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Electronic Flight Rules: An Alternative Separation Assurance Concept

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16. Abstract

This report presents results of a study of alternative concepts for tactically separating aircraft in low altitude en route airspace. It describes a concept designated Electronic Flight Rules (EFR) which allows aircraft to fly under instrument meteorological conditions in a manner that retains most of the freedom and flexibility of VFR flight. Feasibility considerations, potential benefits, applicable technologies, and alternative system configurations are evaluated.

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ACRONYMS

AERA	Automated En Route Air Traffic Control
AGL	Above Ground Level
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance
ATARS	Automated Traffic Advisory and Resolution Service
ATC	Air Traffic Control
ATCRBS	ATC Radar Beacon System
BCAS	Beacon Collision Avoidance System
CAS	Collision Avoidance System
CONUS	Continental United States
CPA	Closest Point of Approach
DABS	Discrete Address Beacon System
EFR	Electronic Flight Rules
GPS	Global Positioning System
ICAS	Integrated Collision Avoidance System
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
TCA	Terminal Control Area
TMF	Transportable Measurements Facility
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

TERMINOLOGY

plane — This term is used to refer to the plane of maneuers, e.g., the horizontal plane (right/left) or the vertical plane/(up/down). It is never used to refer to an aircraft (airplane).

radar — This term may be applied to beacon transponder systems as well as primary radar systems.

EXECUTIVE SUMMARY

Introduction

This report examines alternative concepts for provision of tactical traffic separation services in low altitude en route airspace. In this context the term "tactical" implies that action is required only when aircraft come into conflict, and that otherwise aircraft are free to select flight paths without traffic control restraints. A further characteristic of the concepts considered is that they do not require time-critical decision making by a human controller on the ground. This implies that most decisions are made by pilots or by computer algorithms. Because of the dependence of this type of control system upon electronic data acquisition and electronic data processing, the mode of flight which results has been designated Electronic Flight Rules or EFR.

The potential benefits to be derived from an EFR system include the following:

The greatest growth in the demand for traffic separation services during instrument meteorological conditions (IMC) is expected to come from general aviation aircraft. Since EFR appears especially well suited for general aviation operations, EFR may absorb much of the expected growth in IFR system loading.

EFR is an automated system which may be much less expensive on a "per aircraft" basis than the current IFR system.

EFR may eliminate delays associated with waiting for IFR clearance.

By eliminating the need for filing an IFR flight plan, the workload of the Flight Service Station workforce may be decreased.

EFR may permit direct routing and optimum climb profiles with associated fuel savings.

EFR may enhance the safety of general aviation operations by allowing general aviation aircraft which do not fly IFR to select altitude and routes which avoid terrain and weather hazards.

An EFR system would have several characteristics which are quite distinct from those of the Automatic Traffic Advisory and Resolution Service (ATARS). ATARS is primarily a back-up to conventional IFR. It commands aircraft to maneuver by specifying only the direction of a climb or turn and uses a very short look-ahead time. It does not anticipate return to course after conflict resolution.

An EFR system would also differ in an important way from separation assurance techniques resulting from the Automated En Route Air Traffic Control Program (AERA). AERA is an automation of the IFR process and hence requires knowledge of aircraft intent.

Constraints

Two fundamental requirements were imposed in order for an EFR system to be considered feasible. The first is that the introduction of EFR flight should not prevent aircraft which so desire from being able to fly in instrument meterological conditions at a level of safety which is at least as high as that of IFR today. The second is that aircraft with no special EFR avionics should be allowed to continue normal IFR operations in the airspace in which EFR service is offered. These requirements reduced the number of concepts under consideration by excluding those EFR concepts which would require that special "EFR only" airspace be defined.

Conclusions

It was determined that in order to meet safety requirements as well as other control efficiency objectives, the EFR system must be capable of coordinating resolution actions between aircraft; autonomous resolution was insufficient to meet requirements.

The proper division of decision-making responsibility between pilot and computer logic was considered. In general, decision-making by computer logic is preferred in terms of reliability, pilot workload, avionics simplicity, and feasibility of meeting coordination/interface requirements. However, opportunities for information exchange between computer and pilot should be considered in any concept.

The number of alternative surveillance techniques for EFR is limited by the system feasibility requirements. In order to avoid the requirement for purchase of special EFR surveillance units, it is appropriate to first consider EFR surveillance based upon the standard ATC surveillance avionics (i.e., beacon transponders). Altitude reporting (Mode-C) capability would be a requirement for use of these systems for EFR. Among this class of surveillance techniques the most clearly feasible basis for the surveillance needed by EFR is the Discrete Address Beacon System (DABS). This system can also provide the communication capabilities which EFR requires. Based on current implementation plans the coverage of such a system would not extend to lower altitudes in mountainous western regions, but could provide good low altitude coverage in the eastern United States and Southern California.

Development of a ground-independent surveillance/communication technique would be required to extend EFR service into mountainous western regions and very low altitudes remote from ground radar sites. However, currently no set of techniques has been identified which appear capable of supporting such service at desired performance levels and cost.

Tactical control techniques for EFR appear suitable for traffic densities that occur in enroute airspace today. The density at which the rate of EFR interactions would become unacceptable would appear to be at least twice the density that has been observed in the busiest en route sectors at peak conditions. Even using 1990 traffic forecasts at peak conditions including all the traffic (which is predominantly VFR), critical densities only occur within 10 to 20 miles of a few busy traffic hubs. The exposure of itinerant aircraft to such densities will be so brief that no operational difficulties should result.

Computer algorithms used for EFR control should utilize a cost function structure and issue instructions in terms of specified headings and altitudes. Such a logic has been demonstrated for single pair encounters.

Areas for Further Investigation

This study has indicated that at least one avenue is open for the development of an EFR system which satisfies a set of basic feasibility requirements. Further discussion of the EFR concept within the aviation community is required to verify that this set of requirements or some modified set provides a sound basis for proceding with EFR concept development. For both currently indentified and future EFR configurations, further investigation of the actual level of benefits and the problems of interfacing with other elements of the National Airspace System should be pursued.

1.0 INTRODUCTION

Under the sponsorship of the Federal Aviation Administration, the M.I.T. Lincoln Laboratory has recently completed the first phase of a program entitled Alternative Separation Concepts. The objective of this program was to evaluate a range of tactical control concepts for accomplishing the task of separating air traffic in low altitude en route airspace. In this context the term tactical implies that the system controls aircraft flight paths only while the aircraft are in conflict. A further characteristic of the concepts considered is that they do not require labor-intensive decision making by a human controller on the ground. This implies that most decisions are made by pilots or by computer algorithms. Because of the dependence of this type of control system upon electronic data acquisition and electronic data processing, the mode of flight which results has been designated Electronic Flight Rules, or EFR. This work began with a broad look at the ways in which EFR flight could be accomplished. The work first focused upon the implications of generic classes of systems (e.g. centralized vs distributed) and identified the feasibility issues raised by the choice of the fundamental system structure. Because many critical system issues cannot be understood without considering specific design features, a more detailed look at design alternatives was sometimes required. An attempt was made to focus the detailed analysis upon concept alternatives which appeared most promising in terms of the fundamental system structure.

1.1 Background

Today's air traffic control (ATC) system offers two principal modes of flight: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). Under VFR, aircraft maintain separation from each other using the principle of "see-and-avoid" which is based upon visual detection and evaluation of conflicting traffic. VFR offers unparalleled flexibility and ease of operation to aircraft. But it is restricted to periods of adequate visibility (visual meteorlogical conditions or VMC) and suffers from limitations which make it unacceptable to certain classes of users.

The IFR system assigns the basic responsibility for separation to an ATC controller who utilizes radar and/or pilot position reports to effect separation regardless of weather. In order to properly perform this function, the IFR controller requires that aircraft obtain approved flight plans before each flight. Such flight plans must normally follow established airways for which surveillance, communication, and control sector coordination can be assured. Under normal conditions aircraft are required to comply with all controller instructions and to refrain from any course changes which are not approved by the controller.

As the traffic loading upon the IFR system increases, the delays, constraints, and per-aircraft control costs tend to increase also. One response to this situation is to attempt to increase IFR system productivity (primarily through investment in automation). But the rate at which productivity can be increased is limited both by the inherent nature of IFR control and by the time required to develop automation tools and integrate them into the existing system. In effect a race develops between productivity improvement and traffic growth. The total number of IFR en route operations is forecast (Ref. 1) to grow by a factor of 1.7 between now and 1989. Approximately half of this growth will be attributable to general aviation aircraft. In this context, an approach which complements that of productivity improvement is to define an alternative mode of flight into which some portion of this traffic growth can be diverted. EFR is such an alternative mode.

Because the EFR system avoids most of the human controller labor associated with the IFR system, it would be a less expensive mode of IMC flight. The cost of the controller team required for manual control of smaller aircraft is significant in comparison to their total operating cost. EFR could provide a means by which the portion of total ATC expenses allocated to such users could be decreased. Realization of such benefits is of course, contingent upon design of an EFR system which does not make IFR control more difficult.

Safety benefits may be derived by flying EFR in preference to VFR. The most direct safety benefit is increased confidence in separation from other traffic. Another benefit is that aircraft are able to fly at safer altitudes above terrain and weather. When operating VFR a pilot cannot enter airspace containing clouds or weather which reduces visibility below VFR minimums. Under an overcast layer he may be forced to proceed in poor visibility at low altitudes. EFR allows the pilot the freedom to select the safest altitude and route without the constraints of maintaining VMC (or obtaining an IFR clearance).

Finally, a portion of the delay and indirect routing which is encountered in IFR operations today is occasioned by communications delays and the need to limit workload for the human controller. Aircraft which fly VFR seldom encounter delays or constraints due to the presence of traffic, even though traffic densities generally are greater under VMC. An EFR mode of flight would attempt to restore to the pilot flying in IMC the same freedom and convenience he experiences when flying in VMC.

2.0 FEASIBILITY CONSIDERATIONS

The feasibility of any air traffic control technique is dependent upon a number of general considerations which are not entirely technical, but which involve questions of policy, law, regulation, and the expectations of the various elements of the aviation community. In this section some general characteristics are given which all EFR concepts should strive to meet in order to be implementable.

2.1 Preservation of IFR Safety

Both during the period of initial implementation and after complete implementation, it should be possible for aircraft which so desire to operate in IMC at a level of safety which is at least as safe as IFR today. This requirement is based upon precedents and policy statements which indicate that at least for passenger-carrying aircraft, neither pilots, passengers, owners, nor members of the U.S. Congress will accept a lower level of safety than currently exists. Over the past few decades there has been a trend toward expansion of positive control airspace (airspace in which only controlled aircraft are permitted) whenever safety problems have arisen in connection with mixed IFR/VFR operations. One reason for this trend is the perceived lower level of safety associated with visual flight rules. EFR systems should not exhibit a level of safety which would justify its widespread displacement by positive control (IFR-only) airspace. It should also be noted that as a practical matter stronger arguments must be presented for introduction of a new type of ATC service than for retention of traditional practices. In this regard it is not clear that an EFR system which offered only a VFR level of safety could win acceptance, even in airspace where mixed VFR/IFR operations are currently allowed. Furthermore, allowing lower performance separation assurance to be applied within IMC would result in a net decrease in IFR level of safety, even though the level of safety in any given encounter did not decrease below that of VFR.

2.2 Evolutionary Implementation

Aircraft without special EFR avionics*should be allowed to continue IMC operations in the airspace in which EFR service is offered. This requirement addresses the fact that some conceivable EFR systems are incompatible with

*An altitude-reporting ATC beacon transponder is not viewed as "special EFR avionics", and may, in some EFR configurations, be required for all IMC operations (both IFR and EFR).

conventionally-equipped IMC operations and would require that airspace be defined within which only EFR operations are allowed during IMC. There are several difficulties which arise when airspace must be segregated in this manner. One is that in the earlier stages of the introduction of EFR, the benefits derived from EFR equipage would be minimal while the penalties imposed upon conventionally-equipped aircraft could be substantial. A patchwork pattern of airspace assignment interferes with direct routing, complicates flight planning for both EFR and IFR aircraft, and creates opportunities for blunders in which EFR aircraft fly into a region in which conventional operations are taking place.

A corollary of this requirement is that the system should provide service benefits to EFR-equipped aircraft long before a large number of aircraft are participating. The history of the development of air traffic control indicates that new techniques are introduced and proven by those users who are most willing to try the new service and who can realize the greatest benefits from equipage. Thus a system "grows" in an environment in which only a fraction of users are participating. There should be incentives for the initial investment in EFR equipment or training*.

It should be noted however, that if EFR performance is proven over a period of years and if a substantial majority of aircraft operating in IMC are EFR-qualified or can readily qualify for service, then the designation of "EFR-only" airspace may be acceptable. But such designation should not be required in order to introduce EFR service.

*The New Engineering and Development Initiatives study (Ref. 2) stated the equivalent consideration in the following way: "ATC concepts which provide additional capabilities and benefits for additionally equipped aircraft, regardless of quantity, are preferred. Concepts which provide no additional capability until most aircraft are equipped should not be seriously pursued".

