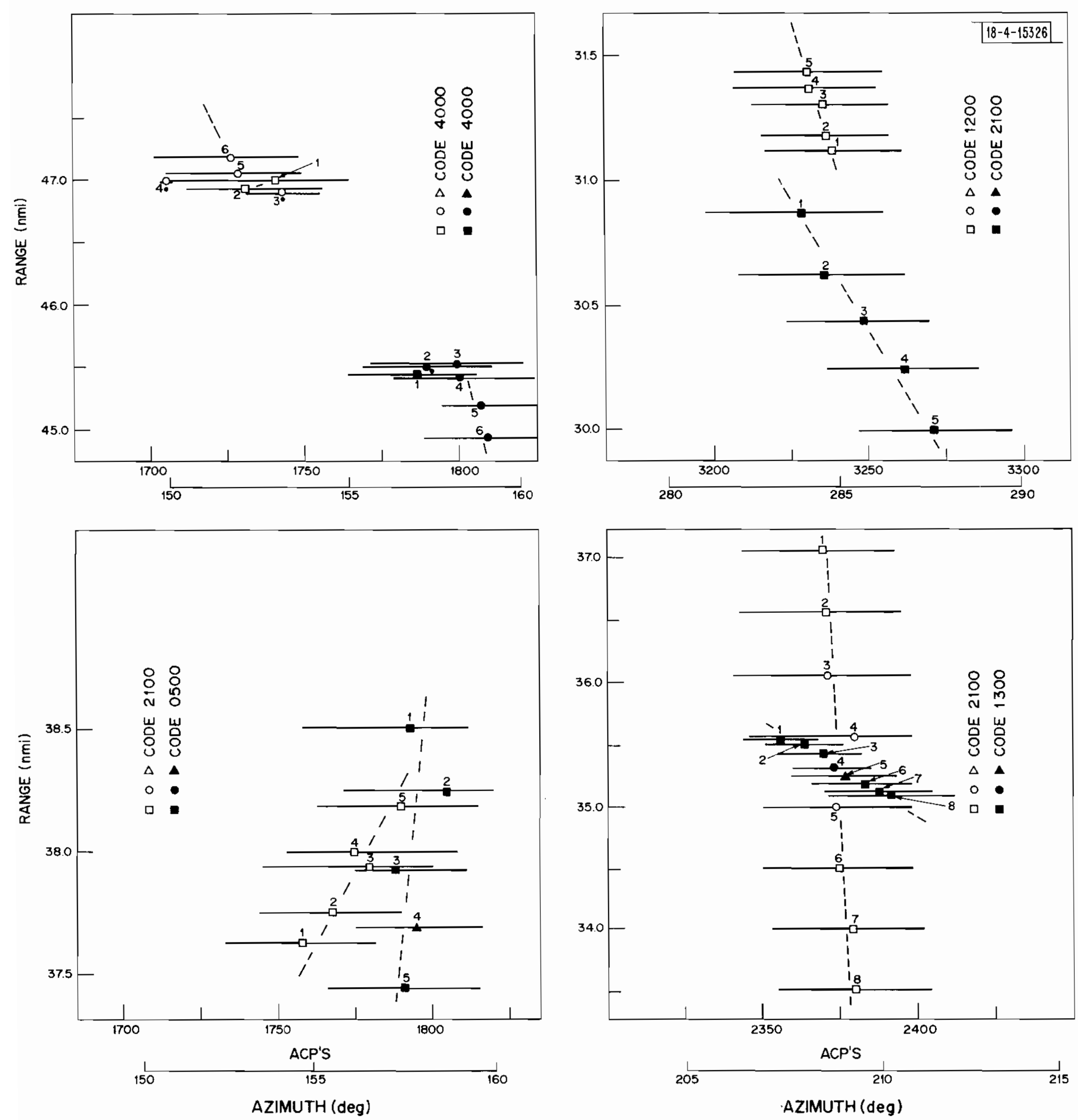


Fig. 42b. Several Synchronous Garble Interactions.

4-15207

REPLY/REPORT	CODE	ALTITUDE	RANGE	AZIMUTH (deg)	(ACP)	X	Y	GMT (hr/min/sec)	GARBLE FLAG	SPI	CODE VALIDITY	ALT VALIDITY	HITS RECEIVED	POSSIBLE HITS (incl. modec)	HIT PATTERN
A	0710	----	4.9375	273.08	3107			1/49/ 3							
A	1200	----	22.6250	273.08	3107			1/49/ 3							
A	1100	----	43.3750	273.08	3107			1/49/ 3							
C		5.5	4.9375	273.52	3112			1/49/ 3							
A	0710	----	4.9375	274.04	3118			1/49/ 3							
TGT	1200	----	22.6250	271.05	3084	41.379	64.417	1/49/ 3			3	0	12	14	CAACAA AA AACA
C		5.5	4.9375	274.31	3121			1/49/ 3							
A	0710	----	4.9375	274.48	3123			1/49/ 3							
A	0710	----	4.9375	274.75	3126			1/49/ 3							
C		5.5	4.9375	275.01	3129			1/49/ 3							
TGT	1100	----	43.3750	271.85	3093	20.648	65.397	1/49/ 3			3	0	8	12	A AA AA AA A
A	0710	----	4.9375	275.19	3131			1/49/ 3							
A	0710	----	4.9375	275.45	3134			1/49/ 3							
A	0340	----	27.7500	275.45	3134• IN THE CLEAR, BUT WEAK			1/49/ 3							
C		5.5	4.9375	275.63	3136			1/49/ 3							
A	0710	----	4.9375	275.89	3139			1/49/ 3							
A	0350	----	27.7500	275.89	3139• IN THE CLEAR			1/49/ 3							
A	0710	----	4.9375	276.15	3142			1/49/ 3							
A	6750	----	27.7500	276.15	3142•			1/49/ 3	G						
A	6110	----	28.1875	276.15	3142▲			1/49/ 3	G						
C		5.5	4.9375	276.42	3145			1/49/ 3							
A	0710	----	4.9375	276.68	3148			1/49/ 3							
A	6750	----	27.7500	276.68	3148•			1/49/ 3	G						
A	7310	----	28.1875	276.68	3148▲			1/49/ 3	G						
A	0710	----	4.9375	276.94	3151			1/49/ 3							
A	6750	----	27.7500	276.94	3151•			1/49/ 3	G						
A	7310	----	28.1875	276.94	3151▲			1/49/ 3	G						
C		5.5	4.9375	277.12	3153			1/49/ 3							
A	0710	----	4.9375	277.38	3156			1/49/ 3							
A	6750	----	27.7500	277.38	3156•			1/49/ 3	G						
A	7310	----	28.1875	277.38	3156▲			1/49/ 3	G						
A	6750	----	27.7500	277.56	3158•			1/49/ 3	G						
A	7310	----	28.1875	277.56	3158▲			1/49/ 3	G						
A	6750	----	27.7500	278.09	3164•			1/49/ 3	G						
A	7110	----	28.1875	278.09	3164▲			1/49/ 3	G						
A	6750	----	27.7500	278.35	3167•			1/49/ 3	G						
A	7310	----	28.1875	278.35	3167▲			1/49/ 3	G						
TGT	0710	5.4	4.9375	275.54	3135	59.086	64.476	1/49/ 3			3	3	17	19	A C ACAACAACAACAACA
A	6750	----	27.7500	278.88	3173•			1/49/ 3	G						
A	6310	----	28.1875	278.88	3173▲			1/49/ 3	G						
A	1200	----	23.7500	279.05	3175			1/49/ 3							
A	6750	----	27.7500	279.05	3175•			1/49/ 3	G						
A	7310	----	28.25[illegible]	279.05	3175▲			1/49/ 3	G						
C		5.5	4.9375	279.32	3178			1/49/ 3							
A	1200	----	23.7500	279.49	3180			1/49/ 3							
A	0100	----	28.1875	279.49	3180▲ IN THE CLEAR, BUT WEAK			1/49/ 3							
A	1200	----	23.7500	279.76	3183			1/49/ 3	G						
A	1100	----	28.2500	279.76	3183▲ IN THE CLEAR			1/49/ 3							
C		0.0	23.7500	279.93	3185			1/49/ 3							
A	1200	----	23.7500	280.20	3188			1/49/ 3							
A	1100	----	28.2500	280.20	3188▲ IN THE CLEAR			1/49/ 3							
TGT	6750	----	27.7500	277.29	3155 ←•	36.475	67.524	1/49/ 3			0	0	11	16	A AA AA AA AA AA
A	1200	----	23.7500	280.46	3191	ERRONEOUS CODE		1/49/ 3	G						
C		0.0	23.7500	280.72	3194			1/49/ 3	G						
A	1200	----	23.7500	280.90	3196			1/49/ 3							
A	1200	----	23.7500	281.16	3199			1/49/ 3							
C		0.0	23.7500	281.43	3202			1/49/ 3	G						
TGT	1100	----	28.2500	278.26	3166 ←▲	36.043	68.059	1/49/ 3			3	0	12	18	A AA AA AA AA AA A
A	1200	----	23.7500	281.60	3204	CORRECT CODE		1/49/ 3	G						
A	1200	----	23.7500	281.87	3207			1/49/ 3							
A	1200	----	31.3750	281.87	3207			1/49/ 3	G						
C		0.0	23.7500	282.13	3210			1/49/ 3							
A	1200	----	23.7500	282.39	3213			1/49/ 3							
A	1200	----	31.3125	282.39	3213			1/49/ 3							
A	1200	----	23.7500	282.66	3216			1/49/ 3							

• 0350 REPLIES
▲ 1100 REPLIES
←• 0350 DECLARATION (erroneous)
←▲ 1100 DECLARATION
NOTE THAT IN SPITE OF INCORRECT DECODING DUE TO SYNCHRONOUS GARBLE, BOTH TARGETS WERE CORRECTLY DETECTED AND BEAMSPLIT.

Fig. 43. ARTS III Extractor Data Incorrect Decoding.

link performance at the beamedge. On the sweep in which garbling commenced, and on all subsequent sweeps, the aircraft was improperly decoded at 6750; that is, the garbling situation caused its return pulses A_2, A_4, and B_4 to appear to be set, while, in fact, they were not. Similarly, the aircraft squawking 1100 (correctly decoded by ARTS III since its last two replies were in the clear and in agreement) was received variously as 6110, 7310, and 7110, indicating that the garbling situation caused its A_2, A_4, B_2, and C_1 bits to be improperly set. (The single 6110 reply indicates that its A_1 bit (actually set) was read as not being set once; note this is also the case in the clear return received on ACP 3180. This could very well be due to poor transponder performance, or a slightly weak A_1 pulse return, and is not attributable to garbling.)

Reply spacing of 0.5 nmi corresponds to overlap of four pulse positions (Figure 44). It can be seen that this overlap is consistent with the observed garbled codes, and that both can be determined consistently from the overlap and the original pulses. In this example, the possible legitimate reaply codes associated with 6750 and the known overlap are 0350, 2350, 4350, 6350, 0750, 2750, 4750, and 6750; similarly, for the aircraft squawking 1100 (had it been incorrectly declared), possible correct codes associated with the various replies and the garble pattern are 1100, 1110, 3110, 5110, 7110, 3100, 5100, 7100, 1300, 1310, 5310, 7310, 3300, 5300, and 7300. An intelligent tracker could in this case associate the garbled replies with the correct aircraft; the task would be even simpler had the C and D pulse been utilized to full advantage.

6. Mode C Degarbling

Our data was also examined to determine whether mode C (altitude) replies could be successfully degarbled; this was felt to be more

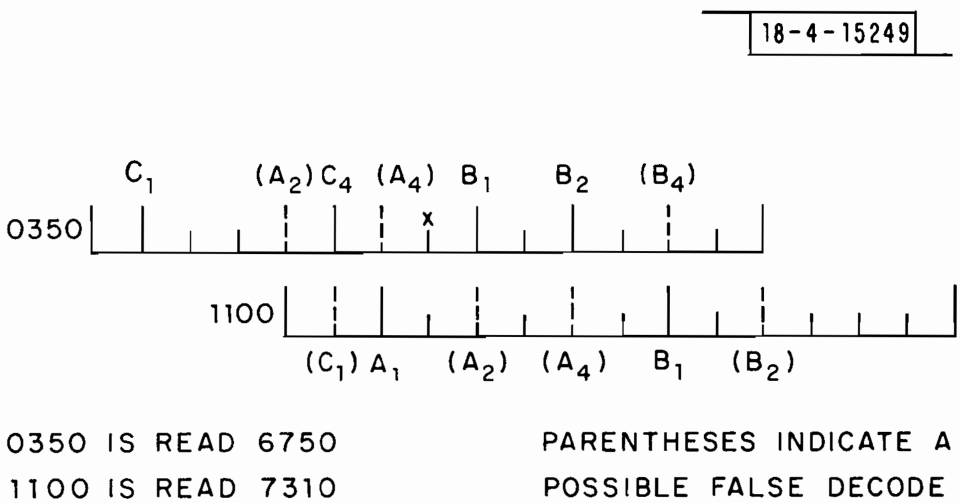


Fig. 44. Garble Pattern for Data Shown in Fig. 43.

representative of a "worst case" garbling situation since 1) more actual "information" is contained in mode C replies, and 2) there are fewer mode C replies per scan. Only one synchronous garble situation was found (in the Andrews data) in which altitude was incorrectly declared. Based on that one case, it appears that altitude codes can be successfully degarbled; of course, far more investigation would be required to confirm that notion.

In the situation observed, an aircraft squawking 2100 at FL 290, (pressure altitude 29, 000 ft) and range 34 nmi garbled another aircraft squawking 1300 at 34, 000 ft. Figure 45 shows the data as decoded by the DAS: Figure 46 shows the overlap patterns. The range difference was 1.13 nmi, suggesting an overlap offset of ten pulse positions. As Figure 46a shows, one would expect the garble situation to cause the 2100 to be declared as a 2700, and the 1300 as a 3300. This behavior can be seen in several replies.

In order to degarble mode C replies, it is necessary to convert from altitude to the original Gray code in which altitude data is telemetered by ATCRBS. In the mode C reply format employed in ARTS III, FL 290 translates into code 0422, which is sent by setting A_1, B_2, and C_2; similarly, FL 235 corresponds to code 0512, with A_1, A_4, B_4, and C_2 set. The overlap of these two reply sequences (Figure 46b) would be expected to produce garbled codes of 1432 and 0712. This first code is consistent with what was read, but the altitude which was read for the second aircraft corresponds to code 0713, implying that the C_4 pulse must have been set, also. This is outside the span of the synchronous garble overlap, and could not have been caused by garbling. The C_4 pulse could have therefore been set only by a change in altitude of the originating aircraft. The only altitude near FL 235 for which the C_4 pulse is set is FL 236. Therefore, it would appear on the basis of the information content of the garbled (and therefore erroneous) altitude that the aircraft had climbed 100 ft since the previous scan. Examination of the altitude on the subsequent scan revealed that this was in fact the case.