3.0 SEPARATION ASSURANCE SYSTEM ELEMENTS

In discussing alternative system architectures it is helpful to divide a separation assurance system into distinct elements and subsystems. Figure 3.1 does this by defining the following system elements:

Data Acquisition System. This system gathers data concerning the aircraft to be controlled and the circumstances of the conflict. That part of the system which determines aircraft positions and velocities is referred to as the surveillance system. In addition to surveillance data, there are other types of information (such as aircraft intent) which may be acquired through communications. A variety of electronic surveillance techniques have been demonstrated or proposed for air traffic control and collision avoidance applications. Although most of these techniques are attempting to measure the same variables, they differ widely in reliability, accuracy, avionics complexity, and region of usefulness. All of these factors must be weighed in evaluating applicability of techniques to EFR.

Data Base. The information upon which control decisions will be made is accumulated in one or more data bases.

Decision-maker. A decision-maker is an entity which examines a particular data base and determines a control action which will resolve a conflict. The EFR decision-maker may be either a human being (pilot) or a computer.

Communication Links. Communications links allow data to be transferred from one element to another. They also allow control actions to be transmitted from a decision-maker to an aircraft. In defining a communication link it is important to note which pieces of data are transferrable by the link.

Aircraft. These are the elements whose motion is to be controlled by executing control actions.

Note that the pilot may be considered to be associated with either the decision-maker or the aircraft depending upon whether or not the pilot determines the control instructions to be used in resolution.

The diagram of Fig. 3.1 is most appropriate when a single decision-maker makes control decisions for all aircraft in a conflict. Such a system is

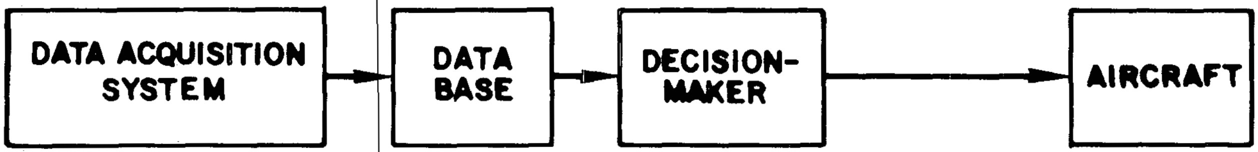

Fig. 3.1. Elements of a separation assurance system.

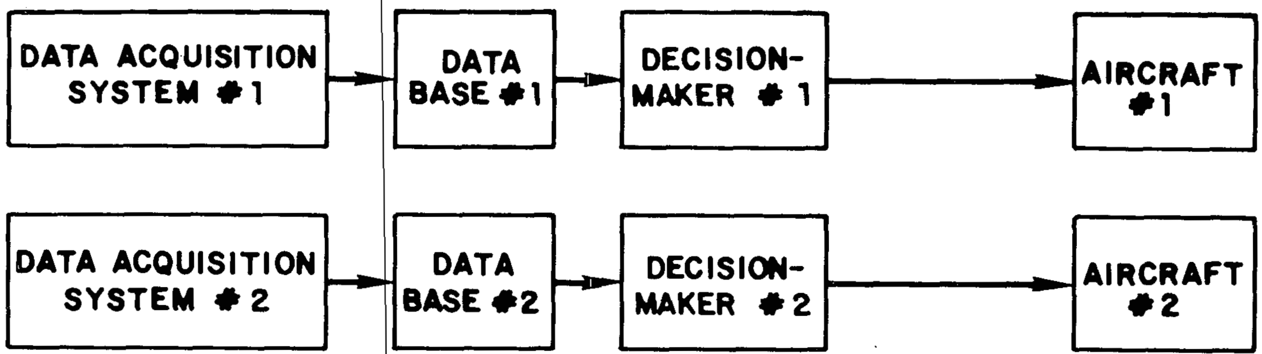

Fig. 3.2. Diagram of a distributed autonomous separation assurance system.

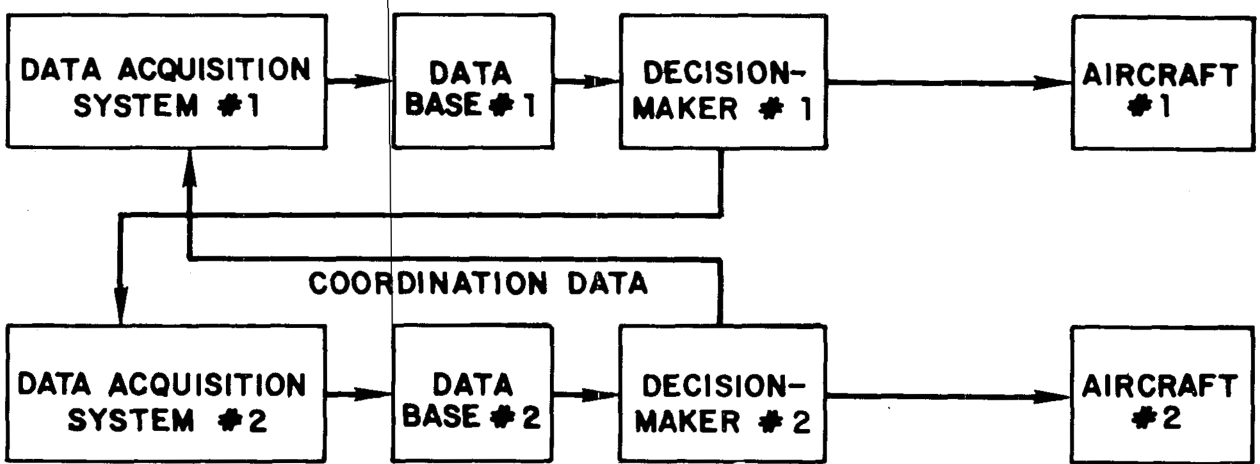

Fig. 3.3. Diagram of a distributed coordinated separation assurance system.

said to be centralized*. Another approach is a system in which decision-making responsibility is <u>distributed</u> between more than one decision-maker. For example, in Fig. 3.2 the basic system elements are duplicated in each aircraft and the control actions for each aircraft are determined independently. A system of this type is said to employ <u>autonomous</u> conflict resolution, i.e., resolution with no provision for coordination of decision-making between the aircraft involved. The alternative to autonomous resolution is <u>coordinated</u> resolution which can be accomplished even when more than one decision-maker is involved by providing a appropriate communication link between decision-makers (see Fig. 3.3).

*Note that this definition of the term "centralized" need not imply a ground-based decision-maker. For example, one aircraft in a conflict could be designated as the control authority for the duration of a conflict.

4.0 REQUIRED CONCEPT CHARACTERISTICS

This section discusses certain characteristics of the EFR conflict resolution process which affect the acceptability of the EFR system.

4.1 Coordinated Versus Autonomous Systems

A basic property of the conflict resolution process is the presence or absence of coordination. Because coordination of resolution actions may require special provisions for communication, an autonomous system seems at first glance to promise a simpler design than a system which provides coordination. But such a system may have difficultly in meeting EFR performance goals. Performance concerns exist in three areas: level of safety, control efficiency, and pilot workload. These issues are discussed in the following paragraphs.

a. Level of Safety. When resolution actions for each aircraft are selected independently they may be incompatible (e.g., both aircraft decide to climb). A capability must be provided for detection of incompatible maneuvers and alteration of previously selected actions. The ability of the system to iterate to a safe conclusion in such cases is hindered by tracking delays, accuracy limitations, and (if performed manually) the display limitations of electronic systems. This failure detection process should be contrasted to that of visual avoidance in which there is an almost instantaneous perception of the maneuver being executed by the threat since the attitude change of the threat can be observed. In electronic systems detection of maneuvers must normally be achieved by tracking a series of position observations and hence requires a finite observation period. If decisions are being based upon pilot interpretation of a traffic display, it will be difficult to discriminate between the relative acceleration induced by own aircraft and that induced by the threat.

Communications is essential to reliable coordination. Prespecified resolution coordination procedures based upon conflict geometry (such as the VFR rules of the road) possess regions in which the rules are ambiguous. It is also possible that differences in surveillance data available to aircraft or in pilot interpretation of data will lead to incompatible resolution decisions. Consider for example the simple rule: "the higher aircraft will climb, the lower aircraft will descend". This rule is ambiguous when aircraft are co-altitude. Furthermore, if one aircraft is passing through the altitude of the other, the maneuver direction to be utilized depends upon exactly when the rule is applied. Without communication, simultaneous application of the rule cannot be assured.

Experience with autonomous resolution in other applications has provided numerous examples of resolution failures related to the shortcomings cited above. Cases are on record in which visual separation failed because pilots disagreed upon appropriate actions and failed to recover (e.g., Carmel, New York, in which both aircraft climbed). Records of maritime accidents contain numerous incidents of so-called "radar-assisted collisions" in which ships collided despite attempts of both to respond to radar display information. The importance attached to coordination in the current IFR systems is evident in the care exercised to prevent "split control" in which conflicts arise between aircraft which are under the control of different controllers. It should also be noted that great effort has been expended in the design of collision avoidance systems to ensure that resolution is coordinated. While autonomous resolution may provide safety levels which are acceptable for some private aircraft, the mixing of such operations with normal IFR traffic is expected to be unacceptable. Hence, the non-exclusion principle could provide an obstacle to system implementation.

b. Control Efficiency. Separation requirements and resolution lead times must be greater for conflicts which are not coordinated. A separation buffer must be allowed in order to detect threat maneuvers which create hazards. Additional time is required in order to allow iteration to compatible resolution maneuvers when the initial choice of maneuvers is incompatible. Furthermore, in coordinated systems it is usually possible to resolve conflicts by altering the flight path of only one aircraft. In autonomous systems it is not possible to coordinate this type of resolution. Hence in many cases both aircraft will maneuver when only one maneuver was actually necessary.

Certain difficulties arise if aircraft elect to employ different resolution planes (e.g., if one aircraft decides to utilize horizontal separation while the other elects to utilize vertical separation). Normally an aircraft is free to maneuver in one plane if separation is guaranteed in the other. However, with autonomous resolution, maneuvers in the "free" plane may cancel the resolution attempt of the threat aircraft. Hence the freedom of aircraft to execute course changes necessary for navigation in one plane while resolving in the other may be curtailed. For instance, an aircraft would not be able to descend to avoid traffic while simultaneously turning to a new heading. Such a set of maneuvers could be incompatible with efforts of the traffic to descend in accordance with his flight plan while turning to maintain separation.

c. Induced Workload. Autonomous systems in which decision-making is performed manually (by pilots) require a high level of pilot vigilance. In some cases a pilot must understand how a conflict developed in order to make proper resolution decisions. Any aircraft in the vicinity which may maneuver in such a way as to precipitate an immediate conflict must be monitored. After a resolution action is chosen, careful monitoring is required to make sure that actions taken by the traffic are compatible. This is in contrast to coordinated systems in which, once the control actions of each aircraft are agreed upon, monitoring serves merely as an optional check upon the compliance of the traffic, and is not fundamentally necessary for resolution success.

Another workload-related issue has emerged from simulation experiments with cockpit display of traffic information in terminal area applications (Ref. 3, page 2-131) which indicate that "route lines" indicating the intended path of traffic, may be necessary to avoid undue pilot apprehension concerning surrounding aircraft. An autonomous system would have to function without such indications.

d. Conclusions

Coordination is required in IFR/EFR conflicts in order to achieve the required level of safety. Coordination is desirable in all conflicts in order to increase control efficiency, reduce pilot workload, and improve the level of safety.

4.2 Equipage Considerations

Some conceivable EFR surveillance techniques would require that special electronic equipment be carried on board aircraft in order to allow their detection. In this context "special equipment" does not include ATC radar beacon transponders with encoding altimeters since IMC operations without such equipment is almost certain to be extremely unusual by the time EFR could be implemented. Systems which require special equipage cannot be used as the basis of EFR unless airspace is defined within which normally-equipped IMC operations are prohibited. Hence, such systems violate the requirements for evolutionary implementation (Section 2.2). Such systems are also unable to provide EFR pilots with traffic advisories on unequipped VFR aircraft in the airspace, and likewise are unable to take the presence of unequipped VFR aircraft into account in the selection of conflict resolution options. Hence they may select resolution options which place EFR aircraft on collision courses with nearby VFR aircraft.

Thus it is concluded that an implementable EFR system can not require special equipment in order to allow collection of surveillance data. EFR surveillance may, however, be based upon ATC radar beacon transponder equipage.

4.3 Information Requirements

In today's air traffic control system a considerable amount of information is provided to the controller via the flight plan, radar surveillance, and radio contact with pilots. Some of this information is seldom used in the control process, yet is critical to safe control on occasion. A separation assurance system which is not aware of some of the limitations under which aircraft operate may issue conflict resolution instructions with which aircraft cannot comply. Conflict resolution based upon incomplete information may result in a hazard which is worse than the one the system was attempting to resolve. Examples of information which may be relevant to conflict resolution are given in Table 4.1.