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REPLY/REPORT	CODE	ALTITUDE	RANGE	AZIMUTH(deg)	(ACP)	X	Y	GMT (hr/min/sec)	GARBLE FLAG	SPI	CODE VALIDITY	ALT VALIDITY	HITS RECEIVED	POSSIBLE HITS (incl. modec)	HIT PATTERN	
A	2100	----	50.8125	204.87	2331			1/49/41								
A	2100	----	50.8125	205.40	2337			1/49/41								
A	2100	----	50.8125	205.66	2340			1/49/41								
A	0500	----	14.5000	206.10	2345			1/49/41								
A	2100	----	50.8125	206.10	2345			1/49/41								
A	0500	----	14.5000	206.37	2348			1/49/41								
A	2100	----	50.8125	206.37	2348			1/49/41								
A	0500	----	14.5000	206.81	2353			1/49/41								
A	2100	----	34.0000	206.81	2353●			1/49/41								IN THE CLEAR
A	2100	----	50.8125	206.81	2353			1/49/41								
A	0500	----	14.5000	207.07	2356			1/49/41								
A	2100	----	34.0000	207.07	2356●			1/49/41								IN THE CLEAR
A	2100	----	50.8125	207.07	2356			1/49/41								
C		2.5	14.5000	207.25	2358			1/49/41								
A	0500	----	14.5000	207.51	2361			1/49/41								
A	2100	----	34.0000	207.51	2361●			1/49/41								IN THE CLEAR
A	2100	----	50.8125	207.51	2361			1/49/41								
A	0500	----	14.5000	207.77	2364			1/49/41								
A	2100	----	34.0000	207.77	2364●			1/49/41								IN THE CLEAR
A	2100	----	50.8125	207.77	2364			1/49/41								CORRECT MODE A
C		2.5	14.5000	208.04	2367			1/49/41								DECODING OF 2100
A	0500	----	14.5000	208.30	2370			1/49/41								ACCOMPLISHED AT
A	2700	----	34.0000	208.30	2370●			1/49/41	G							THIS POINT.
A	3300	----	35.1250	208.30	2370▲			1/49/41	G							
A	2100	----	50.8125	208.30	2370			1/49/41								
A	0500	----	14.5000	208.48	2372			1/49/41								
A	2700	----	34.0000	208.48	2372●			1/49/41	G							
A	3300	----	35.1250	208.48	2372▲			1/49/41	G							
A	2100	----	50.8125	208.48	2372			1/49/41								
C		2.5	14.5000	208.74	2375			1/49/41								
C		32.0	34.0000	208.74	2375o			1/49/41	G							
C		21.9	35.1250	208.74	2375Δ			1/49/41	G							
A	0500	----	14.5000	209.00	2378			1/49/41								
A	2700	----	33.9375	209.00	2378●			1/49/41	G							
A	3300	----	35.1250	209.00	2378▲			1/49/41	G							
A	0500	----	14.5000	209.18	2380			1/49/41								
A	2700	----	33.9375	209.18	2380●			1/49/41	G							
A	3300	----	35.1250	209.18	2380▲			1/49/41	G							
C		2.5	14.5000	209.44	2383			1/49/41								
C		21.9	35.1250	209.44	2383Δ			1/49/41								
A	0500	----	14.5000	209.71	2386			1/49/41								
A	2700	----	34.0000	209.71	2386●			1/49/41	G							
A	3300	----	35.1250	209.71	2386▲			1/49/41	G							
TGT	2100	----	50.812[illegible]	2[illegible]6.81	2353	41.084	18.648	1/49/41			3	0	11	16	A AA AA AA AA AA	
A	2700	----	34.0000	2[illegible]9.97	2389●			1/49/41	G							
A	3300	----	35.1875	209.97	2389▲			1/49/41	G							
C		32.0	33.9375	210.15	2391o			1/49/41	G							
C		21.9	35.1250	210.15	2391Δ			1/49/41	G							
A	2700	----	34.0000	210.41	2394●			1/49/41	G							
A	3300	----	35.1250	210.41	2394▲			1/49/41	G							
A	2700	----	34.0000	210.67	2397●			1/49/41	G							ERRONEOUS RANGE;
A	3300	----	35.1250	210.67	2397▲			1/49/41	G							PHANTOM REPLY
TGT	0500	2.4	14.5000	208.04	2367			1/49/41			3	3	15	16	AA AACAACAACAACA	(F_2 missed)
C		64.0	34.1875	210.85	2399o			1/49/41	G							NOTE FROM REPLY
C		15.6	35.1250	210.85	2399Δ			1/49/41	G							PATTERN THIS ONE
A	2700	----	34.0000	211.11	2402●			1/49/41	G							WAS NOT INCLUDED
A	3300	----	35.1250	211.11	2402▲			1/49/41	G							
A	1300	----	35.1250	211.38	2405▲			1/49/41								IN THE CLEAR
TGT	2100	----	34.0000	209.09	2379 ←●	47.469	34.289	1/49/41			1	1	15	19	AA AA AACAA AACAA A	
A	0000	----	41.7500	212.78	2421			1/49/41								
TGT	1300	21.9	35.1250	209.88	2388 ←▲	46.500	33.545	1/49/41			1	2	14	14	AACAACAACAACAA	
A	2000	----	54.5625	219.90	2502			1/49/41								

MODE A ● } 2100 REPLIES
MODE C o }

MODE A ▲ } 1300 REPLIES
MODE C Δ }

←● 2100 DECLARATION (no altitude)

←▲ 1300 DECLARATION (erroneous altitude)

NOTE BOTH CODES DECLARED SUCCESSFULLY

ACTUAL ALTITUDES (based on prior track information):

AIRCRAFT	ALT
2100	29.0
1300	23.5

NOTE THAT TWO INITIAL ALTITUDE REPLIES FROM THE AIRCRAFT SQUAWKING 2100 WOULD HAVE BEEN IN THE CLEAR BUT WERE NOT RECEIVED. THIS IS PARTLY DUE TO DEFRUITER ACTION; HAD THE DEFRUITER BEEN REMOVED, THE REPLY ON ACP 2367 WOULD HAVE BEEN RECEIVED; THIS COULD HAVE RESULTED IN CORRECT ALTITUDE DECLARATION.

Fig. 45. ARTS III Extractor Data Incorrect Mode C Decoding.

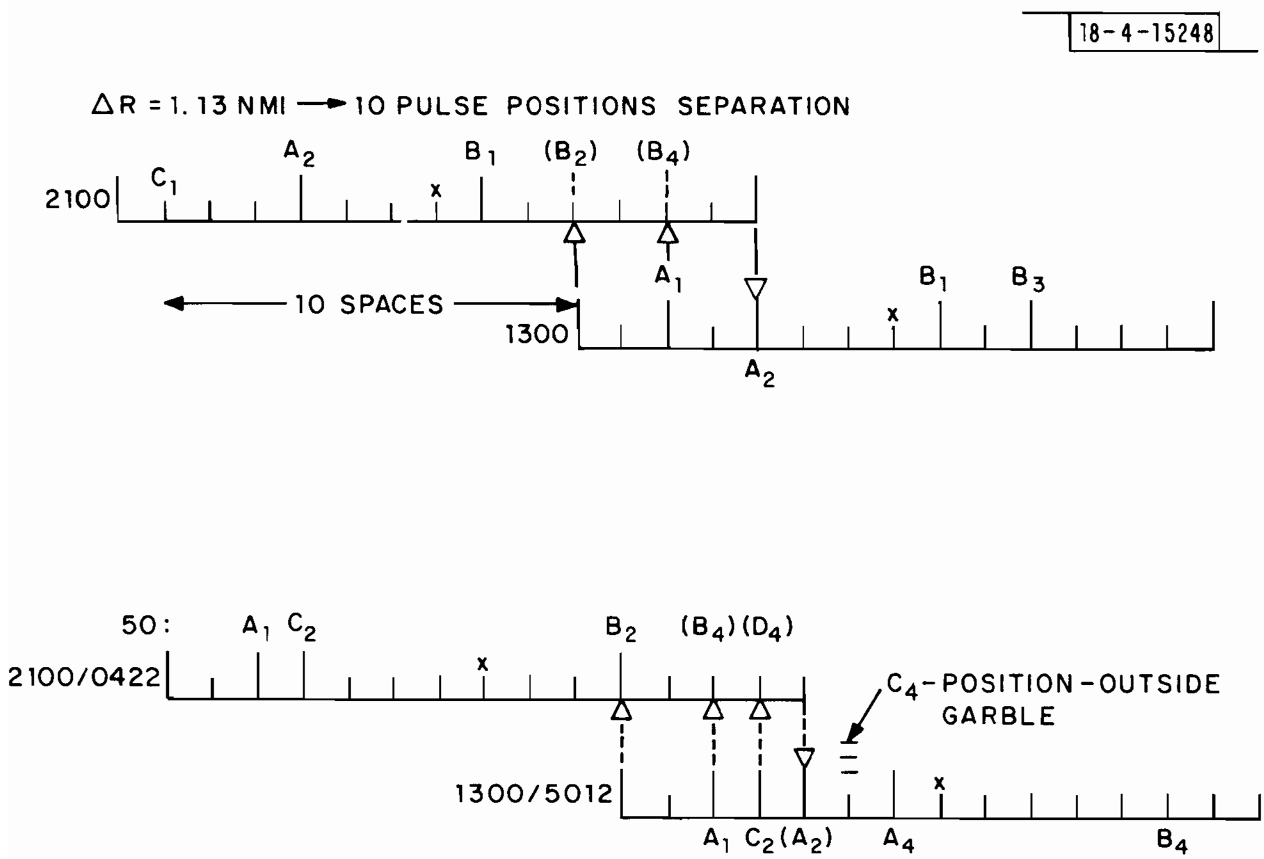

Fig. 46. Garble Pattern for Data Shown in Fig. 45.

7. Fixes

It appears that while the incidence of synchronous garble (as defined by MITRE) is apt to become significant in some dense areas in the near future, it will be some time before the degree to which it affects ARTS III performance becomes significant. Before that time, undoubtedly there will be substantial changes in route structures (due to increased use of R-NAV), terminal procedures, (i.e., implementation of the TCA) and the concept of mixed airspace. Thus, it is difficult to predict when synchronous garble will reach the level where, say, it is responsible for as many track drops as other mechanisms such as weak RF links. However, several potential fixes, capable of improving the (already good) performance of ARTS III, can be implemented, primarily in the ARTS III software, with relatively little difficulty; development of these should be undertaken in the near future.

a) Employ new decoding/tracking procedures in ARTS III. The present procedure for decoding an ATCRBS reply involves waiting for the first set of two good (i.e., not garbled) replies that agree with one another, selecting their code as the correct one, and ignoring all further code data. This is in spite of the fact that <u>all</u> reply codes detected by the DAS are sent to the ARTS III software for target signature recognition, and all replies are employed to advantage by that software in the beamsplitting procedure. A software routine which examines all reply codes, compares those flagged as garbled with those not so flagged, and determines the most likely actual reply code based on all information received could potentially reduce the likelihood of instances where garble occurred on several sweeps but was not recognized. In cases of that sort observed to date, simple "majority-vote" procedures applied to all unflagged codes would have resulted in proper declarations.

An analogous procedure can be implemented in the tracker; since garbling is far more likely to result in additive rather than subtractive interference, the tracker could simply examine any code declared with low validity (or known to be in a potentially garbled situation by virture of proximity to other declared aircraft) to determine whether the declared code contains as a subset any actual code with whose track the target report correlates.*

The notions of feedback from tracker to target declaration logic, or of increased communication in the other direction are also extremely useful in this situation. Whenever a garble occurs, the task of the decoder/tracker combination is not to successfully determine the codes involved exactly (except in the case of altitude), but rather to decide which target declaration should be associated with which track. Note that this task would be trivial in all eight cases of bad decoding discussed in Section 4, since in all cases one aircraft was properly declared. Relatively simple logic, mechanized in the software after the DAS, could determine the extent of the overlap, from that determine which pulses of each reply code are questionable, and which are not, and make a positive correlation of reply with track based on agreement in a small number of pulse positions which are known to be unequivocal. For example, in the case discussed in Part 5 of this section, the tracker could positively associate the closer range reply sequence with the 0350 track, since C_1 of that sequence is in the clear and is set; the only other alternative (based on track history) is to associate it with the other track (1100); since that code does not have C_1 set, there is little ambiguity.

*This idea is not new. MITRE and UNIVAC personnel confirm that the idea has been under consideration in the ARTS Enhancement Program.

A more ambitious procedure could operate in similar fashion within the overlapped region by using to advantage a knowledge of the codes involved. Again referring to the example in Section 5, the degarbling processor, noting pulses in the positions which are eight and ten spaces from the beginning of the first reply, could, in effect, conclude: "either pulses B_1 and B_2 of the closer reply are set, or pulses A_2 and A_4 of the more distant reply are set, or both situations are present."* Since the tracker "knows" that the codes in question are 0350 and 1100, the only one of these hypotheses possible is the first, and the association between the closer reply and code 0350 can be made positively on that basis.

More involved software procedures, with complexity up to the level used in manually degarbling (as described in Sections 5 and 6) are possible in principle; their utility is questionable. At some level, the required amount of additional garble processing would necessitate addition of extra computational capacity; this level was not determined, since there are many other factors besides the desirability of garble processing that drive the system in that direction. Since the present ARTS III computer is but a peripheral equipment (the so-called Input/Output Processor, or IOP) of a more powerful, more general purpose computer (the Central Processing Unit, or CPU), it would appear that expansion in this direction is certainly possible; indeed, it was apparently anticipated in the original system design.

*The likelihood of phase cancellation when two set pulses overlap is remote, since such cancellation must take place prior to limiting; this requires that the RF signal levels be within a fraction of a dB of one another. This is highly unlikely. See Section III. F. 4.

b) Employ new garble-flagging logic in the DAS. Presently, the DAS examines a reply sequence for garbling by simply noting whether any additional F_2 pulses are observed within 20.3 μsec after the F_2 pulse of each reply, in positions consistent with an overlapped, rather than interlaced situation [13]. While this appears proper considering the level of synchronous garbling anticipated during the lifetime of the DAS, and DAS garble performance is substantially better than that of the Production Common Digitizer, several additional design steps could be taken to further enhance DAS performance.

Individual pulses could be checked easily for excessive width and flagged individually. Whenever garbling is sensed, an additional DAS reply word (perhaps called a "garble mask") could be generated for each reply with ones in the questionable bit positions. This would allow the decoding/tracking mechanism to determine which pulses go with which reply sequences with less equivocation, and therefore perform correlation of target declarations and tracks with less likelihood of error. If transponder pulsewidths (and other parameters) are not brought into agreement with ATCRBS standards by policing action, an additional algorithm would be necessary to recognize a non-overlapped reply for which every pulse is too wide as being due to improper transponder operation, rather than an actual garble. Similar schemes could be based upon differences in amplitude rather than pulsewidth; these would likely be far more effective, but would require additional complexity in the ATCRBS equipments preceding ARTS III, and in the analog to digital converter in the DAS front end.

c) Employ Monopulse-on-receive. A monopulse receiving system employs an antenna structure from which two separate signals, a "sum" signal and a "difference" signal, are extracted. Processing of these signals can yield an accurate measurement of the off-boresight angle from which the signal was received. In addition to its use in making accurate azimuth measurements on the basis of a single reply (as is planned in the Discrete Address Beacon System [14]), monopulse techniques can also assist in degarbling of overlapping replies.

When two or more replies are received simultaneously, it is possible, with advanced processing techniques, to determine that a multiple-signal situation exists on a pulse-by-pulse basis. This information can then be used to advantage in correcting synchronous garbles in the same manner as the pulsewidth and amplitude information discussed in the preceding paragraph. In addition, the fact that each individual pulse can be tagged with a unique azimuth permits proper association of single pulses with the various reply sequences in an overlap situation. This requires additional processing; the amount depends on the number of hits desired per target.

While monopulse-on-receive permits some improvements in degarbling capability, it is doubtful that synchronous garble reduction alone would justify its use for ATCRBS.

8. Conclusions

As aircraft density increases, there will be an increased incidence of potentially garbling situations (i.e., another aircraft will be within 1.65 nmi and 4^{o} of the victim aircraft). However, the empirical data shows that when only one other aircraft is involved, the identification code of the aircraft in question will be obtained successfully about 95% of the time (168 successful decodes out of a possible 176 were noted in Section 4), assuming the current ARTS III performance characteristics. Also the probability of decoding the aircraft's reply erronously for several successive scans is likely to be quite low.

It should be noted that the data presented in this report is based exclusively on garble situations where only a single interfering aircraft is involved. Some traffic forecasts suggest that densities might be so high in the future that many aircraft are likely to be garbled simultaneously by several other aircraft. Only one such instance was observed in our data. Three aircraft were involved; all three were successfully decoded, although the validity code of one declaration was set low. Analysis of performance in such situations is very complex, and was not attempted in this study; insufficient data was found to warrant any empirical conclusions. However, it is generally felt that as the number of interfering replies increases, the ability to degarble will degrade.

Many fixes for synchronous garble have been proposed, some of which were discussed in this report. It is not clear at this time which, if any, should be implemented. The case of a single interfering aircraft does not need a substantial improvement. The ability of the suggested fixes to resolve multiple aircraft garbles needs further evaluation, together with a more detailed examination of the seriousness of the multiple garble problem.

D. Poor Angular Resolution

During the data analysis, it was noted that ARTS III occasionally failed to declare a target in spite of its reply pattern meeting the necessary parameters. In each case, the reply sequence was immediately preceded or followed by another sequency in the same or an adjacent range cell. Because of the target declaration and decoding algorithms it employs, ARTS III failed to note that two targets were present, instead declaring a single composite target with azimuth determined from beamsplitting the composite reply sequence. That two targets were in fact present was evident from observing the code reply sequence, which changed abruptly at the point where one aircraft ceased and the other commenced replying. During those sweeps when both were replying, ARTS III did not sense garbling. A typical composite sequence for this situation is shown in Figure 47.

Although no systematic examination of the data was made for this phenomenon, it was noted by chance during a single scan, which turned out to be only one of a sequence of sixteen scans during which one or the other of a particular pair of interacting targets failed to be declared due to this mechanism. Figure 48 shows the tracks of the two aircraft. Besides this interaction, which appears to be quite atypical, only two other instances of this phenomena were noted, each lasting for only a single scan.

1. Analysis

Loss of a target due to this failure to resolve aircraft at equal ranges will occur in ARTS III whenever one aircraft is in the same range cell as another, the azimuths differ by an amount such that T_T is not reached on the first (more counterclockwise) target before replies from the second one commence, and the arrival times are sufficiently close that ARTS III does not sense garbling. In situations where replies do not occur simultaneously on any single sweep, the aircraft need not be in the same range cell; ARTS III will correlate replies in adjacent cells into a single sequence when no overlap occurs. This is the reason for the increased range-difference areas at the edges of the lost target area in Figure 49. It can be seen from

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REPLY/REPORT	CODE	ALTITUDE	RANGE	AZIMUTH(deg)	(ACP)	X	Y	GMT (hr/min/sec)	GARBLE FLAG	SPI	CODE VALIDITY	ALT VALIDITY	HITS RECEIVED	POSSIBLE HITS (incl. modec)	HIT PATTERN
A	1200	----	34.6250	88.59	1008			1/48/49							
A	1200	----	34.6250	89.03	1013			1/48/49							
A	1200	----	28.0625	89.30	1016●			1/48/49							
A	1200	----	34.6250	89.30	1016			1/48/49							
A	1200	----	28.0625	89.74	1021●			1/48/49							
A	0752	----	26.8750	90.00	1024			1/48/49	G						
A	3200	----	28.0625	90.00	1024●			1/48/49	G						
A	1200	----	28.0625	90.53	1030●			1/48/49							
A	2100	----	52.5000	90.53	1030			1/48/49							
TGT	1200	----	34.6250	87.63	997	98.595	65.434	1/48/49			3	0	10	14	AA AA AA AA AA
A	1200	----	28.0000	90.70	1032●			1/48/49							
A	2100	----	52.5000	90.70	1032			1/48/49							
A	1200	----	28.0000	91.23	1038●			1/48/49							
A	2100	----	52.5000	91.23	1038			1/48/49							
A	1200	----	28.0000	91.49	1041			1/48/49							
A	2100	----	52.5000	91.49	1041			1/48/49							
A	1200	----	28.0000	91.93	1046			1/48/49							
A	2100	----	52.5000	91.93	1046			1/48/49							
A	1200	----	28.0000	92.20	1049●			1/48/49							
A	2100	----	52.5000	92.20	1049			1/48/49							
A	1200	----	28.0000	92.64	1054●			1/48/49							
A	2100	----	52.5000	92.64	1054			1/48/49							
A	1200	----	28.0000	92.90	1057			1/48/49							
A	2100	----	52.5000	92.90	1057			1/48/49							
A	0200	----	28.0000	93.34	1062▲			1/48/49							
A	2100	----	52.5000	93.34	1062			1/48/49							
A	0200	----	28.0000	93.60	1065▲			1/48/49							
A	2100	----	52.5000	93.60	1065			1/48/49							
A	0200	----	28.0000	94.04	1070▲			1/48/49							
A	2100	----	52.5000	94.04	1070			1/48/49							
A	0200	----	28.0000	94.31	1073▲			1/48/49							
A	1300	----	49.1250	94.31	1073			1/48/49		S					
A	2100	----	52.5000	94.31	1073			1/48/49							
A	0200	----	28.0000	94.75	1078▲			1/48/49							
A	1300	----	49.1250	94.75	1078			1/48/49							
A	0200	----	28.0000	95.01	1081▲			1/48/49							
A	1300	----	49.1250	95.01	1081			1/48/49		S					
A	0200	----	28.0000	95.45	1086▲			1/48/49							
TGT	2100	----	52.5000	92.37	1051	116.455	61.826	1/48/49			3	0	12	17	AA AA AA AA AA AA
A	1300	----	49.1250	95.71	1089			1/48/49		S					
A	0200	----	28.0000	96.15	1094▲			1/48/49							
TGT	1200	----	28.0000	92.64	1054←	91.970	62.712	1/48/49			3	0	19	30	A AA AA AA AA AA AA AA AA A
A	0200	----	28.0000	96.42	1097▲			1/48/49							
A	1300	----	49.1250	96.42	1097			1/48/49		S					
A	0200	----	28.0000	96.94	1103▲			1/48/49							
A	0700	----	28.0000	97.12	1105▲			1/48/49							
A	1300	----	49.1250	97.12	1105			1/48/49		S					
A	0200	----	28.0000	97.65	1111▲			1/48/49							
A	0350	----	28.9375	97.91	1114			1/48/49							
A	1300	----	49.1250	97.91	1114			1/48/49		S					

● 1200 (declared)
▲ 0200 (not declared)
← TARGET DECLARATION

NOTE RUNLENGTH EXCEEDED RING AROUND THRESHOLD, AND SO WAS TRUMCATED. REPLIES CONTINUED, BUT WERE IGNORED BY TARGET DECLARATION MECHANISM.

Fig. 47. ARTS III Extractor Data Lost Target Due to Insufficient Angular Resolution.

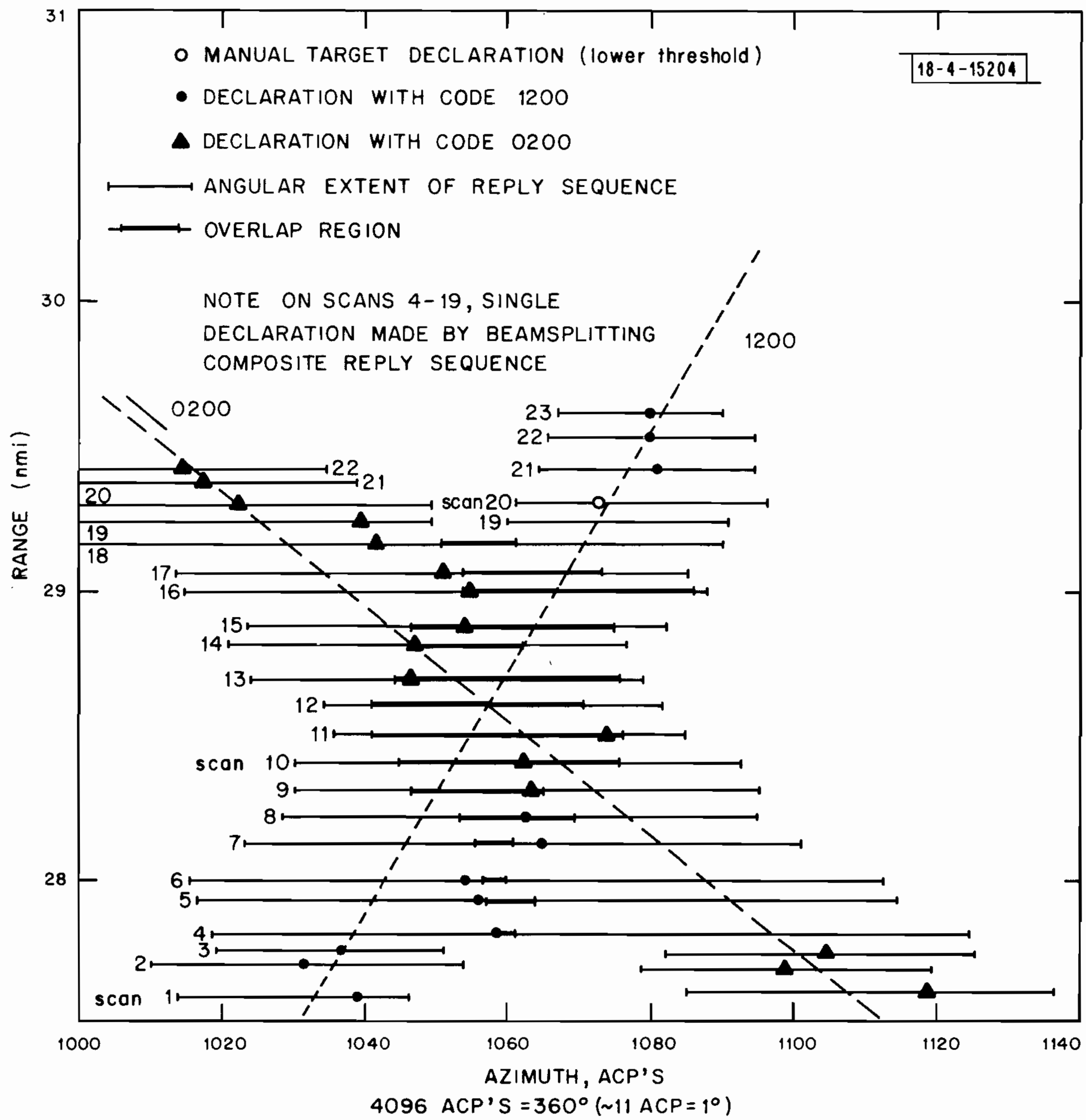


Fig. 48. Aircraft Tracks - Detection Failure Due to Insufficient Angular Resolution.

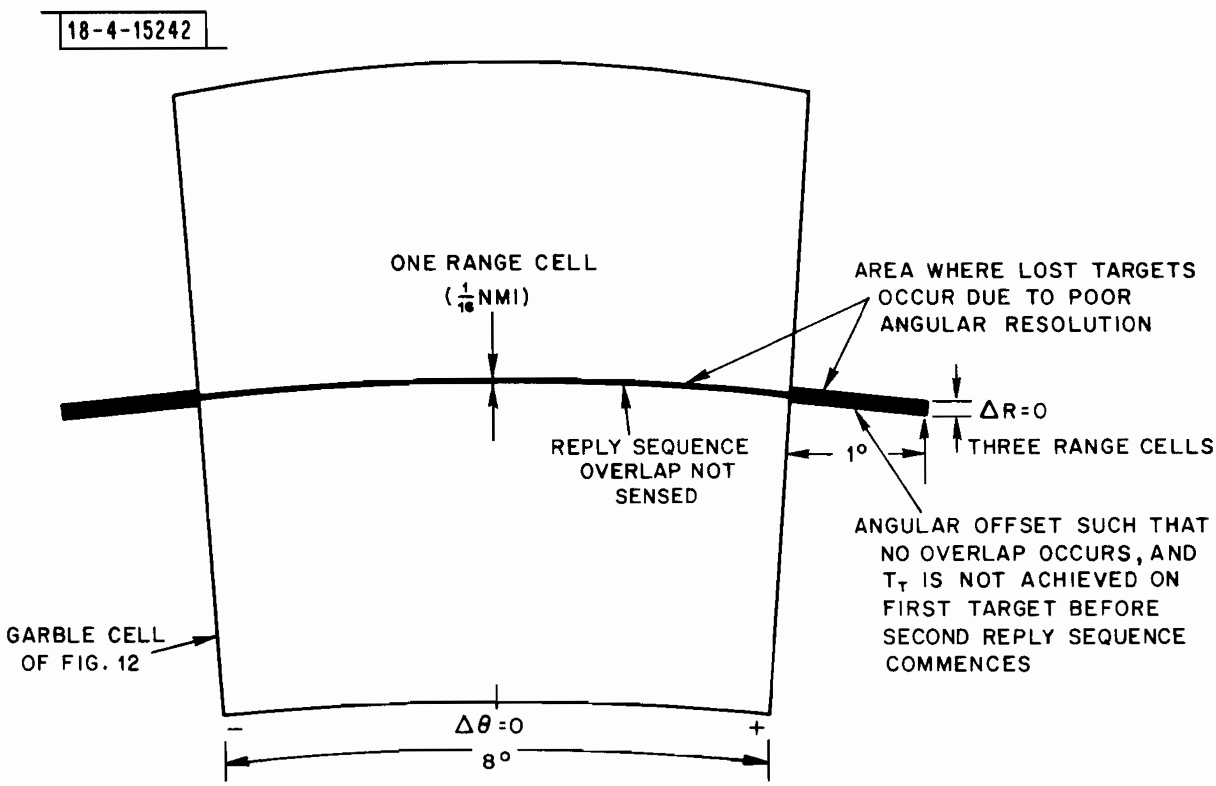


Fig. 49. Angular Resolution Geometry.

this figure that the area associated with the angular resolution event is roughly two-thirds that associated with the erroneous decoding event in the synchronous garble situation (Figure 39). Thus, one would expect loss of targets due to poor resolution to occur roughly two-thirds as often as erroneous decodes due to synchronous garble: the observed data confirms this, although undoubtedly not all cases of lost targets were noted. The two phenomena should increase at a comparable rate as traffic levels increase.

The phenomenon of angular resolution failure is almost equivalent to the relatively infrequent synchronous garbling situation in which $\Delta R \leq \frac{1}{16}$: in that case, both bracket pulses of the garbled aircraft are missed, and the aircraft is not declared. However, for loss to occur by the mechanism considered here no actual signal garbling need occur. One reply sequence can stop before the adjacent one starts. In addition, when aircraft are in adjacent range cells, and garbling occurs, the difference in arrival times that occurs is generally sufficient for ARTS III to recognize excessively wide pulses, and set the garble flag. Under most circumstances of this sort ARTS III will separate the two reply sequences on the basis of range difference, and beam-split and decode each sequence properly. (See the section on synchronous garble.)

It is important to emphasize that the interaction shown in Figure 48 is not at all typical, since the two aircraft remain in the same range cell throughout the interaction; when they finally separate, the separation is in azimuth. Thus, during the course of the interaction, ARTS III never senses two distinct replies on any one sweep. (The fact that in this interaction one of the observed codes is a subset of the other does little to clarify the situation; the other interactions noted all involved aircraft squawking 1200.)

Had ARTS III sensed two replies in adjacent range cells during the overlap period, both targets would have been detected properly; on the other hand, if there were no overlap, and the two targets were in adjacent range cells, ARTS III would have treated the composite sequence as a single reply sequence whose range shifted from one bin to the adjacent one, and declared it as a single target. In neither case would advantage have been taken of the fact that examination of the individual reply decodes generally suffices to resolve the situation.

2. Fixes

A fairly straightforward software fix, similar in many ways to those discussed under synchronous garble, combined with some minor procedural changes involving discrete code assignment which are likely to occur anyway, could have eliminated all cases of lost targets due to this phenomenon which were observed in our data. A new decoding algorithm, with feedback to the target declaration algorithm, would be required. Presently, ARTS III correlates individual replies with one another purely on the basis of range sorting and proximity in azimuth; a modified correlation routine, taking advantage of code information as well, could separate the replies from the individual aircraft and perform beamsplitting separately on each set. This procedure would necessarily be associated closely with degarbling procedures; in the usual situation, where superposition of two replies in the same range cell results in decoding of a third code (the "inclusive or" of the two), this would have to be recognized as such and accounted for in the beamsplitting procedure (Figure 50). In cases such as the one shown in Figure 48, it is not possible on several scans to tell from the reply data where one code ends, since it is completely contained within the other; here, azimuth estimation would be incorrect (indicating greater than actual separation), but recognition of the presence of two targets would certainly still be possible. Note that in some instances during the interaction shown in Figure 48, complete overlap

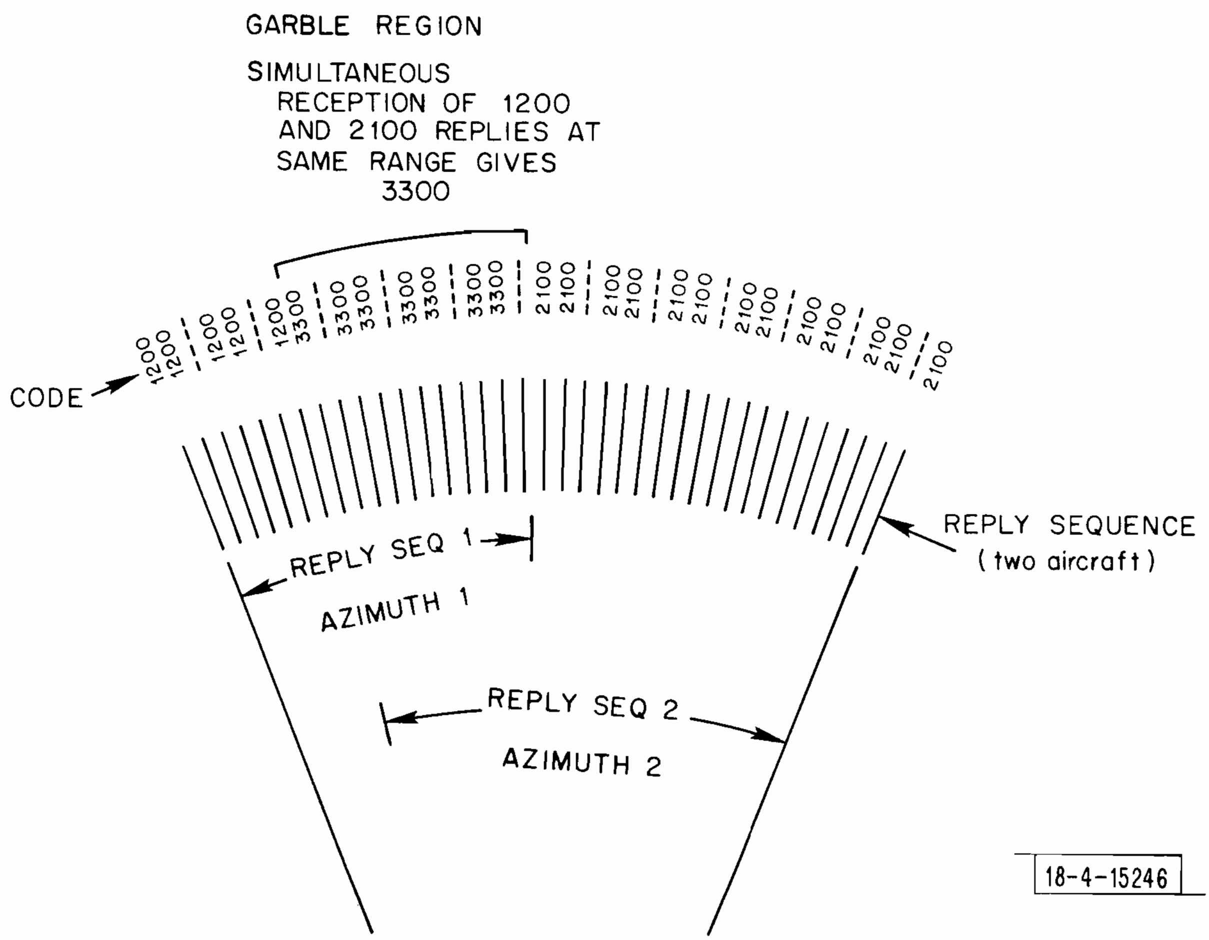


Fig. 50. Beamsplitting Based on Observed Codes.

of one target (squawking 1200) by the other (squawking 0200) occurs. In these cases, a correct azimuth determination would be made for both aircraft.

Just as monopulse-on-receive techniques could be used to advantage to resolve garbles, so too could they provide pertinent information in this situation. The monopulse-estimated azimuth angles of the various replies could be used instead of (or in addition to) code information to allow proper correlation; similarly, in cases where the extent of azimuthal overlap cannot be determined from examination of the resulting reply code, the capability of monopulse to recognize the presence of two simultaneous signals can be used to advantage.