Among the possible responses to a lack of information are the following:

- Adopt conservative standards and procedures which allow for uncertainity (for example, assume every aircraft is heavy and apply maximum wake vortex clearances).

- Avoid situations in which available information is inadequate (for example, offer service only at altitudes high enough that terrain is no factor).

- Accept a higher failure rate or less efficient performance.

4.3.1 Intent Information

a. Usefulness of Intent Information

One of the initial objectives of the Alternative Separation Concepts program was to investigate the value of various levels of intent information in tactical separation assurance. Intent information is information concerning what a pilot wishes to do or has been instructed to do in the future. Although a surveillance system can determine what an aircraft has been doing up to the current time, it provides no information about what control actions will be exerted in the future. Intent information may be useful in determining the degree of hazard which exists or in selecting the most efficient resolution option. The usefulness of intent information depends upon the type of information provided and the accuracy and reliability of that information.

It has been suggested that intent information could reduce the frequency of control actions in a tactical system. For purposes of discussion, consider a system which issues positive commands when some separation standard is violated, negative commands when separation standards can be maintained by preventing accelerations, and no commands when there is no imminent danger of violating separation standards even in the presence of accelerations. In the absence of intent information it is to be assumed that an unaccelerated projection of the current motion defines the most likely future trajectory of the aircraft.

TABLE 4.1

INFORMATION WHICH MAY BE USED IN CONFLICT RESOLUTION

Information	Application
Positions (relative)	Compute relative motion variables, velocities.
Positions (absolute)	Location with respect to terrain, airspace structure, or airfields.
Terrain, airspace boundaries, minimum descent altitudes	Use conflict resolution options which are consistent with flight path constraints.
Turn rate	Assists in flight path estimation and prediction.
Weight class of aircraft	Set wake turbulence avoidance parameters.
Performance limitations	Anticipate maneuver response (minimal climb response possible for aircraft near ceiling).
Flight mode (EFR, VFR, IFR)	Type of resolution coordination to be expected.
Existence of Visual acquisition	Allow pilot to transition to visual avoidance.
Declared in-flight emergencies	Burden of resolution should not fall upon aircraft with emergency. Coordination required with ground.
Formation flight, special operations	Can affect resolution ability.
Aircraft type	Assist visual acquisition. Wake turbulence awareness.
Severe weather or icing	Limitation in response. Preferred maneuver options to avoid weather hazards.
Destination	Aid in selecting control which minimizes delay in reaching destination. Coordinate with control authority at destination (flow control, ETS, NOTAMS).

(Continued)

TABLE 4.1 (Cont')

Information	Application
Waypoint to which proceeding	Select control which minimizes delay in reaching waypoint.
Equipment failures	Accommodate degraded mode of operation. Choose resolution options which aircraft can readily comply with.
Detection of own aircraft by other aircraft*	Check upon other aircraft's capability and whether other aircraft cooperating.
Relative position data gathered by other aircraft*	Redundant relative position data allows comparison, warning when discrepancy.
Other proximate aircraft detected by other aircraft*	Detect multiple aircraft situation which may effect other aircraft's ability to respond.
Resolution option which other aircraft is executing*	Coordination, monitoring.

*Information which may be relevant in distributed systems.

Several observations can now be made:

(1) The presence of intent information is unlikely to significantly reduce the rate of positive commands. In en route airspace aircraft turns are infrequent. If the projected paths of aircraft will lead to a violation of separation standards, then it is unlikely that intent would indicate otherwise.

(2) If acceleration could create a hazardous situation, it is inadvisable to refrain from issuing negative commands merely because intent information indicates that no acceleration is expected. If the intent information is correct, the negative command has no effect upon the aircraft flight path. If the intent information is incorrect, then the negative command prevents a hazardous situation from arising. Only if the intent information was absolutly reliable should negative commands be suppressed.

A special case which is worthy of further study concerns use of intent in the airspace over VOR stations. Airways generally go from one VOR to another. Aircraft following the airways often experience conflicts at VOR's. The traffic density around VOR's is also increased by aircraft engaged in IFR approaches or holding on the VOR. All of these aircraft can be expected to turn often over the VOR. Hence intent may be more useful in control here. It should be noted however that en route EFR aircraft need not fly airways over VOR stations. One of the advantages of EFR flight is that aircraft can obtain direct routing.

b. IFR Clearances

IFR flight clearances are one type of intent information which might be made available to an EFR system. In the current IFR system aircraft are cleared to navigate along airways which extend 4 miles on either side of a centerline. If a pilot perceives that he has drifted off the centerline, he may execute a course change to correct his position. In most cases the heading changes used will be modest, but apparently there is no requirement that it be so. Hence compliance with an ATC clearance or IFR flight path may not preclude course changes which can affect EFR resolution. Adherence to an assigned altitude is typically more precise and could be used in EFR resolution. The usefulness of all such information is limited by the accuracy with which it specifies the aircraft flight path. It is also limited by the fact that the ATC controller may change a clearance on short notice. Some type of coordination with the EFR decision-maker may be required if a clearance to an IFR aircraft is changed while the aircraft is in conflict with an EFR aircraft.

c. Conclusions

Since the assumption that aircraft intend to fly without significant acceleration for the next minute or two is usually valid in en route airspace, the use of intent information would seldom alter the efficiency of resolution. However, in certain cases this information would be useful in selecting acceptable resolution strategies. For example, when an aircraft is approaching a point at which a course change is required a resolution strategy which allowed the course change could be utilized.

In view of the limited benefits to be derived from intent information and the difficulties in making it accurate or reliable enough to be useful, it is concluded the EFR systems should be designed to function well without intent information. This does not preclude limited use of intent information of certain types. For instance, knowledge of destination may be occasionally helpful in selecting efficient resolution options. This information need be reported only once (perhaps before the flight begins). It would not impose any significant communication burden upon pilots and could be part of an "EFR flight plan" which the pilot filed at his discretion.

If a more highly automated IFR system, such as that being developed under the AERA program (Ref. 4), were implemented, then all IFR clearances might reside in computer memory and be available to the EFR system. Some degree of interaction would be required however to ensure that the clearance was not altered while the EFR system was relying upon it for separation.

4.4 Auxiliary Services

There are a number of services which the ATC system currently provides to IFR aircraft other than separation from other IFR traffic. Some of these services provide assistance in airborne emergencies unrelated to the separation function. Others are provided on a "workload permitting" basis to enhance flight safety. Duplication of all of these services in an EFR system may be unnecessary, too expensive, or technically impossible. Thus the value of each service and the ability of particular EFR configurations to provide those services should be considered in evaluating EFR alternatives. Particular auxiliary services are discussed below.

Traffic advisories. Most IFR flight takes place under VMC. In many cases VFR aircraft operate in the same airspace as the IFR aircraft. Traffic advisories supplement IFR instructions and assist the IFR pilot in maintaining safe separation from VFR traffic.

The ability of an EFR system to provide useful traffic advisories depends critically upon the capabilities of the EFR surveillance system. Typical considerations are whether or not the EFR surveillance system can measure threat bearing and whether or not it can detect non-EFR aircraft.

Emergency Navigation. If an IFR aircraft encounters a failure of navigation equipment (either avionics or ground navigational aids) the IFR system can utilize radar to provide the pilot with emergency navigation instructions. The IFR system also detects and warns pilots when navigational errors cause a pilot to deviate from the intended route.

Severe Weather Avoidance. The IFR system has access to pilot reports and, in some cases, weather radar information. The system is thus able to assist aircraft in avoiding hazardous weather.

5.0 CONFLICT RESOLUTION

5.1 Decision-making Alternatives

In Section 4.1 it was determined that EFR systems should provide coordination of conflict resolution actions. This section considers a further basic characteristic of the resolution decision-making process: the extent to which it should be automated. In the EFR context, manual decision-making implies decision-making by pilots (since EFR does not delegate time-critical resolution decisions to any ground-based human controller). Three types of system concepts will now be discussed. They involve systems in which 1) decision-making is done entirely manually, 2) decision-making is done manually within computer-generated constraints, and 3) decision-making is done by computer. Resolution which involves pilot decision-making without the presence of any supervising authority will be termed Unsupervised Pilot Resolution.

a. Unsupervised Pilot Resolution

Under unsupervised pilot resolution, the resolution strategy to be employed is arrived at solely by communication between the pilots involved in the conflict. Because manual decision-making is utilized, this configuration is highly flexible. Furthermore, communication with a third-party supervisor is not required. However, there are many design and performance questions which must be considered:

1. How is the pilot-to-pilot contact affected? Digital communication may prove inadequate since data entry is slow, limited in format, and prone to error during periods of stress. In an experiment with avoidance maneuver coordination for maritime traffic (Ref. 5) a satisfactory definition of maneuver intention codes for digital entry could not be found:

   > "Some felt that there were not enough codes; others felt that the list must be short enough to commit to memory. All the masters said that ships must ultimately go to voice communications in difficult encounters and, therefore, the intermediate step of using a code may not work".

   Voice contact appears more suitable for the type of negotiations required in EFR. But the ability to guarantee a clear voice channel instantanteously for a number of conflicting pairs may require more sophisticated communications equipment than is currently available for civil aviation.

2. Is the available workload increment adequate for the pilot to analyze the conflict situation, and communicate with the threat? Recall that conflict resolution is a time-critical non-deferable task and may come at a time of already high cockpit workload.

3. How extensive must pilot training and proficiency requirements be in order for pilots to exercise effective control? Air traffic controllers require extensive training in order to efficiently handle the wide variety of situations which can arise in ATC operations. It would seem infeasible to impose extensive new training and proficiency requirements upon pilots. Yet without such training pilots may fail to understand the limitations of other aircraft or the nature of particular conflict situations.

4. To what extent can priorities, standards, and procedures be standardized and enforced? A tendency toward differing resolution styles may be unavoidable due to differences in traffic environments, pilot backgrounds, or pilot personalities. This creates opportunities for misunderstanding or differences of opinion when styles clash. Pilots may attempt actions which are personally beneficial but which impose penalties upon their traffic.

5. How is coordination with ground ATC achieved when ground-controlled (IFR) aircraft are in the airspace? Can a resolution strategy worked out between pilots be transmitted to ATC without undue communications workload increase for the controller? What communication channel can be used for such coordination?

6. How are multiple aircraft encounters resolved? Coordination becomes much more difficult when three or more aircraft are involved. What if the pilots do not agree as to which aircraft are involved in the encounter? Can all involved aircraft communicate on the same frequency? What if two pairs coordinating on different frequencies begin to interact?

7. What is the cost of the least expensive equipage option? In all likelihood a high capacity graphics display will be required to allow pilots to successfully resolve conflicts. This equipment, together with more sophisticated communications equipment required for air-air communications, could make EFR equipage prohibitively expensive for most general aviation aircraft.

It appears that several serious feasibility questions can be raised with regard to unsupervised pilot resolution. Those questions which concern workload and pilot performance in resolution would require further experimentation with human subjects to fully resolve. But the number of issues and their seriousness substantially diminish the promise of this control mode for EFR applications.

b. Supervised Pilot Resolution

Some of the difficulties of unsupervised pilot resolution can be alleviated by the intervention of a supervisory authority which establishes guidelines under which a particular conflict is to be resolved. Proposals for such operations within the IFR system have been described in the Boeing CDTI Study report (Ref. 6) and in the deliberations of the FAA New Engineering and Development Initiatives Study (Ref. 2). In a typical scenario the air traffic controller first checks to make sure that only two aircraft are in conflict. He then negotiates an agreement which assigns one aircraft responsibility for maintaining separation from the other. The "passive" aircraft is required to fly without maneuvering for the duration of the encounter. The pilot has the option of refusing responsibility for resolution if he is too busy or otherwise unable to carry out the assignment. Resolution is monitored by either the controller or an automated CAS which intervenes if the pilot fails to resolve the conflict . In order to apply this concept to EFR, it is necessary to envision computer logic taking the place of the human controller. Note that this EFR mode would possess several safeguards which unsupervised pilot resolution lacked. Several comments are in order concerning this resolution mode:

1. If one accepts the fact that conflicts will arise which pilots cannot or do not wish to resolve themselves, then the supervising logic must be capable of assuming complete responsibility for resolution. Thus an algorithmic resolution mode must be designed and integrated into the operation of the system.

2. The specification of an active aircraft and a passive aircraft is necessary to avoid incompatible resolution maneuvers or negotiations of right-of-way. In a manual IFR mode the assignment would be accomplished by partially releasing one aircraft from ATC clearance constraints while the other complied with an assigned heading and altitude. In the EFR mode neither aircraft is initially constrained and flight plans are unavailable. Hence in order to create a passive aircraft, the EFR decision-maker must issue "don't maneuver" commands to one aircraft. These constraints must be applied in both the horizontal and vertical maneuver planes unless the supervisor specifies the dimensions to be used to resolve the conflict. If the active aircraft does not choose a resolution option which speedily resolves the conflict (e.g., if he decides to fly an offset parallel course while slowly overtaking), the passive aircraft may be constrained for an excessive amount of time.

3. It is difficult without knowledge of intent to anticipate whether or not multiple aircraft will be involved in the conflict. Unconstrained traffic in the vicinity may make course changes which lead to a conflict. Or the "active" aircraft in the resolving pair may choose a resolution option which brings it closer to a third aircraft. At this point a rather difficult transition may be required as the supervisory logic attempts to redefine the resolution ground rules or to impose logic-computed multi-aircraft resolution.

4. As in any system requiring pilot decisions based upon traffic displays, the requirements for pilot training and more sophisticated display capabilities may impose burdens upon some potential users.

c. Computer Resolution

A system which uses computer logic to generate resolution instructions for aircraft has the advantage that compatible resolution options are guaranteed. No pilot involvement (communication or study of information) is required prior to initiation of resolution. Multiple encounters can be readily handled. Requirements for information display are minimal. The logic can seek a resolution option which will take costs to both aircraft into account. The disadvantage of this alternative is that computer logic may ignore some objective or information which is important to the pilot. The more capable the logic and the more complete its data base, the less likely it is to select unacceptable instructions, but the potential is always present. If the aircraft is operating under a number of constraints which the logic cannot take into account, then tactical computer resolution may be infeasible. Such constraints are more likely to arise in the terminal area than in en-route airspace.

A tactical computer-based logic generally has no knowledge of intent. Hence it has little choice but to assume that in the near future the aircraft wish to continue to fly upon the same flight paths they are currently on. This assumption is usually valid in en route airspace. But when it is not true, the instructions may force the aircraft to deviate significantly from their desired course. The efficiency of tactical control depends upon the fact that aircraft will be controlled only a small fraction of the time and that most encounters can be resolved by imposing a one-sided constraint in one plane only. This last point refers to the fact than an instruction such as "remain above 6500 feet" allows an aircraft to climb, turn left, or turn right. Hence, even when such an instruction is present, the pilot can alter his flight path in three directions in order to accomplish flight objectives. If this minimally constraining instruction prevents him from flying the desired flight path, the pilot may elect to maneuver away from the threat in the alternate plane in order to force the instruction to be deleted.

The use of computer algorithms need not imply that pilots have no control over resolution instructions. Opportunities exist for allowing pilots to "direct" the logic in finding the resolution option which is most acceptable. Requests input by the pilot can be factored into the computer decision-making process and allowed to replace any prior assumptions concerning what would be most acceptable to the aircraft. In most cases pilot requests could be granted so long as the logic could ascertain that safety would not be compromised as a result. If the logic could not find an option which both granted the pilot request and maintained safety, the granting of the request would be deferred. One form of automation request which is conceivable is a read-out of the navigational waypoint to which the aircraft is proceeding. This would be interpreted as a standing request that resolution instructions be chosen which minimally delayed reaching the specified waypoint. It must be emphasized that such system refinements should not be required in order to provide basic EFR service. However, those aircraft which are so equipped would be rewarded with control of a higher quality than would otherwise be possible.

5.2 Interaction with VFR Aircraft

Much EFR flight may take place under VMC when VFR aircraft are present in the airspace. Under such conditions, VFR aircraft will tend to outnumber EFR aircraft and aircraft traffic densities will usually be greater than those encountered in IMC. Hence, interactions between VFR and EFR aircraft can affect the acceptability of the EFR system.

The most fundamental question to be answered is the extent to which the EFR system assists in the separation of EFR and VFR traffic. It does not appear reasonable to require the EFR aircraft to undertake unilateral actions to provide normal EFR separtion from VFR aircraft. One reason for this is that VFR aircraft may operate in traffic densities which make normal EFR separation procedures infeasible. Furthermore, since the lead time required for EFR-type resolution is greater than that required for VFR-type resolution, unilateral resolution is equivalent to giving right-of-way to all VFR aircraft. Finally, reliable separation is difficult to achieve without coordination.

In view of these considerations it appears that EFR system responsibility for EFR/VFR separation should be strictly limited. The following baseline proposal is advanced for the specification of VFR/EFR interaction:

1. The EFR system will not guarantee any standard separation between EFR and VFR aircraft - the ultimate responsibility for separation rests with the pilots involved.

2. The EFR system will provide traffic advisories on VFR traffic if surveillance data on VFR traffic is readily obtainable during the course of EFR operations.

3. In selecting resolution options for separating EFR aircraft from other EFR or IFR aircraft, the system will consider the known locations of VFR traffic and will favor options which achieve EFR/EFR and EFR/IFR separation objectives while avoiding VFR traffic.

4. Collision avoidance instructions will be allowed if the measured separation between EFR and VFR aircraft deteriorates sufficiently to violate CAS criteria.

5.3 EFR Interface With Air Traffic Control

In Section 2.2 it was suggested that a conventionally-equipped IFR aircraft should not be excluded from airspace in which EFR aircraft are operating. It was also determined (Section 4.1) that coordination of resolution actions was necessary in EFR/IFR conflicts. In conceptual terms it is convenient to think of the coordination as taking place between two decision-makers: the EFR decision-maker and the IFR decision-maker. Initially, the IFR decision maker is likely to be the human controller. Looking futher into the future, it is possible that the IFR decision maker will be a computer, in which case the EFR/ATC interaction may involve an EFR software module interfacing with an IFR software module. In any event, some issues arise which, even at the conceptual level, are not easy to resolve. Because they involve questions of human performance, actual experience with a given technique is necessary in order to verify its acceptability. This section discusses problems and potential solutions for the EFR/ATC interface.

5.3.1 Interface With ATC Controller

The following discussion focuses upon a system in which a human air traffic controller is involved in the control of IFR aircraft. This is probably the environment in which EFR would first be implemented and it is an environment which may persist for some time. One of the objectives of EFR is to reduce controller workload by reducing traffic loading upon the IFR system. Yet any responsibilities which are assigned to the controller relative to EFR traffic entail some workload increment. The extent of the workload savings depends upon differences between the workload induced by EFR aircraft and IFR aircraft. If the responsibilities of the controller require him to make decisions based upon the positions, velocities, or characteristics of the EFR aircraft, then he must either be constantly aware of the relevant characteristics of EFR traffic or must be capable of acquiring the needed information when required. The following considerations affect the viability of this interface:

If the controller attempts to constantly monitor the EFR aircraft in his sector, the workload involved may be great. Monitoring the flight of an EFR aircraft requires greater vigilance than monitoring the flight of an IFR aircraft since EFR aircraft may make unanticipated course changes at any time. The controller must therefore anticipate a greater number of contingencies with EFR aircraft.

With IFR traffic, a controller normally acts early to avoid the need for time critical resolution. This allows him to distribute his workload more evenly over the time available and reduces the likelihood of problems if his attention is momentarily diverted. EFR conflicts may require operation in a time critical mode which places severe demands upon controllers.

EFR traffic in adjacent sectors may suddenly enter the controller's sector. Hence he may be required to monitor EFR aircraft in adjacent sectors as well as those in his own.

Certain information which a controller normally utilizes in control may be unavailable for EFR aircraft. For instance, aircraft type, weight class, destination, and short-term intent may be unavailable.

If a controller ignores the presence of an EFR aircraft until a conflict arises, he may have difficulty absorbing required information in time to make an appropriate decision.

The assignment of ATC control authority is determined by dividing the airspace into control sectors. Special procedures are utilized to coordinate separation between IFR aircraft which cross or fly near sector boundaries. But EFR aircraft are assumed to fly without regard to such boundaries. Hence, an EFR aircraft may encounter an IFR aircraft at a location at which control actions affect two or three different control sectors. The complexity of the coordination process is then greatly increased.

a. Interface Concept Involving IFR Priority

It is obvious from the above discussion that the nature of the EFR/IFR interface requires careful definition if it is to function acceptably. Two possible concepts for the definition of this interface will now be discussed. The first is based upon a "right of way" designation. In this concept, the IFR controller informs the EFR decision-maker of the flight path which the IFR aircraft will follow. The EFR decision-maker must then accept this path as a "given" condition in the EFR decision-making process. In this way each decision maker issues instructions only to those aircraft under his direct control. The IFR controller can thus almost ignore the presence of EFR aircraft since all IFR aircraft have "right-of-way". Some consequences of this approach are as follows:

1. The IFR controller must formulate his instructions in a manner which can be transmitted to the EFR decision-maker. This may imply digital entry of instructions and use of a limited repertoire of instructions.

2. Such instructions must be formulated and executed in a way which allows future flight paths of IFR aircraft to be predicted with sufficient accuracy for making EFR decisions. Instructions which allow wide latitude in exactly how they are to be executed may be unacceptable.

3. Changes to the IFR instructions which are made during EFR/IFR conflict resolution must be consistent with the EFR resolution option. This may require that IFR instructions be frozen for the duration of conflict, or that the IFR controller negotiate any changes with the EFR decision-maker.

4. The conditions imposed by the IFR instructions may make it impossible for the EFR logic to find an acceptable set of resolution instructions for the EFR aircraft. This should not occur unless special constraints in addition to the initial threat traffic are present, e.g., other traffic, service boundaries, terrain, etc.

5. Because the EFR aircraft must accept the entire burden of workload and delay incurred in the resolution, the maximum traffic density at which EFR can function is reduced.

b. Interface Concept Involving Unified Responsibility for Separation

This concept can be considered when EFR decision-making is performed by a highly capable computer logic with access to the ATC data base. Primary responsibility for separation for all aircraft in the sector rests with the EFR system. This eliminates the possibility of uncoordinated resolution actions. For conventionally-equipped IFR aircraft the controller relays EFR-generated instructions to conflicting IFR aircraft using a voice channel. In some cases the instructions may be transmitted directly through digital data link. If under voice control, a special subset of EFR instructions are employed which are consistent with standard IFR terminology. Such instructions contain implied negative commands. On their own initiative controllers may routinely amend clearances to IFR aircraft providing such amendments do not contradict active EFR instructions. Under this provision controllers can issue instructions to IFR aircraft which avert IFR/IFR conflicts or at least establish a set of resolution conditions before EFR conflict criteria are violated. Controllers may also input requests to the EFR system to influence the manner in which it controls IFR aircraft. Suitably equipped EFR pilots may also input requests. The controller may serve as a link between pilots and the system - especially if he has a larger repertoire of instructions or a greater facility with the system. If an emergency so requires, the controller may override EFR instructions by direct use of voice link. For this reason, aircraft operating in data link mode are still required to monitor the sector frequency. If desired, the EFR logic can be biased to favor right-of-way for IFR aircraft.

From the viewpoint of the IFR pilot, the control process in an EFR sector will appear almost identical to that in a non-EFR sector. The fundamental difference with this concept is that the ultimate responsibility for separation assurance rests with the computer logic. The controller interacts with the system in order to enhance control efficiency and to provide services other than separation to IFR aircraft. The controller is not expected to approve all EFR instructions in advance.

6.0 SURVEILLANCE TECHNIQUES

In tactical control systems, separation assurance is dependent upon the determination of the relative positions of aircraft. That portion of the data acquisition system concerned with this function is called the surveillance system. A wide variety of electronic surveillance techniques have been applied or proposed for use in air traffic control and collision avoidance. The list includes ATCRBS, DABS, Active BCAS, Passive BCAS, ICAS and GPS-based systems. In some cases the choice of surveillance technique determines fundamental properties of the system design and establishes definite limitations on performance. Anyone familiar with the dialogue surrounding ATC-related research and development over the past decade probably realizes that often a system is advocated on the basis of its excellent rating with respect to one performance criterion without due consideration of its possible weakness with respect to other equally critical criteria. Most conceivable techniques have certain commendable features, but it may well be that few are free of "fatal flaws". In order to be seriously considered for EFR application, a surveillance technique should be able to meet all critical concerns. The following section discusses the range of considerations which must apply in evaluating EFR surveillance system characteristics. Section 6.2 then discusses the promise of some particular approaches to surveillance.

6.1 Surveillance Evaluation Criteria

6.1.1 Completeness of Data

A number of independent relative motion variables must be measured to completely determine the three-dimensional relative positions and velocities of a pair of aircraft. Some types of surveillance techniques do not determine a complete set of horizontal plane variables - they are capable of measuring the range to traffic, but not its bearing. Such incompleteness will obviously lower the achievable level of performance of the EFR system. The following effects may be observed:

- Altitude separation must be used in order to resolve conflicts since horizontal resolution without bearing information is inefficient or unreliable.

- The inability to completely determine horizontal position can lead to vertical resolution maneuvers when, in reality, the existing horizontal miss distance is adequate. This results in an overall increase in the system alarm rate (see Appendix A).

- Traffic advisories which assist visual acquisition of traffic by telling the pilot where to look cannot be provided. Such advisories are useful since EFR may be used frequently in VMC when VFR traffic is present.

- The unavailability of horizontal resolution can reduce the efficiency with which aircraft conflicts are resolved (e.g., an aircraft may climb a significant amount to resolve a conflict when a very slight heading change would have been sufficient).

- The system cannot deal with situations in which vertical resolution is inappropriate (e.g., aircraft operating near performance limits or near service boundaries).