E. The Storage-Tube Defruiter Problem

Several peculiar examples of erroneous decoding were noted in the Andrews data; Figure 51 shows one such example. In each case, good and bad decoding alternated regularly from one sweep to the next; in each case, only one pulse in the reply train was involved; in each case, the error was subtractive (a valid reply pulse was lost). Examination of all cases noted (most of which resulted in erroneous or low-validity code declaration) revealed that the particular pulses in question arrived at a small number of well-defined instants. It is evident from these facts that the phenomenon is caused by spots on the defruiter-tube faces, which do not properly store the presence of the pulse in question, such that on the next sweep, that pulse is rejected. This phenomenon was responsible for more decoding errors in the Andrews data than all other effects combined.

A storage-tube defruiter employs two storage tubes for each mode of interrogation; during each sweep, the incoming video is written onto one (to be saved until the next sweep in that mode) and compared with the data (from the preceding sweep) stored on the other; this comparison, which allows video to pass only when there is a coincidence, provides the defruiting action.

-4-15990

REPLY/REPORT	CODE	ALTITUDE	RANGE	AZIMUTH (deg)	(ACP)	X	Y	GMT (hr/min/sec)	GARBLE FLAG	SPI	CODE VALIDITY	ALT VALIDITY	HITS RECEIVED	POSSIBLE HITS (incl. modec)	HIT PATTERN
A	2100	----	44.4375	103.18	1174			1/49/48							
A	2100	----	44.4375	103.36	1176			1/49/48							
C		22.3	44.4375	103.62	1179			1/49/48							
A	2100	----	44.4375	103.89	1182			1/49/48							
A	2100	----	44.4375	104.15	1185			1/49/48							
C		22.3	44.4375	104.41	1188			1/49/48							
TGT	2100	22.3	44.4375	102.57	1167	107.373	54.330	1/49/48			3	3	16	17	A AACAACAACAACAAC
A	0200	----	29.3750	106.26	1209			1/49/48							
A	1200	----	38.5000	111.71	1271			1/49/48							
A	1200	----	38.5000	111.88	1273			1/49/48							
A	1200	----	38.5000	112.41	1279			1/49/48							
A	1200	----	38.5000	112.68	1282			1/49/48							
A	1200	----	38.5000	113.12	1287			1/49/48							
A	1200	----	38.5000	113.38	1290			1/49/48							
A	1200	----	38.5000	113.91	1296			1/49/48							
A	1200	----	38.5000	114.08	1298			1/49/48							
A	4000	----	49.6250	114.08	1298•			1/49/48							
A	0000	----	49.6250	114.52	1303○			1/49/48							
A	4000	----	49.6875	114.79	1306•			1/49/48							
A	0000	----	49.6250	115.31	1312○			1/49/48							
A	4000	----	49.6250	115.58	1315•			1/49/48							
A	0000	----	49.6250	116.10	1321○			1/49/48							
A	4000	----	49.6250	116.28	1323•			1/49/48							
TGT	1200	----	38.5000	113.03	1286	99.432	48.940	1/49/48			3	0	8	11	AA AA AA AA
A	0000	----	49.6250	116.72	1328○			1/49/48							
A	4000	----	49.6250	116.98	1331•			1/49/48							
A	0000	----	49.6875	117.42	1336○			1/49/48							
A	4000	----	49.6250	117.69	1339•			1/49/48							
TGT	4000	----	49.6250	116.02	1320	108.597	42.234	1/49/48			1	0	11	16	A AA AA AA AA AA
SCAN NUMBER		22.													

NOTE: CORRECT CODE DECLARED (50/50 chance)
CODE VALIDITY LOW (VA=1) SINCE NO TWO SUCCESSIVE CODES WERE IDENTICAL.
• CORRECT DECODE
○ INCORRECT DECODE
THE A_4 PULSE WAS AFFECTED; THIS PULSE IS THE SIXTH FROM THE BEGINNING. ($6\times1.45=8.70\,\mu s=.71$ nmi; therefore the bad spot is at $49.62+.7=50.33$ nmi.)

Fig. 51. ARTS III Extractor Data - Incorrect Decoding Due to Improper Defruiter Operation.

Since each tube is alternately written onto and read out of from one sweep to the next, loss of data on one tube would result in regular alternation of decoding errors; the regular alternation of decoding errors is what led us initially to suspect a problem in the defruiter.

While a storage tube spot will generally cause a particular information pulse to be improperly decoded, occasionally (two times out of fifteen) it will cause a framing pulse to be dropped; in this circumstance, every other reply in the sequence will be lost; in all instances observed in the Andrews data, this resulted in target declaration failure. This was the third most frequent cause of target declaration failure (after weak RF links and the atypical angular resolution problems observed). The percentage of target declaration failures due to this mechanism was negligible; weak RF links account for almost all target losses. Defruiter problems affect system decoding (rather than declaration) behavior far more severely.

Similar behavior was observed in mode C reply data (with, of course, an entirely different set of "bad" ranges). One aircraft, actually climbing from 39, 200 to 40, 200, remained under the influence of a single mode C defruiter tube spot for twenty-eight scans; during that period, its altitude was declared correctly on only ten scans; on the remainder, altitude readings oscillated wildly, or were not even declared.

Apparently, bad spots on defruiter storage tubes have been a shortcoming in ATCRBS since storage-tube defruiters were introduced. However, their effects were rarely noticeable or deleterious until the use of 12-pulse decoders (such as used in ARTS III) become widespread. The present program within FAA to replace storage-tube defruiters with newer, more modern, less expensive digital defruiters (in particular, the Navy-developed Interference Blanker, MX-8757/UPX), already well underway, is eliminating this problem. No problems due to improper defruiter operation were noted in the Boston data; Boston is equipped with an MX-8757.

F. The Interference Problem

The area of interference to ATCRBS Interrogator/Receivers due to high levels of asynchronous fruit has been analyzed, modeled, and experimentally examined more than any other single problem area in ATCRBS. Yet, little is definitely known about how severe the interference problem actually is, or how severe it is likely to become. Predictions of future levels of asynchronous fruit range over several orders of magnitude with little general agreement on what levels are truly realistic; this is because wide variations are made in the initial assumptions upon which various performance models are based. The models are generally well-understood and mutually accepted, albeit quite complicated; what is difficult is proper selection of appropriate numbers and simplifying assumptions to "plug in" to these models. Predicted total fruit levels depend strongly upon assumptions made about I/R antenna patterns (particularly side and backlobe details), receiver sensitivity (which is a time-function whenever STC is employed), aircraft distribution (in three dimensions), and fruit arrival rate statistics (definitely not strictly Poisson distributed nor stationary). Since each of the numerous analyses of the asynchronous fruit problem has made different assumptions in all these areas, it is perhaps not surprising that their results vary so widely that some conclude that high asynchronous fruit levels will cause severe problems shortly while others conclude that there is no problem, and never will be one. The data discussed in this report, although far from complete, infers that the problem is not as great as generally anticipated; as in other areas, several fixes exist to reduce its effects should it become detrimental to system performance.

The entire area of fruit measurement is critically in need of more carefully controlled measurement programs; while several experiments have been performed in the past few years, and much data has been taken (including that discussed here), in no case has it even been possible to determine precisely the number of I/R's actually involved.

1. Models

In order to predict future degradation in ATCRBS performance due to high fruit levels, the system is generally modeled in two segments: the first, involving such parameters as the number and distribution of interrogators, number and distribution of aircraft, PRF's, and so forth, yields asynchronous fruit arrival rate parameters; the second, starting with these parameters, analyzes decoding and detection operations, and, based on this, yields performance in terms of declaration of false targets, failure to declare actual targets, decoding error rates, and so forth.

Typical of the "first segment" analyses are those performed by ECAC [15, 16] and MITRE [17]. In these, various assumptions are made about the number of interrogators (other than the one of interest, the so-called "victim") in operation, and of how many aircraft in view of the victim each of these "sees." From these parameters, it is straightforward to calculate the expected long-term average fruit arrival rate at the victim interrogator antenna; appropriate assumptions about the pattern of that antenna, the traffic distribution, and the link power budget parameters result in an estimate of the rate of fruit received (passed through the antenna at a level greater than the I/R sensitivity).

For example, assuming N interfering interrogators, each with a PRF of 400 ips, and an effective beamwidth of 3.6°, a typical aircraft will see a peak interrogation rate from each of 400 ips, but will only see this one percent of the time (that time during which he is within the mainbeam). Thus, the average rate of reply generation per aircraft per interrogator is four replies per second. If there are n aircraft in sight of the victim, each in sight of all N interrogators, the total fruit arrival rate (on a long-term average) will be simply 4nN. If RF link parameters and victim antenna sidelobe levels are such that virtually all sidelobe-received replies are received at levels above the I/R sensitivity, then all these will be seen by the I/R.

Of course, this model is based on a sequence of imprecise assumptions, all of which must be taken into account. All aircraft do not see all interrogators; even if they did, reply rate limiting and dynamic desensitization would prevent any aircraft from simultaneously replying to more than three at a time; the mechanism for interrogation is hardly random (as implied by the assumption "1% of the time"), but rather quite deterministic (every four or ten seconds, regularly); in the case of non-SLS equipped aircraft and/or sites (of which a significant number are still apparently operational), proximity of an aircraft to a site (either of which is non-equipped) results not in 4 replies per second, but in 400; I/R patterns are hardly regular, but rather vary widely over small angles. These facts modify the simple model considerably; depending on the extent of one's knowledge of particular circumstances, each parameter in the expression for long term fruit rate must be expressed probabilistically, or as a function of a number of other parameters, such as aircraft position. The entire problem rapidly becomes intractable, even when only gross arrival rates are desired, assuming the fruit arrival mechanism is roughly Poisson-distributed and stationary. When the fact that it is not truly Poisson distributed is fully appreciated, and an attempt is made to determine its actual behavior, the problem becomes even more complex (and sensitive to numerous other parameters). This has prompted the DOT Transportation Systems Center to approach the ATCRBS modelling task from the other direction, namely large-scale computer simulation, based on as many actual system parameters as can be determined. Usually, there aren't many, and these attempts at simulation tend to give results which are in a sense compromises between what the more abstract models predict, and what is actually observed. Whenever actual fruit arrival data is measured in the field, associated parameters which affect the result and are required for precise simulation (e.g., the number of I/R's involved) are generally unobtainable. Thus, the simulation model is generally "adjusted" to fit the observed data by varying unknown parameters. Unfortunately, there are more unknown parameters than necessary to perform this adjustment, and, again, a large amount of judgement (and arbitrary assumption) is necessary.

The second segment of the model attempts to predict the consequences of various asynchronous fruit levels on system performance, in terms of such parameters as the incidence of spurious replies, spurious target declarations, and incorrect decoding; two different mechanisms contribute to the latter phenomenon. ATCRBS/ARTS III behavior in this area has been both simulated [18] and derived analytically [19] by MITRE; since our defruited data provides a direct measurement of the system performance (output) parameters noted above, we exercised the model in reverse in the interference analysis performed on our data, in order to infer from it the fruit levels which must have been present prior to defruiting. Details of this procudure will be discussed in Section 4, following. Section 5 discusses our undefruited data.

2. MITRE (Bedford) Data

The two MITRE studies [4, 5] which focused on the gross ATCRBS performance statistics observed in the New York area measured fruit rates which varied widely, both in the short term (typically 7 sec) and in the long term (5 min). Total fruit was nominally between 1000 and 2000 per sec, with a receiver sensitivity of -85 dBm, and between 1800 and 2400 with a -91 dBm receiver. Relative differences in antennas, transmission line losses, and so forth are not known. These figures equate to per aircraft fruit numbers between six and thirteen per second on a long-term-average (5 min) basis, and up to as much as twenty-one per second over a short term (7 sec). While the variation in short-term rates can be accounted for by variations in the orientations of the many I/R antennas involved in the fruit generation mechanism, one would expect this source to "average out" in the longer-term statistics. Variations in these cannot be accounted for by variations in aircraft populations or distributions; MITRE recognized that proximity of a single aircraft to a single interrogator, when one or the other was non-SLS equipped, was sufficient to account for a major part of the long-term variations, and suggested that this was the most likely cause. Unfortunately, real time fruit arrival data was not gathered, so it was not possible to verify this (for example, by searching for line spectra in the fruit arrival function).

Note that the average fruit per aircraft statistic implies that, with an average of ten interrogators in view of each aircraft (the lowest reasonable assumption for the New York City area), the actual fruit rate is only one-fifth to one-half what the model of part 1 would predict.

3. MITRE (Washington) Data

As a portion of the comprehensive analysis of ARTS III performance, MITRE (Washington) directly measured fruit arrival rates at Newark, Dulles, and Miami, by several methods. Results are summarized in Table 13. It can be seen that the values measured are quite low, considering the number of targets in the area. Unfortunately, neither target position distributions nor the numbers and locations of operating interrogators were precisely determined. In light of these uncertainties and many others, this data is certainly consistent with the measurements made by MITRE/Bedford.

4. Our Defruited Data

No direct measure of fruit arrival rate was possible with our defruited data. However, it was possible to infer the fruit rate indirectly, using the following line of reasoning:*

*For a more extensive derivation of this sort, see Ref 20.

Table 13. Fruit Rates Measured by MITRE.

SITE	NUMBER OF AIRCRAFT	FRUIT PER SCAN PEAK	FRUIT PER SCAN AVERAGE	SAMPLE SIZE (SCANS)
Newark	87	528	338	80
Knoxville	?	325	241	8
Dulles	30*	612	430	450
Miami	32	673	548	150
Boston**	26	464	370	2

*Our measurements, taken at a comparable time, at Andrews (30 miles away), showed 65 targets.
Data taken from Ref. 2, pp. 4-18 and 8-2.

**Our Undefruited Data.

- As fruit rate increases, its effects upon the (defruited) video processed by ARTS III, and the data examined, should be as follows, in order of decreasing frequency of occurrence:
  - False replies (individual, bearing no relation to target distribution in the immediate area) should occur.
  - Added pulses, randomly distributed, should occur occasionally in legitimate replies.
  - Pulses should occasionally be missing randomly from legitimate replies.

  The incidence of these phenomena should be directly related to the fruit arrival rate (through known parameters), and should permit its estimation.

- A false reply should occur whenever a fruit reply falls within a gate centered around a defruiter opening caused by another fruit reply (i.e., a 2-fruit coincidence). Figure 52 illustrates the gate and pulsewidths. As that figure shows, the time gate within which the two fruit must be aligned is G microseconds wide. So the probability of one or more fruit returns occurring during a defruiter opening caused by a particular fruit reply is simply (assuming the fruit is Poisson distributed):

$$p \text{ (one or more replies during G)} = r\,G$$

where r is the fruit arrival rate per second. There are r of these openings per second so:

$$E \text{ (coincident arrivals/second)} = r^2 G,$$

and, for a 4-second scan:

$$E \text{ (coincident arrivals/scan)} = 4r^2 G.$$

Now, a coincidence will cause a false reply only if it occurs while the receiver is active. Each sweep at Andrews is ≈ 2600 µs. in duration, but the receiver is active only out to the maximum range, corresponding to ≈ 620 µs. Thus, the expected number of times per scan that a fruit reply arrives during the "receiver active" time, and is followed on the next sweep within G microseconds by another fruit reply is simply:

$$E \text{ (false replies)} = r^2 G$$

The standard value for Gatewidth in an FAA defruiter is one microsecond; Table 14 shows the expected number of false replies as a function of fruit arrival rate, for this value.

This mechanism (i.e., fruit-generated replies "leaking" through the defruiter) can also occur due to certain combinations of three or more fruit; this was not taken into account in the above derivation, and would only be consequential in extremely high fruit arrival situations.

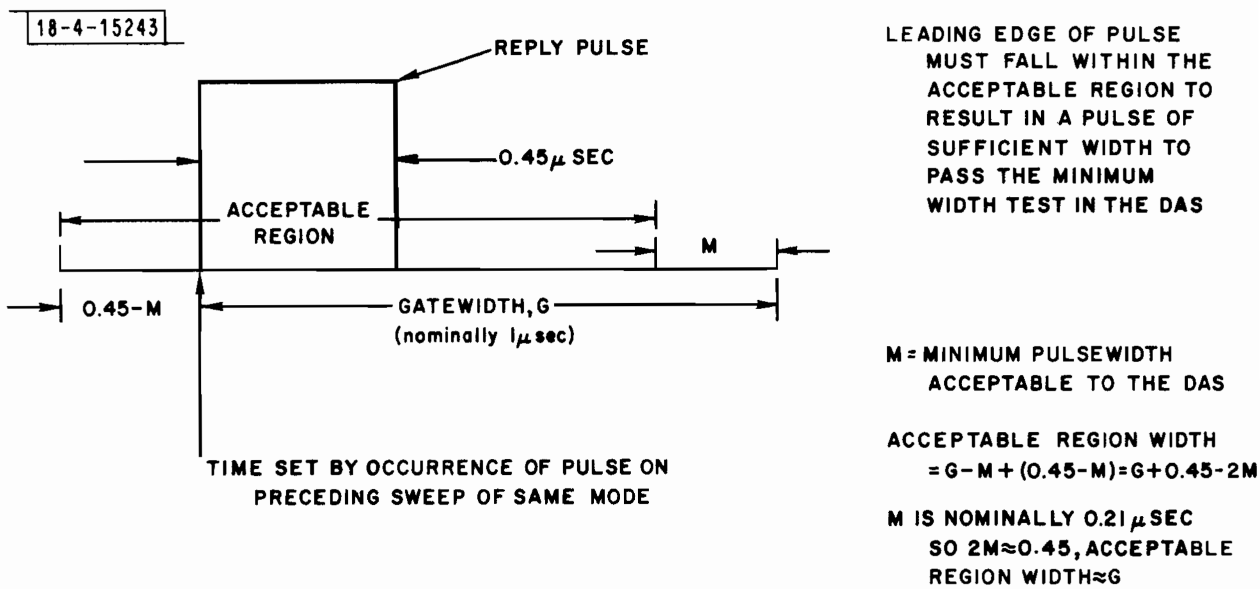


Fig. 52. Defruiter Timing Relationships.