Many of these performance limitations may be acceptable if the EFR system operates only where traffic densities are low and where inefficiencies are tolerable. Multiple aircraft encounters can be handled with vertical-only resolution if aircraft resolve by flying to specific altitudes (rather than simply climbing or descending as in collision avoidance). The availability of bearing data is a desirable property of EFR surveillance, but lack of bearing data does not automatically preclude system acceptability.

6.1.2 Absolute and Relative Position Determination

Another aspect of data content involves the determination of absolute position (e.g., latitude and longitude) as opposed to the mere determination of relative position. Knowledge of absolute position is required if the EFR system wishes to take into account such considerations as terrain clearance, service or control boundaries, intended course, etc. Such information can be provided by the surveillance system directly or obtained by an independent navigation system to which the EFR decision-maker has access.

6.1.3 Surveillance Accuracy

Every surveillance system exhibits some degree of error in the determination of aircraft positions. Small errors can often be ignored. But as errors grow they can lead to ineffective resolution or result in the presentation of misleading information to decision-makers. Larger errors can often be accommodated by increasing separation standards or increasing resolution lead times. however, such adjustments will decrease control efficiency by producing a greater alarm rate or greater deviations from course during resolution. If it is impossible or infeasible to adjust the system to tolerate maximum error, then the errors may limit system reliability or the area of service availability.

6.1.4 Equipment Failure

In any system events will occur which result in surveillance data being suddenly unavailable or being so inaccurate as to be unusable. The prediction of the frequency at which various failure modes will occur for future electronic systems is subject to great uncertainity, especially if the failure rates are dependent upon detailed design features. However, two aspects of equipment failure should be discussed in terms of basic system architecture. They are failure detection and back-up capability.

In some cases failure can occur without the knowledge of decision-makers. This can result in reliance upon a data base which fails to reflect the true conflict situation. This type of problem is of greatest concern in air-derived systems in which automatic self-testing features are more difficult to incorporate and in which complete system checkout may occur only at periodic maintenance intervals.

Back-up capability refers to the capability of a system during periods of equipment failure to continue to provide for the safe movement of aircraft by alternate means. These alternate means need not be as efficient as the normal means, but they should assure separation with high confidence. In order to provide back-up services it may be necessary for the EFR system to maintain critical data bases in duplicate or to incorporate independent back-up components in the system design.

6.1.5 Equipage Requirements

It appears inevitable that aircraft must carry some type of electronic equipment in order for EFR surveillance to be carried out. Conventional equipment, such as beacon transponders with altitude reporting capability, will be carried on most IMC flights before EFR is implemented. If EFR surveillance can be carried out using this equipment, then EFR services would be readily available to most potential users without requiring purchase of a second surveillance unit.

Some air-derived surveillance schemes would require aircraft to carry special EFR avionics in order to be detected. Unless assisted by ground-based radars, an EFR aircraft using such a system would be unable to detect the presence of a normally-equipped IFR aircraft. Coordinated resolution yielding the required level of safety would then be impossible. Hence EFR resolution based upon such surveillance schemes could be used only in regions in which normally-equipped IFR flight were prohibited. Because this would violate the non-exclusion principal (Section 2.2) this is not considered feasible as the principal mode of EFR operation. It might be a feasible mode for limited regions of airspace, especially if EFR equipage became widespread or if equipage with the required equipment became standard for other ATC purposes.

6.1.6 Coverage

Continuous surveillance coverage is highly desirable for the utility of an EFR system. It allows completion of the en route portion of the flight without the need for transitioning to any other separation mode. It also decreases the potential for blundering into regions where service cannot be provided. When surveillance is dependent upon ground-based sensors, there are coverage limitations due to terrain obstruction and range from the sensor. In order to achieve essentially continuous coverage with radar-based surveillance, a minimum service altitude must be defined. Further discussion of this point is contained in Section 6.2.2 and Appendix B.

Some type of air-derived surveillance systems are independent of ground stations and hence can function in all airspace. However, most of these systems fail to meet requirements for mixing with conventionally-equipped aircraft when they are outside ATC radar coverage. That is, if they encounter a conventionally-equipped aircraft they are unable to interface with the ATC controller who is issuing instructions to that aircraft. Direct interaction with the IFR aircraft itself may be possible via an air-to-air link. But this creates the potential for incompatible decisions which may be difficult to resolve with three parties involved (two pilots and the ATC controller).

6.1.7 Avionics Expense

The expense of avionics required for EFR services must be borne by aircraft owners and operators. If such equipment is expensive, then only small numbers of aircraft may choose to equip, and EFR benefits to the ATC system as a whole may be greatly reduced. It may be assumed that in the future all IFR operations will require at least the equipment required today with the addition of an ATC data link (DABS) and possibly a display unit. The expense of EFR should be considered in terms of what must be added to this base in order to receive EFR service. Although no precise statements can be made concerning acceptable cost, some feel for the problem can be obtained from the following discussion:

The major immediate benefit of EFR to the user is the elimination of delay associated with filing an IFR flight plan, waiting for clearance, holding en route, and indirect routing. The fraction of the operation time attributed to such delays represents a non-essential expense which must be borne by the owner or operator. Consequently, one can speak in terms of the fraction of the operating cost which an operator should be willing to invest for EFR service. This percentage should be proportional to the fractional delay. Three to five percent is a reasonable estimate of this number. It will vary depending upon how often the operator flys under IFR. Consider the following hypothetical example: an aircraft operator flys a light twin 500 hours annually. Forty percent of the time (200 hours per year) the aircraft is flown IFR. The operator estimates that 20 hours per year in delays could be avoided if he were to operate EFR as opposed to IFR. His actual annual costs are broken down into fixed costs (interest, depreciation, insurance, hanger, etc.) which are independent of the hours flown and variable costs (fuel, maintenance, overhaul, etc.) which are proportional to the hours flown. The cost of the EFR equipment is to be paid back by eliminating the flight hours attributable to IFR delays. Suppose the variable costs amount to $50.00 per hour. The elimination of 20 hours delay saves $1000 per year. The aircraft operator can afford to add $1000 per year to his fixed and variable costs in support of EFR avionics. If the list cost of the EFR avionics is $3000 then the payback time will be three years. In addition to the cost saving due to delay there are additional side benefits. The cost of traveler's time lost to delay is also important to the operator. Typically air travel is selected over surface travel primarily to save time. Some studies have assumed that the cost of traveler's time lost to a given delay is equal to the operating cost lost to that delay.

It is quite possible that an EFR information display could utilize a device selected for general data link readout. Hence the users decision to purchase the device will be influenced by all the varied benefits associated with the data link, as well as its EFR application. Other multiple-use displays may be present. Digital weather radars are now readily available on the market. For many the $5000-$20,000 price is justified by the added safety. Most of these weather radar displays could be made to serve other functions (data link or EFR). Thus the incremental cost of adding the capability for EFR information display to an aircraft can be quite low as long as EFR requires no special display capabilities which make it impossible to utilize multi-function devices.

In summary, the incremental cost of EFR avionics must be kept low to attract EFR users in numbers which will guarantee benefits to the total system. Readout devices with multiple uses show promise for providing maximum benefits for minimum cost.

6.2 Surveillance Techniques - Preliminary Evaluation

The principal surveillance techniques which might serve as an initial basis for EFR surveillance have been subjected to a preliminary evaluation in order to identify relative strengths and weaknesses and to define critical feasibility issues for more detailed study. Due to the equipage considerations expressed in Section 4.2, the most promising class of surveillance techniques for the near term are those which utilize components (sensors or transponders) of the ATC radar beacon surveillance network. Hence surveillance techniques based upon ATCRBS, DABS, or BCAS components were examined first.

6.2.1 Air Traffic Control Radar Beacon System (ATCRBS)

The ATCRBS is the principal means of providing radar separation between controlled aircraft in the current air traffic control system. Approximately 300 sensors are now deployed to provide coverage in the continental United States. Use of existing ATCRBS sensors for EFR purposes might avoid the delay and expense associated with the purchase and deployment of new surveillance equipment. However, the ATCRBS system was not designed to support the type of automation which EFR employs, and hence its use in this application can be questioned. The following paragraphs outline the principal issues involved.

a. False Tracks

False targets due to reflections from objects near the sensor site can create false tracks. In severe cases as many as 10 percent of the active ATCRBS tracks are false, (Ref. 7). Such tracks may create problems with sign-in (such as the aircraft identity being assigned to the wrong track). These tracks can also result in false alarms. Sites with severe false track problems may be unable to support EFR service. Special ATCRBS processing algorithms to eliminate false tracks have been demonstrated. These algorithms can be quite effective when adapted to the particular site at which they are used. The use of ATCRBS from unmodified sites in support of EFR is questionable.

b. Track/Address Association

In order to communicate with aircraft, a data link which is separate from the ATCRBS surveillance link must be established. The address of aircraft on this data link must be associated with the correct ATCRBS track. Incorrect association results in messages being sent to the wrong aircraft. There are several mechanisms which could lead to incorrect association (e.g., track splits, track swaps, incorrect initialization or association, etc.). Modification of avionics may be required in order to allow repeated checking of track identity through test message acknowledgments.

c. Measurement Errors

Typical measurement errors for four classes of radar beacon sensors are presented in Table 6.1. In general the azimuth error is the more critical to performance since the cross-range position measurement error increases in proportion to range and exceeds the range error for all ranges beyond about 15 miles. The DABS sensor offers increased azimuth accuracy due to the use of a monopulse azimuth determination technique.

d. Effects of Measurement Errors

Conflict detection boundaries must be large enough to guarantee sufficient time for conflict resolution in spite of tracking errors. Thus larger tracking errors result in increased alarm thresholds and increased alarm rates. Errors in horizontal tracking result in less confidence in achieving desired separations for a given horizontal command option. This results in the EFR logic requiring larger magnitude turns and selecting vertical resolution more often. Thus the efficiency of control is degraded.

e. Effect of Update Rate

The ARSR's typically obtain position updates every 10 seconds (compared to every 4 seconds for DABS and ASR's). The lower data rate results in greater tracking error. As an example Fig. 6.1 presents curves for cross-range velocity estimation errors for steady-state Kalman filter tracking. With 10 second data rate it is much more difficult to track the flight of turning aircraft. It becomes very difficult or impossible to monitor the response of aircraft to instructions. If for some reason (such as garble between ATCRBS replies of two conflicting aircraft) the sensor fails to achieve an update on a scan, then 20 seconds will elapse between updates. In the case of maneuvering aircraft, this can result in almost complete loss of knowledge of conflict geometry.

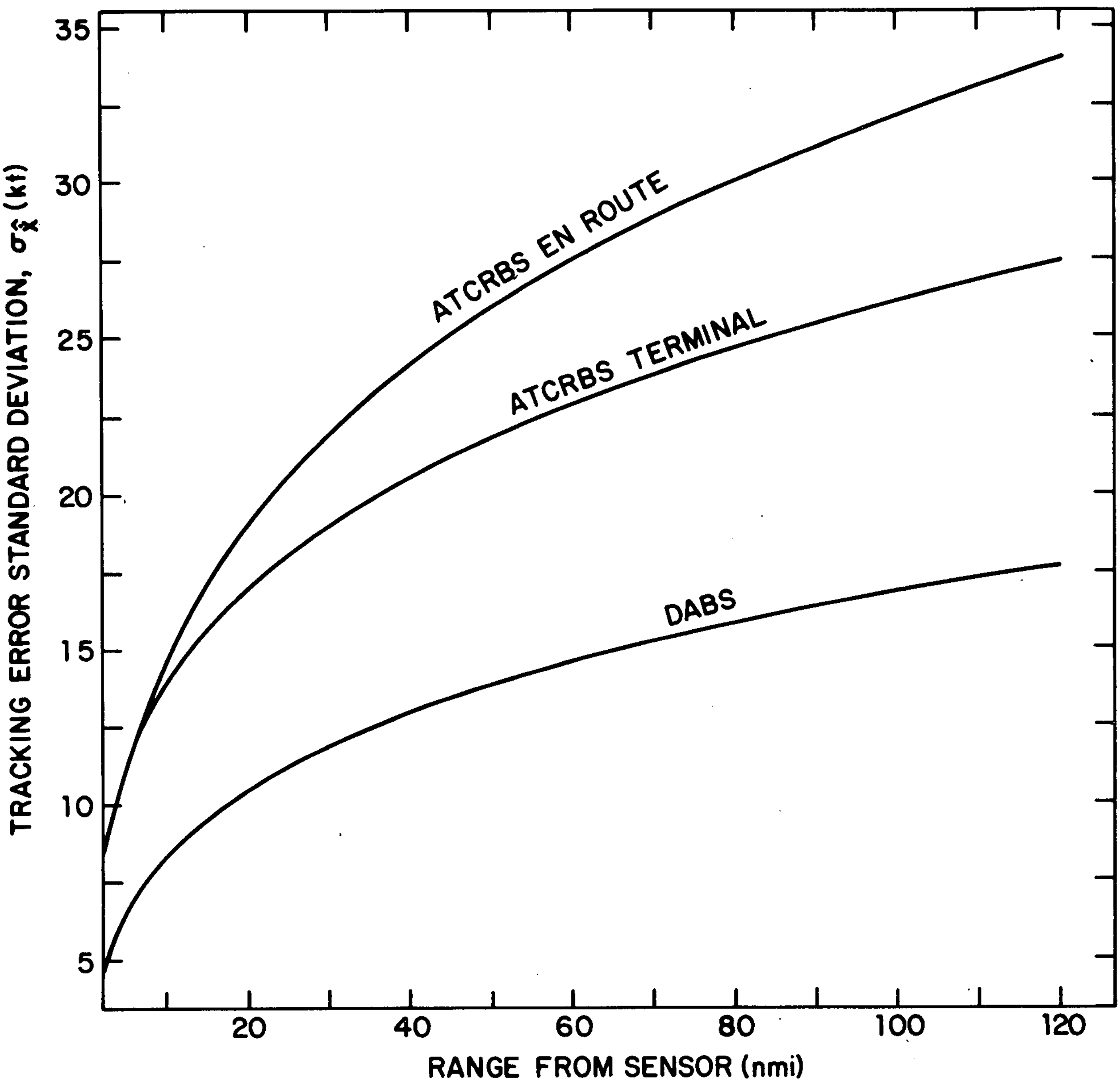

Fig. 6.1. Steady-state Kalman tracking errors (random acceleration with standard deviation $\sigma_a = 4 ft/sec^2$).

TABLE 6.1

Nominal Beacon Sensor Characteristics

Sensor Type	Azimuth Error (1σ)	Range Error (1σ)	Update Interval
ATCRBS - Terminal (ASR)	0.2°	380 ft.	4 sec.
ATCRBS - Enroute (ARSR)	0.1°	380 ft.	10 sec.
DABS (Terminal)	0.04°	40 ft.	4 sec.
DABS (Enroute)	0.04°	40 ft.	5 sec.

f. Conclusions on ATCRBS Surveillance Quality

EFR surveillance would be inferior in regions where only ATCRBS/ARSR coverage exists. EFR service is more readily achieved within ASR coverage, but some modification of reply processing software will be required. the need to upgrade equipment to support EFR brings into question the idea that ATCRBS-based EFR could readily utilize existing ATCRBS coverage. This study has not determined precisely the degradation in EFR performance with range due to increasing position measurement errors. However, it is likely that either service limitations will be imposed which make it difficult to obtain continuous radar service in en route airspace, or that the quality of service offered will degrade significantly in areas which are distant from ASR sites.

6.2.2 Discrete Address Beacon System (DABS)

The Discrete Address Beacon System (DABS) was designed to support automated tactical air traffic control services and is an obvious candidate to provide surveillance and communication functions for EFR. DABS includes an integral discrete-address digital data link which provides message delivery with high confidence. Most aircraft which are candidates for EFR service will already possess a DABS transponder and may possess some type of data link display device. Hence there are excellent prospects for holding the incremental avionics cost of EFR service to a low level. Performance issues surrounding the DABS system alternative are discussed below.

a. Surveillance Quality

The nominal position measurement accuracy of DABS (see Table 6.1) is significantly better than that of ATCRBS, especially in the critical azimuth coordinate. At 120 nmi range the cross-range error (one sigma) is only 500 ft. This value appears acceptable for separation assurance since the aircraft densities at longer ranges (and higher altitudes) is not great.

b. Coverage

DABS sensor coverage is limited to airspace within line-of-sight of sensor sites. Deployment of DABS sensors is scheduled to begin in the 1980's. A critical question is the number of DABS sensors which must be deployed before sufficient coverage exists for meaningful EFR service. An analysis of radar coverage is presented in Appendix B. This analysis concludes that a network of approximately 80 properly sited DABS sensors could provide essentially continuous EFR surveillance coverage down to 6000 ft in the Eastern CONUS and Southern California. Coverage in the remainder of the CONUS is unavoidably discontinuous due to terrain obstruction and greater distances between sensor sites. It is estimated that the potential continuous coverage is sufficient to cover more than 75% of all en route traffic.

The impact of man-made obstacles upon ATC radar coverage at low elevation angles has not been fully characterized for existing radar sites. Diffraction of aircraft replies by obstacles can lead to abnormally large azimuth errors for aircraft within line-of-sight This problem can be addressed by using more conservative separation standards for traffic flying near obstacles or by utilizing data from adjacent unobstructed sensors. Proper siting of sensors is also important in this regard.

6.2.3 Active BCAS Surveillance Techniques

The Active Beacon Collision Avoidance System (Active BCAS) provides collision avoidance protection to aircraft through use of surveillance techniques based upon air-to-air interrogation of ATC beacon transponders. This section discusses the potential of Active BCAS surveillance (or a modified version of it) to serve as a basis for EFR operations.

a. Radar-independent Surveillance

Active BCAS techniques allow surveillance to take place independently of ground-based radars. This allows radar-based separation techniques to provide an independent check upon EFR system performance and to serve as a back-up to EFR equipment failure. It should be noted that radar-independent surveillance does not necessarily allow EFR operations outside radar coverage since other necessary functions may be lacking there. For instance, outside radar coverage an EFR aircraft may be unable to coordinate with air traffic control in the event of a conflict with an IFR aircraft.

b. Traffic Density Limitations

Because of signal interference effects, BCAS surveillance is limited in the traffic density at which it can operate. For collision avoidance purposes the current Active BCAS is intended to be used only up to densities of 0.02 aircraft/nmi^2. Because EFR requires detection at longer ranges than collision avoidance, the density limitations upon EFR are more severe. Furthermore, because EFR is a primary separation assurance system rather than a back-up system, its reliability must be greater than that of BCAS. Several interference and system design phenomena should be considered in order to precisely determine the densities at which a BCAS-based EFR system could operate. Consider however that the number of aircraft within a given detection range is to remain the same, then an EFR system which desired to detect threats at twice the range of a CAS system would have a maximum tolerable traffic density four times less than the CAS. Such a density limitation (about 0.005 aircraft/nmi^2) would severely limit the regions of EFR utility. Note also that the nature of the interference problem makes it impossible for an aircraft to overfly a region of excessive density even though it flies well above the bulk of the traffic. Furthermore, since traffic densities fluctuate unexpectedly from day to day it may prove operationally difficult to define exactly where operation of a density-limited EFR system could be permitted.

c. Bearing Information

The basic Active BCAS surveillance technique does not provide threat bearing information. A study was undertaken to determine the utility of air-derived bearing information in conjunction with Active BCAS-type information. It was concluded (see Appendix A) that use of small antennas for angle-of-arrival measurement would support the issuance of traffic advisories, but that the accuracy of such measurements would be insufficient for use in alarm filtering or horizontal resolution. Use of bearing information in combination with exchanged heading and airspeed has greater performance potential. But such a technique would be more expensive, more vulnerable to equipment failure, and would be applicable only to conflicts between fully-equipped EFR aircraft. Hence it was concluded that an EFR system based upon Active BCAS surveillance techniques would utilize bearing data only for the issuance of traffic advisories. This limits the quality of service (see Section 6.1.1).

d. Avionics Expense

The unit cost of Active BCAS is expected to be between $10,000 and $20,000. It is generally assumed that only airline transports and larger general aviation aircraft would be able to invest in such equipment. The cost for a BCAS suitable for EFR support would probably be greater due to more stringent performance requirements and the need for more sophisticated data link capabilities. The expense of such a unit is not beyond reason, but it is great enough to discourage many potential EFR users.

6.3 Summary of Surveillance Alternatives

It has been shown that general feasibility and implementability considerations (Sections 4.2 and 6.1) indicate that for the foreseeable future the most promising surveillance techniques for EFR service are those which are based upon equipage with air traffic control radar beacon transponders. Three alternatives within this class of techniques were examined. They involved use of ATCRBS, DABS, and Active BCAS surveillance techniques. Problems of surveillance quality and data link reliability were identified in the use of ATCRBS surveillance. Avionics cost and traffic density limitations were associated with use of Active BCAS techniques. The principal question concerning use of DABS is the time period required for deployment of a number of sensors to provide sufficient coverage. On the basis of performance and avionics cost, the DABS system is the most promising of the three alternatives considered.

7.0 TRAFFIC ENVIRONMENT

Many aspects of the air traffic environment can affect the performance level of the EFR system and influence the relative attractiveness of system alternatives. In this section attention is focused upon one of the primary traffic environment parameters -traffic density. An attempt has been made to provide a general model of traffic distributions which is sufficient for the initial assessment of EFR viability. In the discussion which follows, the term aircraft density refers to the expected number of aircraft per square nautical mile including all altitudes. The term co-altitude aircraft density is used to mean the expected number of aircraft per square nautical mile which are near enough to a specified aircraft altitude to require separation assurance actions by the EFR system.

7.1 Traffic Density Distribution

The area of the CONUS is about 3 million nmi^2. The peak airborne count is currently about 20000 aircraft which corresponds to an average aircraft density of 0.007 aircraft per nmi^2 over the whole country. In fact, most of the country has a density that is lower than this amount while some areas near the airports of major cities have peak aircraft densities that are twenty times the national average. The high aircraft density near such centers falls off rapidly as the distance from the center increases. A model that has been found to give a good fit to available data assumes that aircraft density associated with a given traffic center decreases exponentially with distance (see Appendix C) i.e.,

$$\rho(r) = \rho_o \exp(-r/R) \qquad (7.1)$$

where

ρ_o = peak density
r = distance from center
R = characteristic decay distance

A typical characteristic decay distance, R, (at which point the density is only 1/e of its maximum value) is about 20 nmi. It should be mentioned that analysis of data collected by the Transportable Measurements Facility (TMF) shows that the peak density of aircraft is not inside the TCA, but outside, near general aviation airports along the edge of and under the floor of the TCA. Because the majority of aircraft are VFR, the peak densities of IFR aircraft are considerably lower than the total peak aircraft density. The density of IFR aircraft en route is very low by comparison to the VFR density near terminal areas. Typical peak airborne counts in IFR enroute sectors are under 15 aircraft (a density of about 0.002 controlled aircraft/nmi^2 in a control sector 80 nmi across.)

Since traffic is not uniformly distributed in altitude, the co-altitude aircraft density depends upon the altitude of interest. On the basis of filed flight plans and detailed traffic models, it appears that the bulk of the enroute aircraft population is at low altitude with the peak co-altitude aircraft density occurring around 5000 feet. For typical altitude distributions the peak co-altitude aircraft density (using ±1000 feet as the co-altitude band) is about one-fifth of the aircraft density for aircraft at all altitudes.

Because the EFR service will treat IFR, VFR, and EFR aircraft differently (see section 5.2) the distribution of traffic among these three flight categories must be considered. Previous traffic model predictions are useful if one assumes that the introduction of EFR service does not significantly increase the total number of aircraft. The question then centers upon the number of aircraft designated IFR and VFR in the traffic model which would choose to fly EFR if given the opportunity. It is expected that only a small number of aircraft which would otherwise be unequipped for IMC operations would choose to fly EFR under IMC. The bulk of the EFR traffic would then consist of general aviation aircraft which would otherwise fly IFR under IMC.

Currently about 23% of en route instrument operations are attributable to general aviation (Ref. 8). General aviation aircraft handled under en route IFR are expected to grow at an annual rate of 7.2% from 1977 to 1989 as compared to a growth rate of only 2.3% for air carriers (Ref. 1). Thus more than 50% of the predicted growth in instrument operations will be attributable to general aviation[1]. Without EFR, general aviation should account for more than one-third of the total number of IFR aircraft handled in 1990.

Weather conditions have an obvious impact upon the composition of air traffic. Under IMC, all traffic must operate IFR and the exclusion of non-qualified aircraft results in decreased traffic densities. Under VMC, peak densities occur and VFR traffic is typically assumed to account for two-thirds to three-fourths of the total traffic. Hence less than one-third of the peak traffic density contributes to the issuance of resolution instructions by the EFR system.

7.2 Terminal Interface Considerations

As aircraft approach a traffic hub the number of conflicts which arise in purely tactical control will increase. At the same time, it becomes necessary to begin sequencing aircraft along a common path which leads to the runway in use. Thus at some point prior to landing, traffic can no longer be considered random, but begins to exhibit structure and to follow a time schedule. Some control process must provide metering and provide protection from disruption by other aircraft in the area. Under VMC at non-tower airports the structure is provided by a traffic pattern, and the individual pilots provide

[1]At the beginning of the time period involved the fractional growth due to general aviation is 0.23 x .072 = .0166 and the fractional growth due to air carrier operations is 0.77 x .023 = .0177. Hence general aviation initially accounts for 0.0166/(0.0166 + 0.0177) = 48% of the traffic growth. This fraction increases with time.

their own metering and spacing. At tower airports the structure is provided by the tower controller who must be contacted before passing inside a 5 nmi radius and 3000 ft. altitude of the airport. Under IMC the structure is provided by the appropriate sector controller or approach controller. Around major terminals a Terminal Control Area (TCA) has been established to provide positive-controlled airspace that eliminates uncontrolled traffic which might otherwise interrupt the metered flow to the terminals. The requirement for some area of structure around every terminal, large or small, means that there must always be an EFR service boundary between the en route airspace and the terminal. At that boundary a control transition is required which is analogous to the transition which occurs today when a VFR aircraft enters a TCA or a Terminal Radar Service Area (TRSA). That boundary could take several forms. The boundary could be a floor at a specified altitude. In order to descend below that floor an aircraft would have to transition to VFR or else obtain an IFR clearance. The boundary could take the form of an extended airport traffic area (extended to include the area required for an instrument approach). A clearance would be required to enter the extended area under IMC.