Table 14. Expected Numbers of False Replies and Pulses as a Function of Fruit Rate.

FRUIT RATE	FALSE REPLIES PER SCAN	ADDED PULSES PER SCAN	CANCELLED PULSES PER SCAN
500	0.25	0.05	0.15
1000	1	0.2	0.3
2000	4	0.78	0.6
4000	16	3	1.2
8000	64	12.5	2.4
12000	144	28	3.6
16000	256	50	4.8
20000	400	78	6

- Since a typical reply (based on the population of assigned beacon codes noted; see Table 15) has three A and B pulses set, then the probability of any particular A or B pulse being set in the fruit-generated reply (whose pulses are each the logical "and" and those of the two fruit causing it) is 1/4. From this, given that a fruit-generated false reply is received, its apparent code has the following properties:

$$\text{pr (00XX)} = (\tfrac{3}{4})^6 = 0.18$$

$$\text{pr (one A or B pulse set)} = 6 \times \tfrac{1}{4} \times (\tfrac{3}{4})^5 = 0.36$$

$$\text{pr (two A or B pulses set)} = 15 \times (\tfrac{1}{4})^2 \times (\tfrac{3}{4})^4 = 0.30$$

$$\text{pr (three A or B pulses set)} = 20 \times (\tfrac{1}{4})^3 \times (\tfrac{3}{4})^3 = 0.13$$

$$\text{pr (four)} = 15 \times (\tfrac{1}{4})^4 \times (\tfrac{3}{4})^2 = 0.03$$

$$\text{pr (five)} = 6 \times (\tfrac{1}{4})^5 \times (\tfrac{3}{4}) = 0.004$$

$$\text{pr (six)} = (\tfrac{1}{4})^6 = \quad = 0.0002$$

In the Andrews data (Table 15), only about one-fifth of the aircraft were employing discrete codes (C or D pulses set); within this subpopulation, the average number of C or D pulses set was again roughly three. Thus, the probability that one or more C or D pulses is set in a reply code caused by fruit coincidence is:

p (C or D pulse set) = p (two fruit from discrete code aircraft) x p (<u>not</u> XX00)

$$= \frac{1}{25} \times (1 - (\tfrac{3}{4})^6) = 0.033.$$

The fact that a few aircraft were squawking mode C, and the typical mode C reply is of slightly higher weight (average of $4\frac{1}{2}$ pulses set), affects the above assumptions only very slightly, and was not taken into account in the above analysis.

- A pulse will be <u>added</u> to a legitimate reply whenever any two pulses of any two fruit replies bearing the proper timing relation to one another coincide to allow a single pulse through the defruiter, and, in addition, that pulse falls in an acceptable time slot of a legitimate reply. Fruit replies contain on the average five pulses (counting framing pulses.) Each of these in one reply can coincide with each pulse in the other. Thus, there are twenty-five possible alignments of fruit which can produce a single pulse (or more) at the defruiter. Of course, a lot of these are not distinct; for example, the time relationship which results in alignment of F_1 pulses always results in the alignment of

Table 15. Aircraft Codes (Mode A) Observed at Andrews AFB.

Under approach or departure control:

		No Mode C	Brackets Only	Mode C
Nondiscrete:				
	0100	4		
	0200	2	1	1
	0300			1
	0400	2		
	0500	1		1
	0700	1		
Discrete:	0710			1
	0712			1
	0717	1		
	0720			1
	1011	1		
	1605	1		1
	1717		1	
	1720	1		
	2013	1		
	3613			1
	2020	1		
VFR	1200	8	4	
Enroute	2100	1		10
Military	4000	6		2
IFR Climbing/ Descending	1100	7	1	1
	1300	1		1
	2000			1
High Altitude IFR	2300	1		
TOTALS		40	7	23

F_2's as well. To account for this, the number of possible alignments should be reduced somewhat below the maximum of 25; we have assumed twenty. Now, the probability of two fruit occurring in any one of these alignments is just rG (as in the preceding discussion). So the probability of a single pulse getting through the defruiter is roughly 20 rG, and the expected rate of this is 80 r^2G. That is, if we could look at single pulses coming out of the defruiter (which ARTS III for the most part ignores), we would expect to see eighty times as many of them per second as false replies, as shown in Table 14.

For one of these pulses to cause a problem, it must fall into an open space of a legitimate reply. During one scan there are ns legitimate replies, where n is the number of aircraft scanned by the interrogator, and s is the average number of replies per target declaration. Each reply contains thirteen information pulses (including the X-bit, whose setting would be indicated in our data), of which three are typically filled. Thus, there are ten empty reply pulse locations per reply and a total of 10 ns of these per scan. The time gate associated with each is roughly 300 ns; that is, ARTS III will falsely associate a spurious single pulse caused by fruit with a legitimate reply code position whenever that pulse occurs within a 300 ns window centered on that position. The total time per scan during which this can happen is thus 3 ns μsec, and the expected number of occurrances of this phenomenon (spurious setting of an individual information pulse) is 240 nsr^2G. Substituting values appropriate for Andrews reduces these expressions to 2440 μsec per scan, and (0.195) r^2G expected false pulses per scan. This is approximately one-twentieth of the rate of false reply generation (Table 14).

- A high fruit level will cause a valid reply pulse to be missed whenever a fruit pulse occurs simultaneously with a legitimate reply pulse and the phase and amplitude relationship of the pulses at the I/R input is such that RF phase cancellation results. Note that this mechanism does not involve the defruiter; the effect of the defruiter is to cause such missed pulses to be absent from two sweeps in a row. Reference 2 presents an exact derivation of the probability of this; since so many parameters (such as the distributions of relative amplitudes) are not well known, a far less exact derivation would appear to suffice.

Here, "cancellation" is arbitrarily defined as a reduction by 6 dB in power (a factor of two in voltage), a very pessimistic assumption. This will occur whenever the pulses bear the phase and amplitude relationships illustrated in Figure 53a. Assuming the ratio of voltage magnitudes at the input to equal X, and a uniform phase distribution, the probability of this is given by:

$$p\left(\left[\int_{\substack{\text{range}\\ \text{over all X}}} \int_0^{2\pi} [x^2 + 1 - x\cos\theta]\, \frac{p(x)}{2\pi} \quad dx\, d\theta\right] \le \frac{1}{2}\right)$$

An approximation to this expression can be obtained by separating the amplitude and phase relations; this is hardly exact, but serves to provide physical insight into the phenomenon. From Figure 53b, we see (roughly) that:

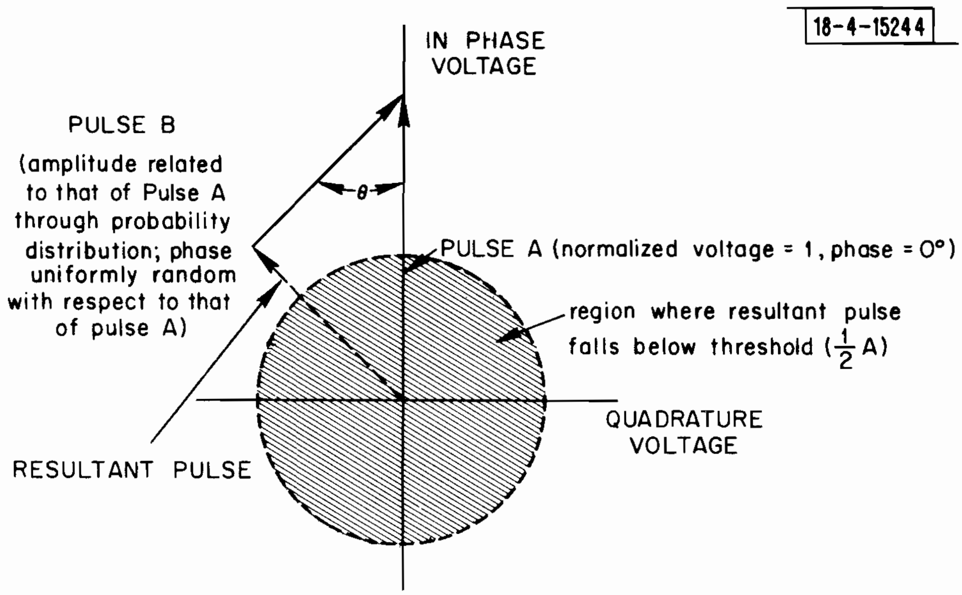
$$p[\text{cancellation}] \approx p[\,|\theta| \le 30^\circ]\; p[\tfrac{1}{2} \le x \le 2]$$

For lack of a better assumption, since this parameter has never to our knowledge been experimentally measured, we assume the ratio of the two signals to be uniformly distributed in decibels over the range -20 dB to + 20 dB (remember that fruit replies arrive largely through antenna sidelobes). Thus, the probability that the two pulses are within a factor of two in voltage of one another, is simply 6/20 = 0.3.

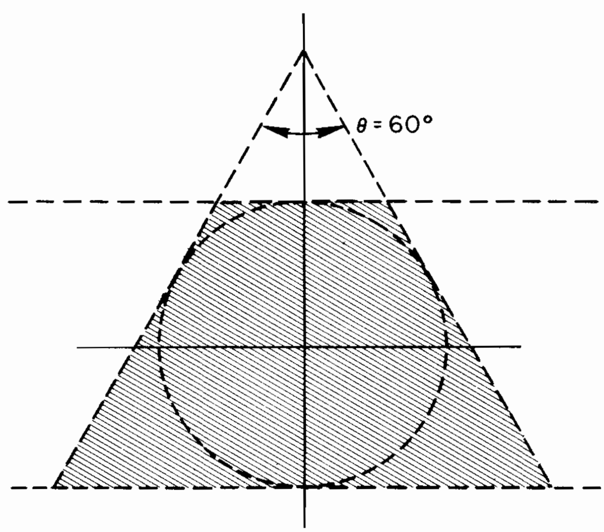
Similarly, for the phase angle, assuming equal amplitude signals (Figure 53b), cancellation will only occur when the phase angle of the interfering signal is within $\pm$ 30° of that of the other signal. Assuming that θ is uniformly distributed, the probability of this is just 0.167.

The probability that phase cancellation occurs, then, given that a fruit pulse overlaps a legitimate pulse to begin with, is 0.167 x 0.3 = 0.056.

Phase cancellation will affect the data whenever the legitimate and fruit pulses are aligned so closely that the nonoverlapping portions of the two pulses are of insufficient width to be passed by the minimum pulsewidth circuit of the DAS. This implies that the interfering pulse must fall within a 0.45 μsec time gate centered on the legitimate reply pulse.



(a.) Pulse cancellation geometry



(b.) Approximation used in text

Fig. 53. Pulse Cancellation Geometry.

There are 65 (aircraft) x 12.5 (replies per aircraft) x 3 (information pulses per reply) = 2400 of these legitimate reply pulses per scan, or 600 per sec. The probability that any single (Poisson-distributed) fruit pulse falls onto one of them is therefore $600 \times 0.45 \times 10^{-6}$. During each scan there are 4r (fruit replies per scan) x 5 (pulses per reply) = 20r such fruit pulses. Thus, the expected incidence of coincident pulses is $600 \times 0.45 \times 20 \times 10^{-6} \times r = (0.54 \times 10^{-2})r$, and the incidence of cancellations is this times the probability of cancellation given this, 0.056, or about $(3 \times 10^{-4})r$. (Table 14.)

We see from Table 14 that the most prominent consequence of high asychronous fruit on ARTS III output data is likely to be creation of anomalous single replies. Six scans of Andrews data were searched to determine how many replies of this sort were present. These replies are plotted in range and azimuth in Figure 54. Approximately fifty were found on the first pass. However, thirty of these occurred within the 1 nmi band centered on 50 nmi, all on mode C sweeps. This clustering ties in with other observed anomalous behavior seen at maximum range, and is believed to be the result of extraneous pulse interference within ARTS III. The remaining twenty-four superfluous individual replies plotted in Figure 54 are listed in Table 16. As Figure 52 shows, they are essentially randomly distributed in R and θ (as one would expect if they were fruit-generated); several of the codes are identical to those of aircraft within the system; it is not possible to positively assign many of these replies to the mechanism under discussion. Elimination of those replies whose high weight (i.e., large number of code pulses set) or frequent repetition suggests that their source is some other mechanism leaves eleven replies during the six scans, or an average of 1.83 replies per scan. From Table 14 this corresponds to roughly 1400 fruit per second. This is

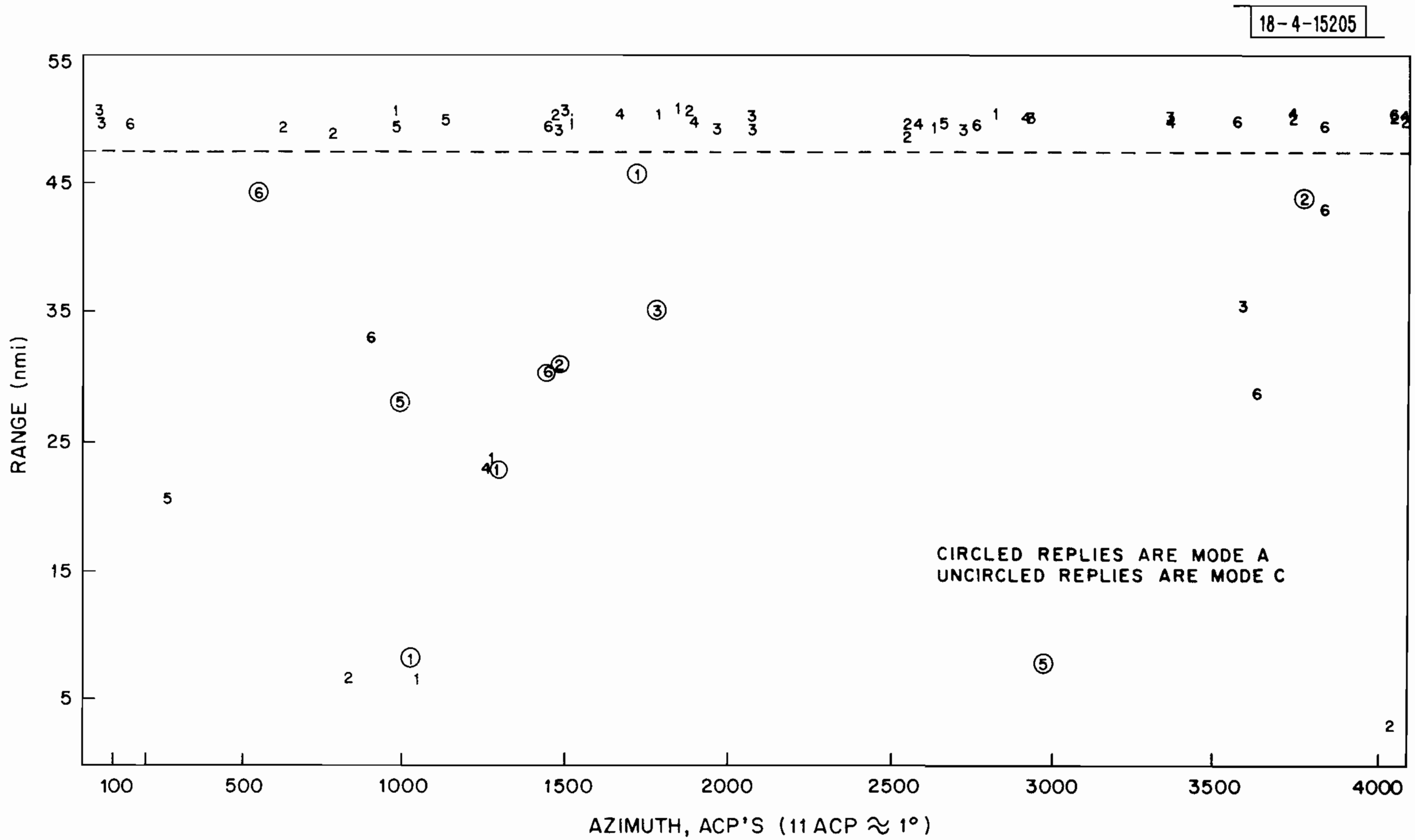


Fig. 54. Spurious Replies Due to Fruit.

Table 16. Anomalous Replies Seen During Six Scans at Andrews Air Force Base.

	Due to fruit	
Scan 30:		
1300		False Target
04600 *		? - Corresponds to 1300
00000 *	X	
1200	?	
0712		False Target
Scan 31:		
04600 *		
0000	X	
1100	X	
00700 *		
Scan 32:		
0300		Ringaround
0000	X	
00400 *	X	
Scan 33:		
1100		False Target
00000 *	X	
Scan 34:		
04200 *	X	Corresponds to 1200
0000	X	
1300		False Target
2300		False Target
Scan 35:		
00000 *	X	
2000	X	
0112		
00000 *	X	

* Five-character code signifies altitude reply

higher than rates measured by MITRE, which suggests that consideration should be given to the fact that other mechanisms were undoubtedly responsible for some of the replies listed in Table 16.