7.3 Conflict Rates

Tactical resolution of aircraft conflicts becomes infeasible when the percentage of time in conflict becomes too great. In the limit, the need for constant conflict resolution prevents accomplishment of flight objectives. But before that limit is reached, problems may develop with resolution of multiple aircraft conflicts or with pilot workload level. For purposes of EFR system evaluation, it will be assumed that it is unacceptable for an aircraft to be in conflict more than 10% of the time. If the average duration of a conflict is one minute, this means that no more than 6 conflicts per hour could be allowed. In computing the conflict rate it should be kept in mind that encounters with some aircraft (e.g., VFR aircraft) may require only traffic advisories and hence may not qualify as a full conflict.

For aircraft which are not previously constrained by air traffic control, a reasonable prediction of conflict rate can be derived from a random encounter model. The conflict rate for a single aircraft is then given by the product of the width of the horizontal conflict area, the average relative speed, and the co-altitude aircraft density. For a horizontal conflict area of width 6 miles (3 nmi separation radius) and an average relative speed of 180 knots the conflict rate for aircraft flying at the average en route aircraft density* (.007 aircraft/nmi^2) would be no greater than approximately 1.5 conflicts per hour. The maximum acceptable co-altitude aircraft density (for 6 conflicts per hour) would be about 0.005 aircraft/nmi^2. If this co-altitude aircraft density is allowed at the most crowded altitude, then the maximum total aircraft density would be 0.025 aircraft/nmi^2. If resolution is not required relative to VFR aircraft (which constitute 2/3 of the traffic), then the maximum total density is about 0.075 aircraft/nmi^2. TMF traffic tapes collected in 1976 at Los Angeles, Washington, Philadelphia, and Boston (Ref. 9) indicate that densities this high occurred only within 10 nmi of the

*A density of approximately .007 aircraft/nmi^2 or .007 ÷ 5 = 0.0014 co-altitude aircraft/nmi^2 at the densest altitude.

busiest terminals. Because the traffic falls off exponentially the density near the terminal could double and still permit EFR operations at a relatively short radial distance away.

Itinerant aircraft which proceed directly from en route airspace into the airport control area will spend only a small amount of EFR flight time at these higher densities. Hence a more meaningful way to describe the conflict situation might be in terms of conflicts per operation. Consider the case of an aircraft which approaches a traffic hub for which the density follows the exponential form of equation 7.1. Assume a constant approach rate. Integration of the conflict rate shows that the expected number of conflicts which will have occurred by the time the aircraft is r miles from the hub center is:

$$\text{no. of conflicts} = \frac{2\,\eta\,\overline{V}\,r_o\,R\,\rho_o}{U}\,\exp(-r/R) \tag{7.2}$$

where

η = fraction of aircraft which are co-altitude

$\overline{V}$ = average relative speed between aircraft
r_o = protected radius which defines a conflict
R = characteristic decay distance
ρ_o = aircraft density
U = speed of approach of aircraft of interest

By setting r equal to the range at which the aircraft transitions from EFR to terminal or airport control, this equation becomes the number of EFR conflicts per operation. Using typical 1995 L.A. Basin parameters (η = 0.20, $\overline{V}$ = 160 Kt, ρ_o = 0.20 ac/nmi^2, R = 15 nmi, r = 15 nmi, U = 120 knots) the expected number of conflicts per operation is 1.8 for a 3 nmi separation standard and 0.6 for a 1.0 nmi separation standard. Hence it appears that the EFR aircraft would be able to complete the flight without an excessive number of EFR conflicts, even if conflict resolution were required relative to all other aircraft.

7.4 Summary

On the basis of general traffic environment models and system performance goals, it appears that traffic densities which threaten the viability of EFR operations occur only within 10 to 20 miles of the busiest traffic hubs. Itinerant EFR aircraft which enter such traffic hubs in order to transition do not remain in high density regions for a length of time which is operationally significant.

8.0 EFR RESOLUTION VIA COMPUTER LOGIC

In order to investigate the feasibility of EFR configurations which use computer logic for the control of aircraft, a control algorithm structure was devised and studied via a fast-time simulation. Because primary separation assurance requires more efficiency and reliability than back-up separation assurance, the EFR algorithms differ in several ways from collision avoidance algorithms. The principal features of the algorithm are discussed below. More details on the logic are provided in Appendix D.

8.1 Resolution Lead Time

Collision avoidance systems are usually designed to wait as long as possible (approximately 25 seconds before collision) before initiating a resolution. The EFR logic initiates resolution earlier (60 to 90 seconds before a potential collision could occur). This extra time allows smaller course changes and more gentle maneuvers to be utilized. It may also allow the logic to alter the path of only one conflicting aircraft rather than both. Additional lead time is also critical for effective monitoring of compliance and for providing time for a second set of resolution instructions to be issued should the first set prove inadequate.

8.2 Specified Heading/Altitude Assignments

EFR resolution is accomplished by assigning specific headings and/or altitudes to aircraft. This allows use of minimally disruptive command magnitudes and prevents excessive turns which are counterproductive in terms of generating separation. It also enables the EFR system to predict the future paths of aircraft and it allows other control authorities (e.g., human controllers) to anticipate the path which the aircraft will follow. Specified heading/altitude assignments assist in the resolution of multiple-aircraft encounters (a three-aircraft encounter can be resolved by assigning three distinct altitudes). Specified heading and altitude assignments also enable safer operation near airspace and service boundaries (instructions can be selected which are less likely to precipitate a blunder into prohibited airspace).

8.3 Separation Standards

Because of the accuracy of most EFR surveillance systems, the fast reaction times of automated system logic, and the presence of improved traffic advisory services, conventional IFR radar separation standards may prove overly conservative for EFR purposes. But it is likely that conventional standards will be adopted for the initial introduction of EFR and that they will be reduced only after satisfactory initial experience with the system.

A question which arises with regard to separation standards concerns the separation required for wake vortex clearance. If the EFR data base does not include aircraft weight class, then a conservative interpretation of wake vortex clearance requirements could impose large separation requirements upon the EFR system.

8.4 Discrete Resolution Options

Only a finite number of discrete heading/altitude assignments are allowed. For heading, possible assignments correspond to heading changes of 0°, ±30°, and ±60° from the heading at which the aircraft is initially flying. (See Fig. 8.1). The five heading options for each aircraft produce 25 possible horizontal command sets for each pair of aircraft.

In the vertical dimension, five possible altitude assignments are possible (see Fig. 8.2) corresponding to 0, ±500 and ±1000 feet altitude changes from the current aircraft altitude, rounded off to the nearest 500 foot value. The five possible command set options for each aircraft produces 25 possible command set options per aircraft pair for vertical resolution.

Except for unusual situations, it is inefficient to maneuver one aircraft horizontally and one vertically. When this is done, an additional negative command must be issued to each aircraft to prevent pilot initiated maneuvers from canceling the effects of the positive commands. Thus the initial resolution choices involve either strictly horizontal or strictly vertical resolution. This results in a total of 50 possible commands sets (25 horizontal and 25 vertical).

8.5 Cost Function Structure

In order to select the best resolution option from the 50 options available, the test-bed logic examined each option and computed a cost for each. This cost is the sum of a number of cost terms, each of which reflects some independent aspect of a command set desirability. The option with lowest cost is selected for issuance.

The cost term algorithmic structure offers a number of advantages which are desirable in a system which seeks to provide primary separation assurance. Such a system is required to take a number of factors into account in selecting control actions. For example, it may evaluate not only separation from the principal threat, but terrain clearance, the probability of secondary conflict, violations of airspace structures, penetration of coverage boundaries, etc. The proper evaluation of many of these factors requires specification of proposed trajectories. The use of discrete resolution options makes this possible.

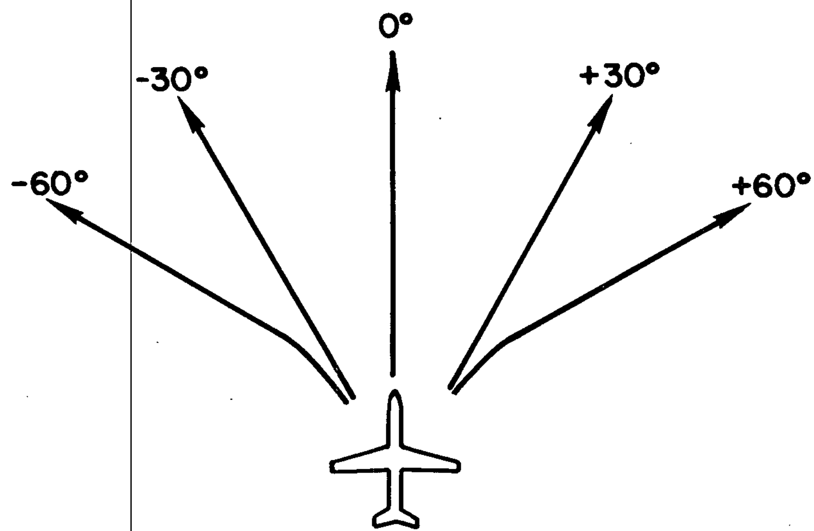

Fig. 8.1. The resolution logic considers five possible heading assignments for each aircraft.

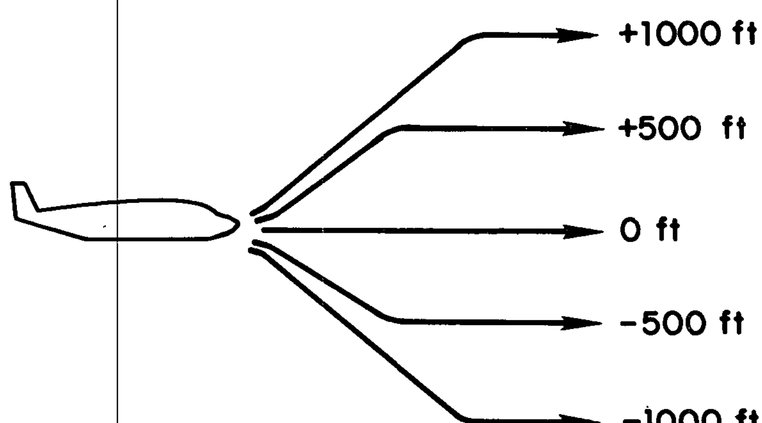

Fig. 8.2. The resolution logic considers five possible altitude assignments. The altitude assignments are centered upon the multiple of 500 feet MSL which is closest to current aircraft altitude.

The total cost computed is independent of the order in which the cost terms are evaluated. This is in contrast to "tree structure " algorithms in which the order of tests is critical to the final resolution.

There are two general classes of cost terms: those which are related to safety and those which are related to control efficiency. The relative influence of each term is determined by the maximum value it is allowed to assume. Terms which consider safety are allowed to assume substantially greater magnitudes than the efficiency terms. Thus, no significant amount of safety can be forfeited in an attempt to attain greater control efficiency. But when, as is usually the case, several safe options exist for resolution, the most efficient will tend to be chosen.

8.6 Simulation of the EFR Cost Function Logic Concept

The performance of the EFR logic concept was examined by running approximately one hundred encounters in fast time simulation using a variety of encounter geometries. Although this limited testing is insufficient to draw any final conclusions concerning the viability of the concept, the results obtained were encouraging as the following observations indicate:

1. The logic appeared to make "reasonable" command choices in all situations - it was not prone to totally irrational or unjustifiable errors.

2. In most encounters there were several command sets which achieved the safety goals (i.e., which drove the computed risk of insufficient separation to zero). The final choice of command set was usually based upon control efficiency considerations (e.g., minimizing deviation from flight path).

3. In many cases only one aircraft was maneuvered to resolve the encounter.

4. The system performed well over a wide range of detection threshold parameters - basic changes in the logic structure were not required to accommodate parameter changes. (Warning time and separation standards were varied in the simulations).

5. Recovery encounters (i.e., encounters with the same aircraft which occur upon return to course) were largely eliminated due to anticipation of such situations in the command selection process.

9.0 SUMMARY OF RESULTS

This report has defined a concept known as Electronic Flight Rules which involves provision of tactical traffic separation services in IMC without the requirement for adherance to pre-filed flight plans and without the need for time-critical decision-making by a human controller. Such a mode of flight would benefit the ATC system by reducing the loading upon the IFR system. It would benefit pilots primarily by providing greater freedom and convenience when operating in IMC.

Examination of the air traffic environment indicates that EFR tactical control techniques are feasible en route for both current and anticipated traffic densities.