The same six scans were searched for extra or missing pulses in legitimate reply sequence, as discussed in this section; none were found. The only extra ones noted were straightforwardly attributable to synchronous garble or improper transponder operation (one particular transponder frequently replied with a particular pulse set erroneously).

Missing pulses occurred far more frequently; a total of ninety were observed. Of these, nineteen occurred at random on single sweeps; decoding was correct on adjacent sweeps; these do not appear attributable to a phase-cancellation mechanism, but rather to pulse arrival times which are out of specification; see the discussion on lost replies in Section A of this Chapter. Seventy occurred at beamedges (regularly from scan to scan with some transponders), or due to defruiter spots (the pulse would be missed repeatedly during a scan, but on alternating replies, rather than any two in a row). In one instance, a pulse was lost on two replies in a row.

These results are consistent with the estimate of fruit rate derived above; given 1400 fruit/sec, one would expect to observe perhaps a single case of additive or subtractive fruit interference in six scans.

5. Our Undefruited Data

In order to obtain some more direct data on the fruit generation process, we obtained two tapes from Boston which were made with the defruiter bypassed. No adverse effects on ARTS III performance were noted during the recording. One of these tapes was analyzed manually. Two scans of the tape, separated by approximately 14 seconds (three scans), were examined in detail. For each, replies which correlated with one another were identified and associated with real or false targets found during the first few scans on the tape; during those scans the defruiter had been turned on. All correlated replies agreed with actual aircraft positions, or with known reflection mechanisms and actual aircraft positions. Aircraft positions are tabulated in Table 17 in order of increasing range. (Note from the table that since the Boston Terminal Control Area (TCA) was operational, discrete codes are used on many aircraft; this made the analysis that follows possible.)

In addition to the replies associated with legitimate targets, a fairly severe ringaround was observed at 42.06 nmi; replies due to this were similarly identified. It is of interest to observe that the number of ringaround replies was reduced substantially when the defruiter was switched off. This is probably because of the amplifying and limiting action of the defruiter, which tends to boost the level of weak signals that otherwise would not be detected. This same effect would also be expected to cause runlengths of targets at long range to be diminished slightly when the defruiter is turned off. Although this effect has not been quantitatively determined, a cursory examination of the data suggests that runlengths are, in fact, very slightly reduced when the defruiter is removed.

The remaining replies were considered to be fruit, and were individually examined to determine which targets they were associated with. This process was complicated by the facts that each reply could be read as either a mode A or mode C reply (depending on which mode the Logan I/R happened to be in at the moment), and that most aircraft were squawking both code and altitude. Thus, for each mode-C equipped target, four different apparent reply codes were possible:

Table 17. Aircraft Within the Logan Area.

CODE	ALTITUDE (FL)	RANGE (nmi)	AZIMUTH (deg)
0313	001	1.0	63
0326	048	3.94	224
0215	015	4.06	84
0406	061	7.5	192
2000	059	8.56	266
1200	---	9.18	46
0267	074	9.5	149
1200	---	9.81	348
0105	---	11.25	132
4600	---	11.3	282
1200	---	22.56	151
1100	149	22.9	255
1200	---	27.43	309
1200	---	29.94	344
0432	---	30.59	332
1200	---	38.59	337
1200	---	39.09	319
0000	---	42.06	**
1249	---	43.5	215
1200	---	46.43	234
1200	---	48.25	222
1200	---	48.37	205
0152	---	51.3	201
1100	--	53.78	241
1100	---	54.18	222
1500	206	53.65	298

**Ringaround target; azimuth indeterminate.

The actual mode A code, as read in mode A.

The actual mode C code, as read in mode C.

The mode A code erroneously interpreted as a mode C reply.

The mode C code erroneously interpreted as a mode A reply.

As an example of the above situation, the aircraft squawking code 0215 was at an altitude of 1500 feet (mode C code 0064). The following reply codes, all of which were observed, were directly attributable to him:*

I/R in Mode A:
- 0215 (his mode A replies)
- 0310 (his mode C replies)

I/R in Mode C:
- 5024 (his mode A replies)
- 0064 (his mode C replies)

Fortunately, all mode-C equipped aircraft were at different altitudes, and there was relatively little similarity among altitude and ID codes, so positive association of a reply with an aircraft was possible with most fruit replies, even when reply codes were corrupted due to garbling or missing pulses (which indicated that the reply path signal levels were marginal). Only one reply was noted which could be readily associated with more than one aircraft. On the other hand, many replies were observed which did not appear to correlate with any aircraft. Some of these were 2100 codes and high altitudes, and appear to be mainbeam fruit from aircraft beyond the range of the I/R (note from Table 17 that there are no 2100 aircraft in sight). Others consisted of empty brackets or high-weight codes which did not even vaguely resemble actual codes in use by the aircraft in the vicinity. These

*The ARTS III Mode C code readout format is somewhat different from the usual ABCD format; in mode C, the DAS outputs the characters in sequence DABC, with the order of the subscripts reversed.

latter replies were most likely the result of garbling between replies (frequently in these cases, the G-flag would be set, but no other reply would be detected).

Four hundred sixty-four fruit replies were observed on one scan; 469 were observed on the other. During both periods, 26 aircraft were within the interrogation coverage area; this gives a gross average of 17.9 fruit replies per aircraft per scan, which is comparable to the numbers measured in the MITRE New York Studies. However, judging from the details of the data gathered here, it appears that this method of normalizing and presenting the data (i.e., calculating fruit per aircraft in the coverage area) is not especially meaningful. Table 18 presents breakdowns of the total fruit counts for the two scans, associating the various replies with the various aircraft. It is evident from this table that the vast majority of the fruit is due to a small fraction (30%) of the aircraft in the coverage area, namely those aircraft within about ten miles, and at sufficient altitude to be in view of other interrogators. (Note that relatively few fruit are received from the aircraft squawking 0313 at a range of only 1 nmi; his altitude, velocity, and location infer that he is not airborne, but rather awaiting takeoff at the threshold of rwy 33L; thus, he is not in view of many interrogators.)

In the entire set of data, only one sidelobe fruit reply (out of 933) was definitely attributable to an aircraft at a range greater than 10 nmi; this suggests that antenna sidelobe levels are well below what would be expected (Table 19), perhaps because the Logan installation is less than a year old.

6. Conclusions

All data indicate that with present-day traffic and interrogator densities in busy areas (between 50-100 aircraft in sight; perhaps 20 interrogators operating), the incidence of asynchronous fruit at an I/R is so low that, upon defruiting, its effects are too small to determine with precision.

Table 18. Fruit Breakdown.

(a)

Scan 3 (total 464 fruit replies)

SIDELOBE

105	due to aircraft squawking 0215 at 4 nmi
55	due to aircraft squawking 0326 at 3 nmi
35	due to aircraft squawking 0406 at 8 nmi
28	due to aircraft squawking 1200* at 8 nmi
27	due to aircraft squawking 0267 at 7 nmi
20	due to aircraft squawking 2000 at 7 nmi
19	due to aircraft squawking 0313** at 1 nmi
289	Total identifiable sidelobe fruit from aircraft within 10 nmi

MAINBEAM

57	due to identifiable aircraft
10	due to aircraft in the PCA beyond 60 nmi (code 2100)
67	

UNKNOWN

108 empty brackets, severely garbled codes, or unrecognizable codes***

(b)

Scan 6 (total 469 fruit replies)

SIDELOBE

145	due to aircraft squawking 0215 at 4 nmi
84	due to aircraft squawking 0326 at 4 nmi
37	due to aircraft squawking 0313 at 1 nmi
33	due to aircraft squawking 0267 at 9 nmi
19	due to aircraft squawking 1200 at 8 nmi
18	due to aircraft squawking 0406 at 7 nmi
1	due to aircraft squawking 2000 at 7 nmi
1	due to aircraft squawking 0432 at 30 nmi (90° off mainbeam)
338	Total identifiable sidelobe fruit, all but one from aircraft within 10 nmi

MAINBEAM

37	due to identified aircraft
33	due to aircraft in the PCA beyond 60 nmi

UNKNOWN

61 empty brackets, severely garbled codes, etc.

---

*Presumably; there were other aircraft squawking 1200 in the system. Several of the empty brackets could perhaps be attributed to this aircraft's mode C replies, but were not.

**On airport surface; see text.

***Individual replies were processed as follows: if the G- flag was set and another reply was close-by, manual degarbling was performed to remove additive errors. If the unrecognizable reply was in the clear, subtractive errors (up to two errors) were assumed due to marginality of RF link.

Table 19. Power Relationships - Sidelobe Replies.

Power output (200 W)	53 dBm	
Freespace pathloss (10 nmi)	-120 dB	
Power incident on I/R antenna	-67 dBm	
Tangential sensitivity	-92 dBm	
Level above tangential sensitivity necessary for bracket detection*	12 dB	
Required received signal level at front end	-80 dBm	
Cable losses	2 dB	
Required signal level at antenna terminals		-78 dBm
Signal attenuation due to antenna (relative to isotropic)		-11 dB
Peak antenna gain		22 dB
Maximum sidelobe level relative to mainbeam		> 33 dB down

*Parameter estimated, based on amount of noise (rather than fruit) observed on scope.

This has apparently not always been the case; use of power reduction and Interrogation SLS have apparently been significant factors in this improvement.

As aircraft density grows, assuming the number of interrogators remains constant, the amount of fruit can be expected to increase roughly in direct proportion. An increase of more than an order of magnitude would be necessary before the incidence of spurious replys "leaking" through the defruiter would be so high as to cause difficulty in ARTS III performance.

To the contrary, it has been suggested [2, 20] that defruiters should be removed from the ARTS III DAS input lines at some sites, because in today's environment, their deleterious effects with respect to runlength reduction and introduction of azimuth errors more than offset any advantage they might provide. The ARTS III software performs a sort of generalized defruiting function already; adjustment of a few parameters could allow defruiter removal while holding the probability of overload to an acceptable minimum. Of course, the defruiter would still be employed in the analog signal line to provide clean display video. The data observed to date support this reasoning; at worst, as the situation degrades with increasing traffic density, defruiters could be switched into the ARTS III video line once again.

G. The Ringaround Problem

Ringaround (sidelobe interrogation) was at one time a severe problem in ATCRBS; due to widespread implementation of Interrogation Sidelobe suppression both at I/R sites, and in transponders, the incidence of this effect has been reduced to the point where it is barely noticeable. Only three instances of severe ringaround were observed in all of the Andrews and Boston data. One of these was partial (perhaps two dozen sidelobe replies in a scan), and emanated from a commercial airliner within one nmi of the interrogator (on takeoff - see Section III. B. 5 which discusses the false target mechanism at Boston). The second involved an (apparently military) aircraft on final to Andrews at three nmi, squawking a nondiscrete code; it was similarly limited in extent, to the point where ARTS III had little difficulty in correctly determining the aircraft's position. The third instance involved an aircraft squawking 1200 at approximately 12 nmi from the Boston I/R. The ringaround caused by that aircraft was virtually complete; this is consistent with the high power and sensitivity of the Boston I/R. ARTS III did not declare the aircraft position correctly (or at all, on some scans); it was not possible to determine actual azimuth from the data.

A less severe but more often noted effect of improper SLS operation observed occasionally in the Andrews data involved Navy Aircraft, apparently not SLS-equipped, operating in the vicinity of NAS Patuxent River. Several would regularly reply to the first sidelobes as well as the mainbeam, resulting in a slightly longer than usual reply sequence. One of the ARTS III target detection logic parameters is maximum allowable runlength prior to declaration of ringaround, set at thirty. In these cases, declaration terminated in the middle of the scan through the target; the result was a slight (between one-half and one degree) azimuth error. This situation could be corrected merely by increasing the value of the maximum acceptable runlength parameter.

Clearly, the joint FAA/Military program to eliminate ringaround through installation of the Setrin (Interrogation SLS) fix has been successful, and when the last few aircraft (and Interrogators) have been fixed, the problem should disappear. This fix has also had a substantial beneficial impact on asynchronous fruit levels.

H. The Problem of Split Targets

On occasion, due to low round reliability or other causes, a single target reply sequence is mistaken for two or more targets by the target declaration logic. This phenomenon is allegedly far more prevalent in the en route system than in the terminal system. ARTS III properly accounts for range splits (which occur whenever a target crosses the edge of a range cell during the instant that it is illuminated) by associating all replies within two adjacent cells with one another. Azimuth splitting occurs only in areas of especially low round reliability; round reliability was extremely high in all the data examined here. No improper target declarations were noted in the data due to either range splitting or azimuth splitting. The only phenomenon observed in ARTS III which even relates to target splitting arose because of transponders whose pulsewidths were excessive, such that ARTS III mistook each pulse for a pair of overlapped pulses, inserted a (pseudo) leading edge, and declared two targets in adjacent range cells; since the pulses were closely aligned in time with one another, ARTS III sensed garbling, and set the garble flag on each reply.

Proper study of the problem of split targets should focus on the en route system; few general conclusions can be reached from the ARTS III data, except that splitting is hardly widespread in the terminal area.

I. Accuracy

Only a cursory examination of the accuracy of the ATCRBS/ARTS III system was performed, since proper treatment of this area would necessitate a study for larger than this one; simply determining what accuracies are required for various services, and how they are to be defined, would require more time and information than was available here.

Several aircraft tracks were examined in order to gain preliminary insight into the accuracy performance of the system. Performance in the two coordinate axes measured by the system, range and bearing, appeared quite different, both in magnitude and behavior; the two are discussed separately below.

In no case was any random variation in declared target range even noted. The entire random component of declared range error appeared due to the 1/16th nmi range quantization employed by ARTS III. Radial velocity appeared almost constant over particular flight segments, rarely varying by more than one range increment per scan over a series of scans. For example, a target flying a roughly radial track might change range regularly by three range cells (3/16 nmi) on each scan, with an occasional change of only two cells. A faster target would occasionally jump four cells, rather than two. A still faster target would regularly change by four cells. It was noted for some targets that when the target was apparently near the boundary between adjacent range cells, the reply sequence included replies from both ranges in random sequence. Simple averaging of these numbers allowed us to establish range to an additional factor of two, with an improvement in range accuracy, as determined by smoothing and uniformly interpolating range over a number of scans.

Of course, transponder turnaround time bias errors are very likely responsible for greater errors than the random ones noted here; since no external source of position data was available, it was not possible to determine whatever bias errors might have been present. (Note that while these affect position on a random basis from one aircraft to the next, they do not affect the calculation of velocity performed by ARTS III, since they cancel in the velocity estimation process.)

A particular pattern of range errors was noted regularly on a few targets. With these aircraft, the first and last few replies of a sequence would regularly fall within the range cell adjacent to (usually more distant than) the one in which the remainder of the replies were observed. This appears to be due to transponder turnaround time bias error that is dependent upon input signal level; at the edges of the beam, where the signal level is lower, the turnaround time is somewhat greater as a result. In no case observed did this situation result in range variations greater than one range cell. Even the most severely affected aircraft exhibited this phenomenon only occasionally, suggesting that they were close to the edges of range cells at those times. Thus, the effects on range accuracy of that portion of transponder turn-around time error that is dependent upon signal level appear small compared to a range cell.

Azimuth errors appear to be greater than range errors by perhaps a factor of five to ten, depending on range. Typically, azimuth error standard deviations of two to three ACP's (on the order of 0.25°) were noted in the tracks of approaching commercial aircraft at elevations well above the horizon; the track of an aircraft slightly less accurate than most, is shown in Figure 55. This aircraft was departing from Washington National Airport, roughly six miles to the east of the I/R, and was not mode C equipped. The error standard deviation for this aircraft over 90 scans (corresponding to an 18 nmi change in range) was calculated to be 4.6 ACP's (0.4°). This accuracy is somewhat lower than normal primarily because of the several quite bad

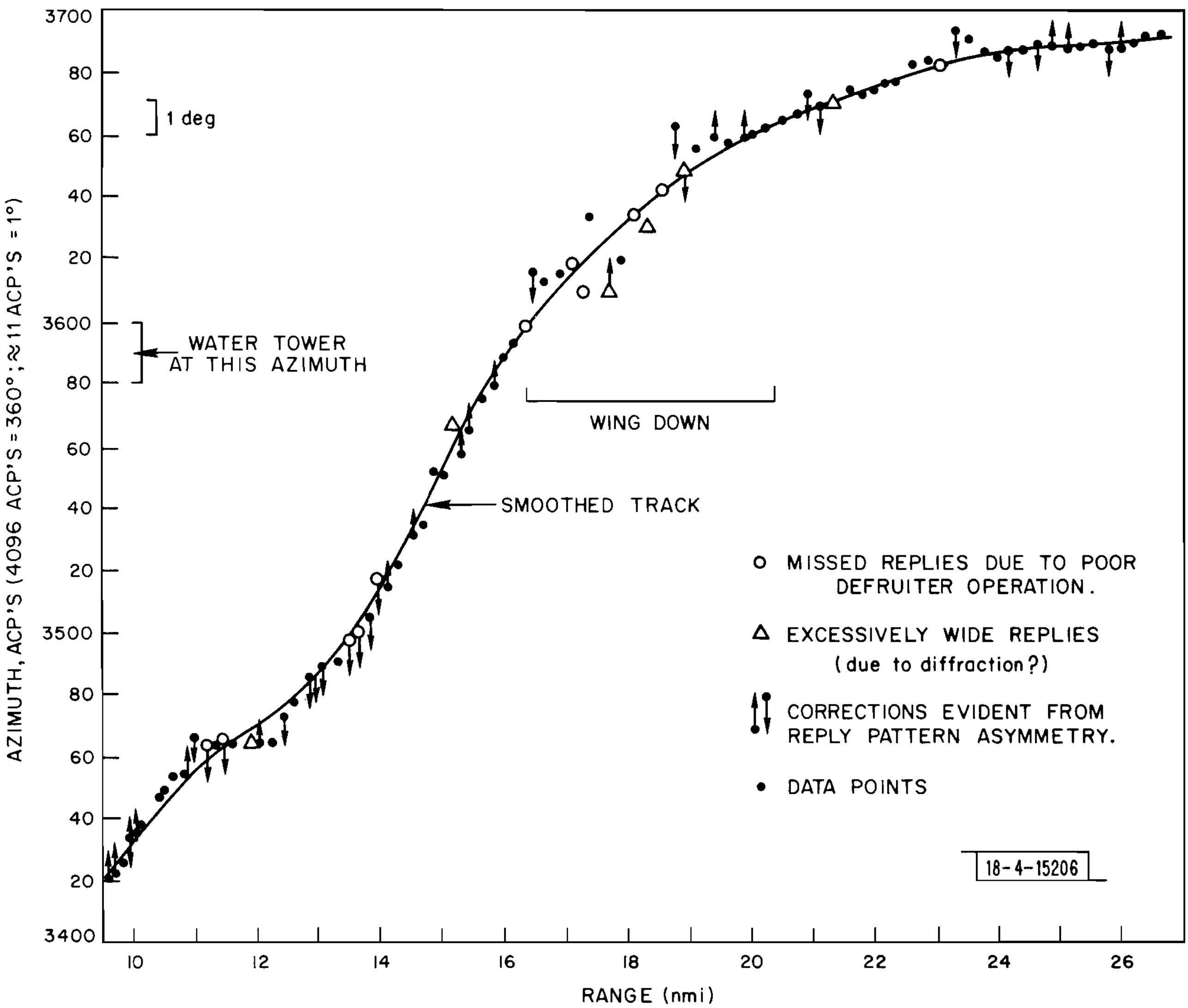


Fig. 55. ARTS III/ATCRBS Accuracy.

azimuths reported at ranges between 16 and 20 nmi, during which times the aircraft was in a slight turn. (The geometry of the turn was not favorable to aircraft antenna shielding; it is likely that the bank angle was quite small.)

It is of interest to note that the reply probabilities associated with the data points with the larger azimuth errors are not especially different from those of the other points. Examination of individual sweep data reveals that some of the poorest quality azimuths resulted from beam-splitting on solid reply sequences (no missing replies); conversely, on several reply sequences with reply probability on the order of 0.5, beamsplitting performance was quite good. However, observation of the locations of "holes" in reply sequences generally allowed proper prediction of the direction of the resulting azimuth error. These holes were primarily due to a mechanism other than low reply probability; see Section III.a.

It is also interesting to note that there is a large water tank with multiple support columns approximately one mile away from the Andrews I/R at the azimuth shown in Figure 55 (see also Figure 32a). Although the data is insufficient to draw definite conclusions, it appears that diffraction through the base structure of this tank could be responsible for some of the more erroneous readings. Similar effects, amounting to as much as a degree of azimuth error were noted in the Andrews data with other aircraft as a result of improper beam widening due to building-edge diffraction. Errors of as much as two degrees were also noted due to diffraction at Boston as VFR aircraft flew behind the stacks at approximately 260° (Figure 32b).

No attempts were made at systematic investigation of the data to determine how ARTS III processing might be modified to improve accuracy; this is because there is little agreement as to whether present accuracy suffices, or, if not, just what accuracy is needed. Proper treatment of this entire area is far beyond our current capabilities, and would require at the outset the analysis of far more data than has been considered here.

IV. INITIAL IMPLEMENTATION

The data discussed and analyzed in this report are hardly of sufficient breadth and depth to serve as an adequate foundation for a detailed evolutionary plan to remedy the weaknesses of ATCRBS. Indeed, much additional discussion and examination of data will undoubtedly be necessary before a complete consensus is reached regarding which ATCRBS problems are the most severe, and most in need of remedial action. Conversely, some conclusions in the area of planning future ATCRBS improvements are clearly in order, in light of the information gathered in the course of our study. This section discusses those several initial steps in the evolution from ATCRBS to DABS which follow from the information contained in the previous section, and which could be commenced at the present time with little techrical risk, and relatively little expense. They are discussed in the order in which they should be implemented.

A. Development of a Comprehensive ATCRBS Performance Data Base

Perhaps the most important finding of this study is that a surprisingly complete indication of the performance of an individual ATCRBS installation can be developed from a relatively small quantity of computer-derived data, which can easily be obtained from any ARTS III installation. It is now possible, with the widespread implementation of ARTS III, to gather data pertinent to the performance of the secondary radar system in the terminal area on a nationwide basis; with so many widespread and diverse data sources available it would be simple to gather and analyze a sufficiently broad set of data, from which quantitative measures of system performance could be derived through techniques similar to those discussed in the preceding section, but taking more advantage of automated data reduction procedures, and processing far larger (and more representative) quantities of data. A data gathering, analysis, and reduction program of this sort, making effective use of input data from all ARTS III sites, is a necessary prerequisite to any ATCRBS improvement programs requiring the long term commitment of funds.

Such a program would satisfy three immediate objectives: it would validate (or perhaps refute) the conclusions reached on various problem areas in this report, it would provide quantitative information regarding the extent of the various problems, allowing the priorities for their solution to be set on that basis, and would uncover a fairly complete set of atypical problems (and determine whether they are unique, or in fact more widespread than generally realized).

It should, of course, be emphasized that those ATCRBS installations employing ARTS III hardly comprise the complete set of FAA interrogators, and, because of this, care must be exercised in extending conclusions reached from ARTS III-derived data to the entire system. Initial studies of the scope of this one are essential for both the remainder of FAA TRACON secondary radar installations (which will be equipped with ARTS II or the AN/TPX-42), and for the entire en route system. We suspect, especially in the latter case, that the results will differ dignificantly in several areas from those presented here.

Once a relatively complete and representative group of data tapes from the various ARTS III and similar systems has been assembled, sufficient processing time and programming resources should be allocated to develop automated data processing routines in many areas including the following:

1. Determination of Gross Reply Probability Statistics

Reply probability statistics should be developed from reply-by-reply data of the type used in this report, by suitable reply-counting procedures. These should take note of the two different mechanisms (discussed in Section III.A) leading tc missed replies, and should perform statistical analysis on a suitably large ensemble of reply sequences. If sufficient data were available, reply probability, which is primarily a function of the localized uplink environment, could be measured separately in various relatively small geographical areas; this would provide quantitative data on uplink interrogation rates (by inference), which could be used for the same purposes as the "Hot Spot" data currently gathered by SAFI (Semi Automated Flight Inspection) flights. Such information could be gathered for particular areas of interest in as much depth as necessary for as much time as necessary to resolve the actual uplink situation, without the need for special aircraft; it has been noted [21] that under the present procedure for measuring "Hot Spots" (areas of over-interrogation) only those spots that happen to be "hot" at the instant the SAFI aircraft passes through them are detected. While this provides a good probabilistic indication of what local areas should be examined in greater detail, a processing procedure applied to reply data gathered by ARTS III would shed far more light onto the particular mechanism behind each "hot spot." (That is, whether it is due to regular interrogation at excessive rates by a small number of interrogators or rather due to occasional azimuthal alignment of a far greater number of lower PRF interrogations.) Based upon the data we have observed, it appears that the incidence of low reply probability (the most pronounced consequence of a "hot spot") will be surprisingly low.

2. Determination of Gross Fruit and Interference Levels

A comprehensive data reduction program could easily obtain bounds on received fruit levels throughout the system as a function of traffic density, interrogation power levels, and so forth. This could be done either by searching for spurious replies, as outlined in Section III.F, or by direct analysis of ARTS III data obtained while defruiters have been switched out. Such undefruited data has been obtained from the Boston ARTS III site during a period of high activity (45 aircraft), with little operational difficulty; the data has not yet been analyzed in detail, but initial indications are that the gross numbers of fruit replies are of the same order as the number of legitimate replies; thus, collection of data on all the excess replies processed, and on the performance of the DAS in their presence, appears to be well within the capabilities of the ARTS III extraction routine.

A data reduction program of this sort could provide a comprehensive indication of fruit levels throughout the system, and of whatever fruit statistics are necessary to either improve the performance of the system in a high fruit situation, or determine the cause of excessive fruit rates, and correct the situation at its source.

3. Determination of Gross Aircraft Movement Parameters

It was noted in Section III that no examples of improper decoding due to synchronous garble were observed on two or more consecutive scans of the same pair of aircraft. On the other hand, the example used in connection with the poor angular resolution problem showed two aircraft whose ranges were equal for more than a minute. Additional processing of much more data gathered at various sites appears desirable in order to determine the incidence of events such as these, as they actually occur. Gas models and more contrived situations have been used in the past for purposes ranging from analysis of surveillance performance to determination of Collision Avoidance System effectiveness. While such models suffice to give gross measures of system behavior, there are many statistical parameters of the Air Transportation system that undoubtedly differe markedly from what these models predict. For example, do aircraft velocities really obey a Maxwell-Boltzmann distribution? Conversely, in the gas model, what is the probability that two particles in a row follow the same trajectory (as do IFR aircraft on final approach)?

Data in this area would be particularly valuable in filling in some of the weaker areas in this report. For example, regarding aircraft interactions in the synchronous garble situation, the fact that no bad decodes were noted on two or more scans in sequence certainly does not mean that that phenomenon never occurs. Incidence of such phenomena could be quite dependent on site geometry, runways and approaches in use, and so forth. False target incidence also appears to be heavily dependent on site and flight-path geometry. A much broader foundation of data is needed before any useful general observations can be made in these and many other areas.

Many statistical parameters of the air transportation system which could be quite useful to those engaged in many research and design areas (in addition to the one under which this study was performed) could be gathered with little additional difficulty from ARTS III-extracted data.

4. False Target Parameters

As noted in Section III. C, the fixes applicable to the problem of false targets must be tailored to individual sites. Assumptions were made that the reflecting surfaces contributing to the bulk of the problem at most airports were relatively few in number and well defined. Analysis of data such as performed in Section III. C should be repeated for all sites when false targets are perceived to be a problem, in order to properly "size" the fixes to the problem, and to determine which phenomena are in fact typical, and which are not.

5. Accuracy

The entire area of measurement accuracy, and what external error sources influence it, is in need of a detailed data-gathering program. Much could be accomplished in this area by appropriate processing of ARTS III extractor-derived data, along with a realtively small amount of auxiliary data, such as obstruction charts, panoramic photos, and so forth. As noted earlier, a study of this sort can only be accomplished profitably when new insight has been gained into the questions of what accuracies are needed, how they are defined, and where they are needed.

6. Antenna Pattern and Coverage Determination

While most controllers have a good qualitative understanding of where surveillance coverage "dead spots" occur in ATCRBS installations, it would be advantageous to perform a quantitative measurement of the three-dimensional coverage volume of each I/R; this could be accomplished by processing of a relatively large amount of data derived from mode C equipped aircraft, observing when target dropouts occur, and attempting to correlate these dropouts with position. For example, observation of VFR aircraft in Section III.A led us to the conclusion that building blockage was recognizable and significant. Had these aircraft been altimeter-equipped, and had sufficient flights been observed, it would have been possible to define with high accuracy that (three-dimensional) volume where, say, greater than fifty percent of the aircraft have their runlengths reduced below a certain threshold. This could yield accurate bounds on the volume of coverage imposed by blocking objects on the horizon (buildings, hills, etc.), vertical lobing due to ground reflection, and the cone of silence of the antenna.

In addition, analysis of sufficient quantities of undefruited ARTS III extractor data could yield an indirect measure of the sidelobe response of the antenna by correlating the angles relative to boresight over which fruit replies are most frequently received (at particular ranges); these could be determined with aircraft squawking discrete codes since their actual positions are known. Enough data would be required to properly smooth over the irregular nature of the fruit generation process.

Of course, such measurements are no substitute for direct antenna pattern measurements, as might be performed with appropriately instrumented aircraft. Such measurements are essential if certain fixes, such as monopulse, are to be implemented.

The listing of areas in need of additional data gathering is by no means complete; the astute reader will no doubt by this stage have noted many areas in which analysis of fresh data in sufficient quantity might reveal many different surprises. Assignment of relative priorities to the many different directions that could be pursued is needed; it is our belief that the five areas listed in this section are the five most important.

B. Development of Appropriate Software-Based Improvements

It is clear from the data discussed in this report that a large fraction of present-day (and future) ATCRBS problems can be mitigated or eliminated by widespread implementation of digital processing systems such as ARTS III, and appropriate updating of the software associated with these systems. Development of new software which is directed at solving particular problems such as those discussed in this report appears to offer high promise at low risk in terms of investment; since, for the most part, no new hardware is involved, such development could be commenced on a large scale immediately. In many instances, the software could be developed based on data available from ARTS III, tested off-line using actual ARTS III extractor-derived target reply data (rather than data generated by a "simulator"), and implemented initially on a limited basis in ARTS III installations with little disruption; many improvements in this direction could fit well into the present ongoing ARTS III software updating and improvement program. Several promising software development programs which have been alluded to in the text are enumerated below:

1. Development of a Subroutine to Eliminate False Targets

As noted in Section III. B, it is relatively straightforward to determine by analysis of a limited quantity of extractor data the locations and orientations of reflecting objects causing false targets, and the relative severity of the problem caused by each. From this information, several techniques such as those described in Sections III. B. 8 and 9 for identifying and suppressing false targets become apparent. A program should be pursued to develop, in the appropriate machine language, algorithms to accomplish this objective. Several should be developed, assuming variously that RDAS data is/is not available, small/large numbers of reflectors are involved, small/large azimuths are subtended by each, and so forth. The parameters of each process (such as the number of scan correlations needed to verify that a target is false in the process described in Section III. C) should be optimized for a particular site, based on data gathered from that site; the process could then be run against other tapes from that site in order to gain an actual rather than simulated measure of the improvement. The particular solution best suited to each site could then be implemented and tested in real time at that site.

The results of a program of this sort would be significant; from the data observed here, the incidence of false targets at sites such as Andrews could be reduced by perhaps two orders of magnitude. Given the severity of the false target problem at present, this could be the deciding factor in whether or not such future programs as automatic conflict prediction and Intermittent Positive Control are successful. Another area in which a successful false target elimination program would have significant effects is that of weak target enhancement, since a major reason why weak targets are lost in today's ARTS III and other systems is that their runlenths do not achieve the declaration threshold, which is set high in order to discriminate against false targets. Elimination of false targets by other means would allow this threshold to be set quite low, with little likelihood of spurious detection.

2. Weak Target Enhancement

Examination of replies from aircraft that are apparently at low altitudes, such that they do not return sufficiently long reply sequences to be declared on every scan clearly reveals that much additional information on their position could be obtained by using to advantage replies which are obviously legitmate but are now discarded by the processor since they comprise a sequence which is too short. Very short reply sequences arise in ARTS III either from weak actual targets or false targets (Figure 28). Just as suspected false targets can be correlated with established tracks to determine their validity, so too could short runlength sequences be examined for correlation with existing tracks. Present-day ARTS and PCD target declaration mechanisms employ parameters established to maintain a low false alarm rate per scan; to be declared, each target must meet runlength and other criteria which were essentially established for detection of new targets; no advantage is taken of the fact that replies from a particular aircraft are anticipated in a certain region. The notion of feedback from the tracker is especially helpful here; the threshold necessary to declare a target could be adaptively adjusted to a lower value in those regions where targets are anticipated. Code could be used to advantage in this operation, to allow selective adjustment of parameters. A typical tracker-to-digitizer command might be: "if more than three replies with code 1241 or altitude 4.2 are noted within $\{\Delta R, \Delta\theta\}$, then declare that target." Additional flagging of target declarations to indicate the level of certainty (more levels of gradation than the current "strong/weak" indication) appears useful in this application.

Indeed, when one notes that the number of short (i.e., greater than two but less than the present declaration level) reply sequences is small compared to the total number of targets declared in the present system, it appears that perhaps feedback to the digitizer is comparable to an equally practical process wherein all targets regardless of the number of replies, are declared, and an additional "quality" parameter is associated with each. (The "quality" parameter might be simply the number of hits counted in the target.) The process of target declaration in the tracker feedback case would be replaced in this situation by a selective process of editing these reports at the tracker, (Figure 56) based on a combination of information involving the quality parameter and tracker-derived parameters. Whether one of these two concepts is preferred would be determined primarily by economic considerations imposed by such elements as the tracker-to-digitizer data link.

Since beamsplitting accuracy would likely degrade with smaller numbers of replies, it is reasonable to assume that azimuth data quality would be

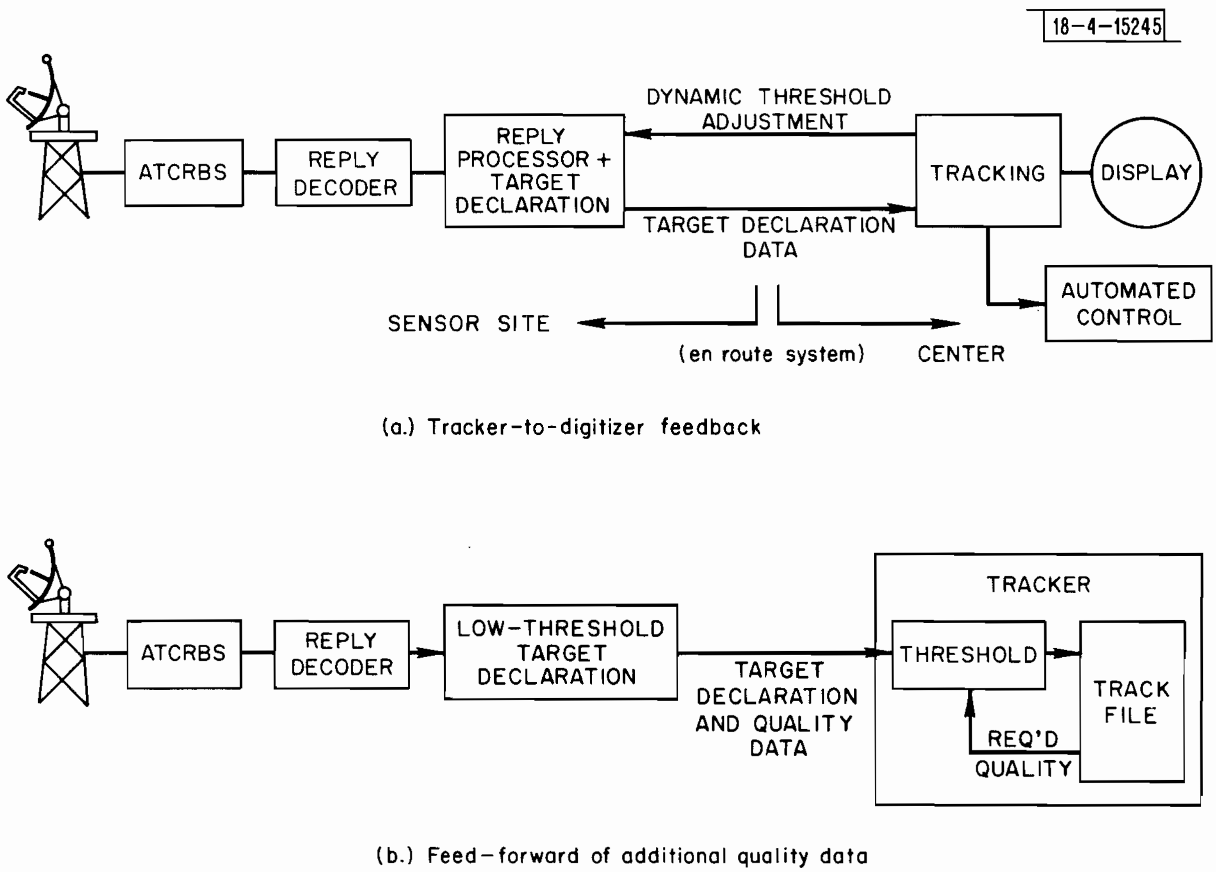


Fig. 56. Various Target Declaration/Tracking Relationships.

correlated fairly strongly with the "quality" parameter, and to properly account for this. Observation of weak targets in our data indicates that range data quality is high regardless of the number of hits. The tracker could use these relationships to advantage in the correlation process.

Once the "noise" in the present system caused by false targets has been culled out by new processes, there are many procedures such as these which would allow proper detection and tracking of targets through situations where they are temporarily lost in the present system. Given sufficient extractor-derived data, it appears relatively simple and straightforward to develop these new procedures and select the best for each site.

3. Reply Code Processing

Several shortcomings of ARTS III which become significant in areas of extremely high traffic density could be corrected by using to full advantage the information contained in the reply codes. These shortcomings comprise the major part of the synchronous garble and poor angular resolution problems discussed in Section III. Again, these could be largely corrected by simple and straightforward modifications to the software; this was not done in the original ARTS III software apparently because the problems were not considered to be of sufficient importance at the time the system was specified.

The application of a few basic principles of error-correction decoding, combined with the notions of tracker feedback discussed in the previous section could lead to improved performance in both areas; various levels of sophistication could be applied at various times and locations depending upon the severity of the problems observed.

In the angular resolution case, only relatively minor modifications would be needed to perform a running check of reply code, and note sudden changes in the code. If the code changed once, the point at which this occurred could be identified as the point when one reply sequence stopped and the other began; if two changes were made, a straightforward check on the middle sequence, described in greater detail below, could determine whether it was consistent with garbling of the two outer sequence codes (Figure 48). If this were found to be the case, the middle region could be identified as an overlap region, and beamsplitting done accordingly. If not, the three segments could be treated as separate target reports, and attempts made to correlate them with nearby tracks. Sequences observed near beamedges whose codes were subsets of the code scan in the remainder of the reply sequence could be tested to determine whether the code errors were a result of weak RF link performance, by attempting to correlate them with other nearby tracks. It was noted in our data that those targets whose codes were read in error at the beamedges were generally consistently misread from one scan to the next; that is, a particular pulse in the reply was consistently weaker than the rest. Information of this sort could conceivably be kept in the track file and used to advantage in testing whether a short reply sequence should be associated with an adjacent sequence or with another aircraft.

A procedure such as this would not perform perfectly in a situation such as the one noted in Section III. D, where one aircraft code was a subset of the other; in that case, the presence of a middle region where both aircraft are replying would not be noted, and azimuth determination would be erroneous. However, such a process would at least recognize the existence of two aircraft throughout the interaction, and tracking could continue with only slight error in azimuth.

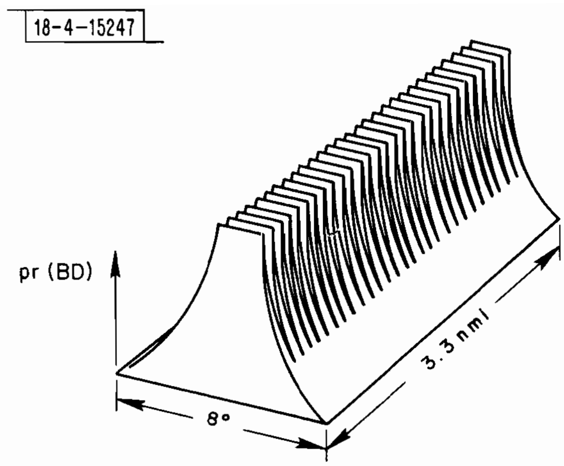
Use of monopulse-on-receive (to be discussed later) would greatly enhance processes such as these, since it would; 1) provide an additional piece of data with each reply (i.e., azimuth information) which could aid in the correlation process, and 2) positively identify a garbled reply under conditions of exact range alignment, where the present ARTS III DAS does not detect garbles.

Several techniques to correct the effects of synchronous garble, which vary in complexity and effectiveness could be developed and implemented gradually as needed. These range from addition of a simple degarbling subroutine operating on an entire reply code to a bit-by-bit garble-sensing procedure (perhaps involving monopulse) which would associate various confidence levels with individual reply code pulses, and use this to advantage in the process of associating replies and target declarations with tracks.

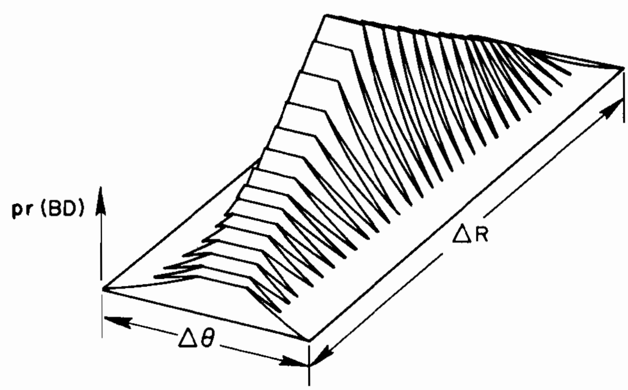
A simple degarbling subroutine might, whenever synchronous garbling is observed which results in code declarations with low validity, 1) determine which aircraft are most likely to be involved by examination of track file information, 2) tentatively assign the various codes to the various garbled reports in all possible combinations, 3) compute the resulting garbled replies in each case, from the knowledge of range difference available to the device, in a manner similar to that shown in Figure 44 and 46, and 4) compare these with the observed garbled reports and replies, to determine which assignment of beacon codes to observed garbled targets is most likely to be the correct one. A procedure such as this would successfully deal with all eight erroneous decodes observed in our data (Section III.C). Indeed, a simpler procedure, associating garbled target codes with tracks simply on the basis of whether the legitimate code is a subset of the observed one, would have also performed properly in seven of the eight cases.

A similar degarbling process might note from the observed range overlap which pulses of each reply are potentially corrupted (the overlapping ones) and which are definitely in the clear (the ones that are outside the garble region). Correlation of a few definitely uncorrupted reply pulses with the tracked codes could establish successfully on many occasions which reply sequence is associated with which aircraft. Use of a procedure of this sort would modify the relationship between the probability of success and garble call geometry (Figure 39) as shown in Figure 57.

A more sophisticated process could measure its confidence in each pulse of a garbled reply, either by monopulse techniques, by examination to determine if the pulse in question is corrupted by a known pulse in the garbling reply, or by sensing rapid changes in phase or amplitude. Again, since only a limited number of hypotheses are involved (i.e., H_1: Code A goes with aircraft a, Code B, with aircraft b; H_2: Code B goes with aircraft a, Code A goes with aircraft b), proper selection of the correct hypothesis can be accomplished a large percentage of the time based upon relatively little information of this sort; the fact that two pulses are present in one timeslot, that that timeslot corresponds to pulse i of reply sequence A, and that airplane a has pulse i set while airblane b does not are sufficient to correctly associate airplane a with reply sequence A. Processes of this sort, where presence (rather than absence) of pulses is used to associate a reply with an aircraft,



(a) Probabilistic model of garble cell.
(today's system)
(same as Fig 12(b))



(b) Modification to above model, obtained by using partially clear replies to advantage

Fig. 57. Improvement in Synchronous Garble Performance.

would perform successful association on almost all garbled individual sweeps observed to date.

As with the other recommended developments, a program should be commenced to develop software to correct decoding and poor resolution errors in sufficient time to allow implementation before these problems become severe. Since the mechanism is not site-dependent, it would appear that a single set of preferred programming approaches could be developed, for implementation in stages as the problem worsens at various sites. Once an approach has been developed, it could be tested against actual data if it involves only post-DABS processing; the more complex approaches would require development of prototype hardware before operational performance could be verified.

4. Azimuth Accuracy Improvements

Since an apparently significant portion of the azimuth error associated with low-flying aircraft appears to result from diffraction due to buildings, towers, etc., and since the effects of these are well-understood and easily measurable, a subroutine to provide azimuth correction at those few azimuths were the problem is noted could be developed and implemented, if deemed necessary. Data in this area is limited; more automated processing is necessary before the extent of such improvements can be determined. Similarly lacking is an understanding of which (if any) circumstances would clearly indicate a need for such improvements.

C. Hardware Changes

A few hardware modifications show sufficient promise relative to the expenses involved to be worthy of consideration at an early phase of the transition to the DABS system:

1. Removal of Defruiters

As Freedman noted, in many installations where fruit levels are low, removal of the defruiter from the ARTS III video input line would improve overall system performance. This concept should be tested and implemented in such locations. As fruit levels increase, the first performance degradation to be noted will likely be memory overloading, since every fruit reply would cause a new potential target file to be created. At present, in ARTS III the parameter MY3, the number of misses in a row prior to leading edge declaration which must be reached in order to drop a record as being due to fruit, is set at three or four at all ARTS III sites. Readjustment of this parameter to one or two would reduce the additional demands on the memory imposed by fruit replies, by clearing target files caused by fruit from the memory more rapidly. Unless proper steps were taken (such as correcting the source of single reply misses discussed in Section III.A), reduction of this parameter might counteract the improvements in azimuth accuracy gained by removing the defruiter in the first place. Detailed information pertinent to the considerations involved in removing the defruiter (and adjusting the ARTS III target declaration logic to compensate) has not been gathered at present, but could be obtained by appropriate analysis of ARTS III extractor tapes, containing both defruited and undefruited video.

2. Replacement of Storage-Tube Defruiters

It was noted (in Section III. E) that improper storage-tube defruiter performance was responsible for erroneous decoding more often than any other mechanism. If this performance degradation is considered sufficient to warrant correction, steps should be taken to accelerate the procurement of MX-8757 digital defruiters, which do not exhibit any of these adverse effects.

3. Antenna Modifications

Several significant improvements in ATCRBS performance above today's level could result from the successful development of a new I/R antenna system. Changes in the antenna would affect system performance in practically all the problem areas discussed in Section III.

Use of monopulse on the uplink would allow beamwidths to be artificially narrowed; this would result in fewer hits per scan if the interrogation rate were held constant, and would thus reduce the overall fruit level. Azimuth accuracy would be degraded, but since our measurements show that round reliabilities are quite high, the degradation might not be significant. Tradeoffs in this area become involved with antenna horizontal aperture and costs, and have not been examined in detail here.

Use of monopulse-on-receive results in far greater performance improvements, but adds significantly to the system cost and complexity, compared with uplink monopulse. Monopulse-on-receive would allow improvements in synchronous garble and poor angular resolution performance, when used in conjunction with the software discussed in section three of this chapter; it would allow improvements in azimuth estimation in those cases, where very few replies are received; it could improve performance in levels of high asynchronous fruit.

If receive monopulse is adopted, a tradeoff arises as to whether the defruiter is required; since a monopulse system could attach an azimuth "tag" to each target report, fruit replies could be identified by correlation with known target azimuths; those resulting from aircraft in the mainbeam could be measured, and used to advantage in the azimuth determination process. Elimination of the defruiter would thus greatly increase the flow of data into the processor; monopulse angle estimation would allow spurious data to be identified and edited out.

Since a receiver monopulse processor could erroneously process a sidelobe reply, and associate an improper aximuth with it, it appears that use of techniques akin to RSLS (receiver sidelobe suppression) should be used in conjunction with it; here, the technique would be used only to identify sidelobe replies; they would again be edited out after analog-to-digital conversion had been accomplished.

Although our data did not reveal any problems associated with vertical lobing, undoubtedly this phenomenon causes difficulty at some sites. Use of an antenna with sufficient vertical aperture to allow a vertical pattern with sharp cutoff at the horizon would reduce its effect.

It appears that an antenna employing monopulse-on-receive (and perhaps uplink monopulse and vertical directivity as well) could provide significant improvements to ATCRBS in the short term. Since such an antenna is anticipated for DABS, it appears appropriate to develop it as soon as possible for use with ATCRBS in the pre-DABS period. The study described in

Section V.A.6 should focus intially on the issue of vertical lobing at all FAA I/R installations for which DABS is contemplated; if the number at which severe vertical lobing is found is sufficiently high, the antenna development should include an increase in vertical aperture; if it is relatively low, a program to develop two separate antenna systems, one with vertical aperture and one without, might be pursued. Consideration should be given to use of a modified AT-7202 (the present FAA standard ATCRBS antenna) for applications where vertical aperture is not needed. The primary problem associated with this approach would appear to be development of an appropriate rotary joint.

4. Other Fixes

A continuing program to implement other hardware fixes such as those suggested in Section III.C for application to the peculiar false target problem at Boston should be given high priority in the overall program to improve ATCRBS. While sweeping changes to the entire system are in order, and can accomplish a great deal, still each site is different from all the others, has its own peculiarities, and must be dealt with on an individual basis. While continued "patching-up" of the system on a large scale is by no means sufficient to maintain the levels of performance that will be necessary in the future, neither are there any panaceas. A properly-weighted program of overall modifications and site-peculiar "fixes" appears indicated.

V. CONCLUSIONS

Over the past several years, much discussion and though have been addressed to the problems associated with the ATCRBS system. Since the system is so large, imprecisely defined, and fully involved in the day-to-day operation of the ATC system, it has not been possible to perform a large-scale comprehensive measurement program to determine what the most serious system shortcomings actually are. The radar beacon community has been forced to resort to far too much simulation based upon unverified assumptions; far too little actual empirical data derived from the operating system has been available. This situation is changing dramatically at the present time. With the advent of surveillance equipments which combine digital processing and radar technologies, it is now possible to derive much data from which actual performance can be determined from the operational system. In addition, this data will be invaluable in the "calibration" of the several simulations now in operation, which can then be used to address more precisely their proper task: prediction of system performance in the future at traffic levels greater than what can be observed today. This report has been a preliminary attempt to analyze and reduce such data based on manual examination of a relatively small quantity of ARTS III extractor-derived data. It strongly suggests that a more thorough and comprehensive examination of data, based upon the procedures established here, will provide a large increase in the extent of understanding of actual system performance within the community. Trends which have been suspected (and inferred from data available now) can be quantified precisely; an exact understanding of the weak and strong points of the system can be obtained.

It is clear from this preliminary analysis that certain evolutionary improvement steps are needed in the present system, and should commence immediately; development of a performance data base more comprehensive than the few minutes of ARTS III data from a handful of sites upon which this report is based can provide a far more quantitative basis for management decisions regarding the path that should be taken in the future to achieve the final solution to the problems of ATCRBS (DABS).

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(Note: References associated with Table 1 have been grouped together and placed next to Table 1 in the text.)

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