Two fundamental requirements have been identified which EFR systems must meet in order to be considered promising for implementation. The first is that the introduction of EFR flight should not prevent aircraft which so desire from being able to fly in IMC at a level of safety which is at least as high as that of IFR today. The second is that conventionally-equipped aircraft should be allowed to continue IMC operations in the airspace in which EFR service is offered.

These fundamental requirements have significant implications when particular options for implementing the EFR concept are considered. They imply that coordination of resolution actions between aircraft is required. They also imply that configurations which do not require special avionics onboard aircraft are desired. For the foreseeable future, this tends to favor the use of surveillance techniques which utilize ATC beacon transponders.

The proper division of decision-making responsibility between pilots and computer logic was considered. In general, decision-making by computer logic is preferred in terms of reliability, pilot workload, avionics simplicity, and feasibility of meeting coordination/interface requirements. However, opportunities for pilot inputs should be considered in any concept in order to enhance control efficiency.

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APPENDIX A

UTILITY OF AIR-DERIVED SURVEILLANCE DATA FOR HORIZONTAL CONFLICT RESOLUTION

A.1 INTRODUCTION

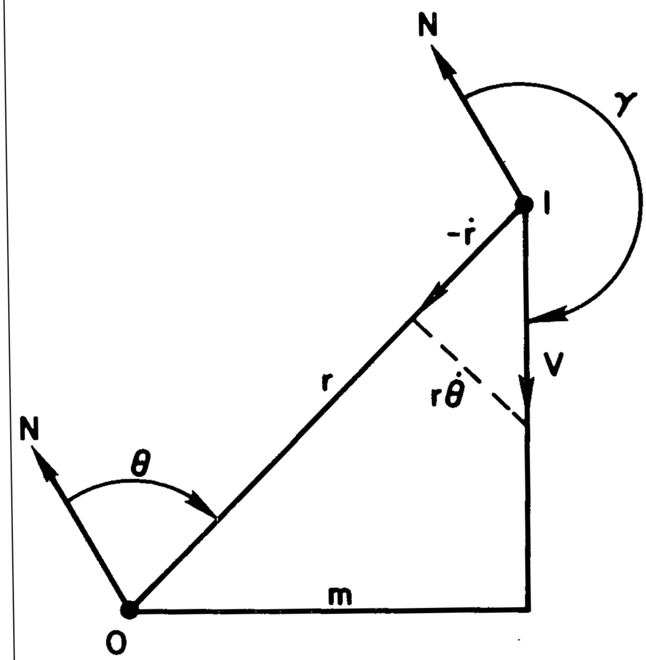
This appendix provides an evaluation of the ability of air-derived data to support horizontal conflict resolution decisions. The problem is considered from the view of providing EFR resolution with current IFR separation standards. Thresholds appropriate to lower standards approaching those associated with collision avoidance are included for completeness.

The horizontal resolution of air traffic conflicts requires information about the relative horizontal position and velocity of one aircraft with respect to the other. The question under consideration is whether the required information can be obtained from measurements made on board the aircraft in conflict. Measurements of the range and altitude components of relative position and velocity are assumed to be available, as they are common to existing and proposed air-derived systems. Measurements of the components of relative position and velocity in the bearing direction are generally more difficult to obtain. Two techniques considered here are: 1) bearing measurement through angle-of-arrival determination using a multi-stub antenna and 2) exchange of airspeed and heading data from onboard flight instruments.

A.2 ANGLE-OF-ARRIVAL MEASUREMENT

In the absence of bearing information, detected threats have to be resolved in the vertical dimension. If adequate quality bearing information were available, it would be possible to resolve detected conflicts with positive (e.g., "turn 30° right") and negative commands (e.g. "do not turn left") in the horizontal dimension as well. The advantage of horizontal negative commands is that they require no course change on the part of the aircraft and are a desirable alternative to vertical positive commands in those cases where the horizontal separation is adequate. An advantage of positive horizontal commands is that multiple encounters can be resolved using the additional control dimension. The advantages cannot be obtained, however, if the precision of the measurements is inadequate.

Figure A.1 defines the mathematical variables which describe the geometry of an encounter. The critical variable for horizontal resolution is the miss distance, m. The value of m determines the need for positive or negative commands. It also determines the magnitude and direction of commands. Therefore, the critical question relates to how well this distance can be determined at the time of resolution.



N	NORTH REFERENCE
O	OWN AIRCRAFT
I	INTRUDER AIRCRAFT
r	RANGE BETWEEN AIRCRAFT
$\dot{r}$	RANGE RATE
θ	BEARING OF INTRUDER
$\dot{\theta}$	BEARING RATE
V	RELATIVE VELOCITY
γ	HEADING OF RELATIVE VELOCITY
m	MISS DISTANCE

Fig. A.1. Variables describing relative motion geometry.

How accurate does the miss have to be known for resolution? It is certainly desirable for safety that the miss expected as a result of the commanded resolution be several times greater than the uncertainty in the estimate of the miss. This can be accomplished by keeping the uncertainty small or the commanded miss large. However it is inefficient to make the commanded miss much greater than the desired separation. At some point it becomes more desirable to use vertical separation than to use extremely large horizontal maneuvers just to compensate for uncertainty. At that point the horizontal resolution option is no longer attractive. In this study an accuracy of 0.5 nmi, one sigma, in miss distance determination was considered desirable for horizontal resolution. For this accuracy, a one mile separation standard is only two sigma while a three mile separation standard would be six sigma.

The time at which resolution begins is usually based on a modified tau criterion which is satisfied when

$$r = r_o - \dot{r}\tau_o \qquad (1)$$

where

r_o = protected range parameter

τ_o = modified tau parameter

The bearing rate, $\dot{\theta}$, is the time rate of change of the angle between the line of sight to the threat and an inertial reference. For evaluation, one is interested in the bearing rate <u>at the time of tau detection</u> since this is the point at which resolution decision-making takes place. This bearing rate is a function of the range rate and the miss distance, m. Specification of r_o, τ_o, $\dot{r}$ and m is sufficient to determine the bearing rate at detection when equation (1) is satisfied. In Fig. A.2 the relationship has been plotted for the case where τ_o = 10 sec and r_o = 3 nmi.

Observe that the curves do not span the entire space. For a given range rate, there is a limit on the magnitude of the bearing rate that can exist at the time when the modified tau criteria is satisfied. The maximum value which the normalized bearing rate, $\tau_o\dot{\theta}$, can achieve is one radian (57.3°). Consequently the maximum value of $\dot{\theta}$ approaches a limit of $\frac{1}{\tau_o}$ as the range rate gets large.

To be able to detect that the miss is under 3 nmi the sensor would have to be able to detect that the bearing rate was under 0.3 deg/sec. To determine the miss to a precision of 0.5 nmi a bearing-rate precision of 0.05 deg/sec is typically required. These levels of precision are not available

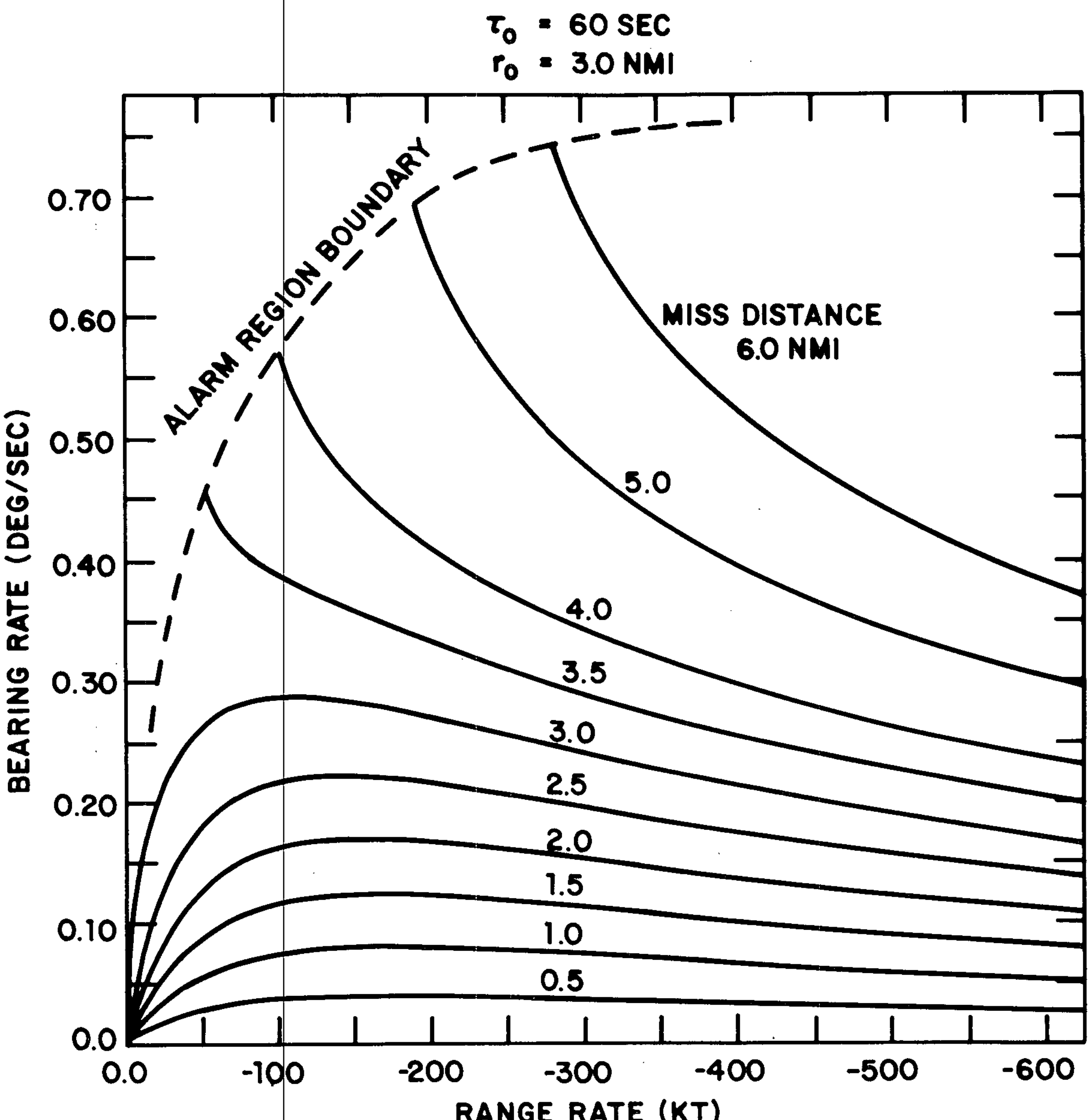


Fig. A.2. Bearing rate at time of detection versus range rate at time of detection.

from the class of antennas being considered. Furthermore, the heading rate of the aircraft is also needed to obtain the true bearing rate measurement. (Since rotation of the antenna must be distinguished from rotation of the line of sight).

Possession of bearing information may make possible an additional stage of conflict filtering. In this application an aircraft which violates a tau alarm criterion will not require resolution actions unless it also violates bearing rate criteria. Such additional conflict filtering can reduce the number of alarms which require resolution. The following example shows how the curves previously introduced can be used to estimate the effect of bearing rate errors on conflict filtering capability. For a range rate of -200 knots, only miss distances less than approximately 5.2 nmi will violate the tau alarm criterion. If a miss of less than 3.0 nmi is considered a "true" alarm, then a fraction 3.0/5.2 = 0.577 of the tau alarms will violate the "true" criterion and a fraction 0.423 will not. Thus 42.3% is the greatest fractional reduction which bearing filtering could provide in reducing the number of "true" alarms. Note however that the bearing rate difference between m=5.2 nmi and m=3.0 nmi is only 0.43 deg/sec. Hence uncertainties in the bearing rate estimate of greater than 0.43 deg/sec make it impossible to determine with confidence that any alarm which satisfies the tau criterion has adequate miss. The margin for error is even less at lower range rates.

The physical reason that the critical bearing rates are so low is that resolution decisions must take place early at long range. Ground radars can do better since their antenna aperture is much larger (by a factor of ten or twenty) and their antenna base is fixed with respect to the ground. In addition the range measurement, which tends to be more accurate than distance measured in the azimuth direction, may be more favorably oriented with respect to the miss. In the airborne case, miss measurement depends entirely upon angle-of-arrival measurement.

For comparison, the relationship of equation (1) has been plotted for τ_o=30 sec and γ = 1.0 nmi in Figure A.3. The bearing rates are generally increased over the case of interest but not enough to show promise for practical use.

Figure A.4 plots the relationship in non-dimensional form, which makes the curves universally valid for all choices of alarm threshold values. For particular parameter choices, one need only scale the axes by the particular values of τ_o and r_o which are of interest. The ordinate has units of $1/\tau_o$ and the abscissa has units of r_o/τ_o.

Alarm Filtering Efficiency

A more comprehensive picture of filtering capabilities in the presence of errors can be derived from the information contained in the normalized plot. Define those aircraft with miss distance, m, greater than the protected range

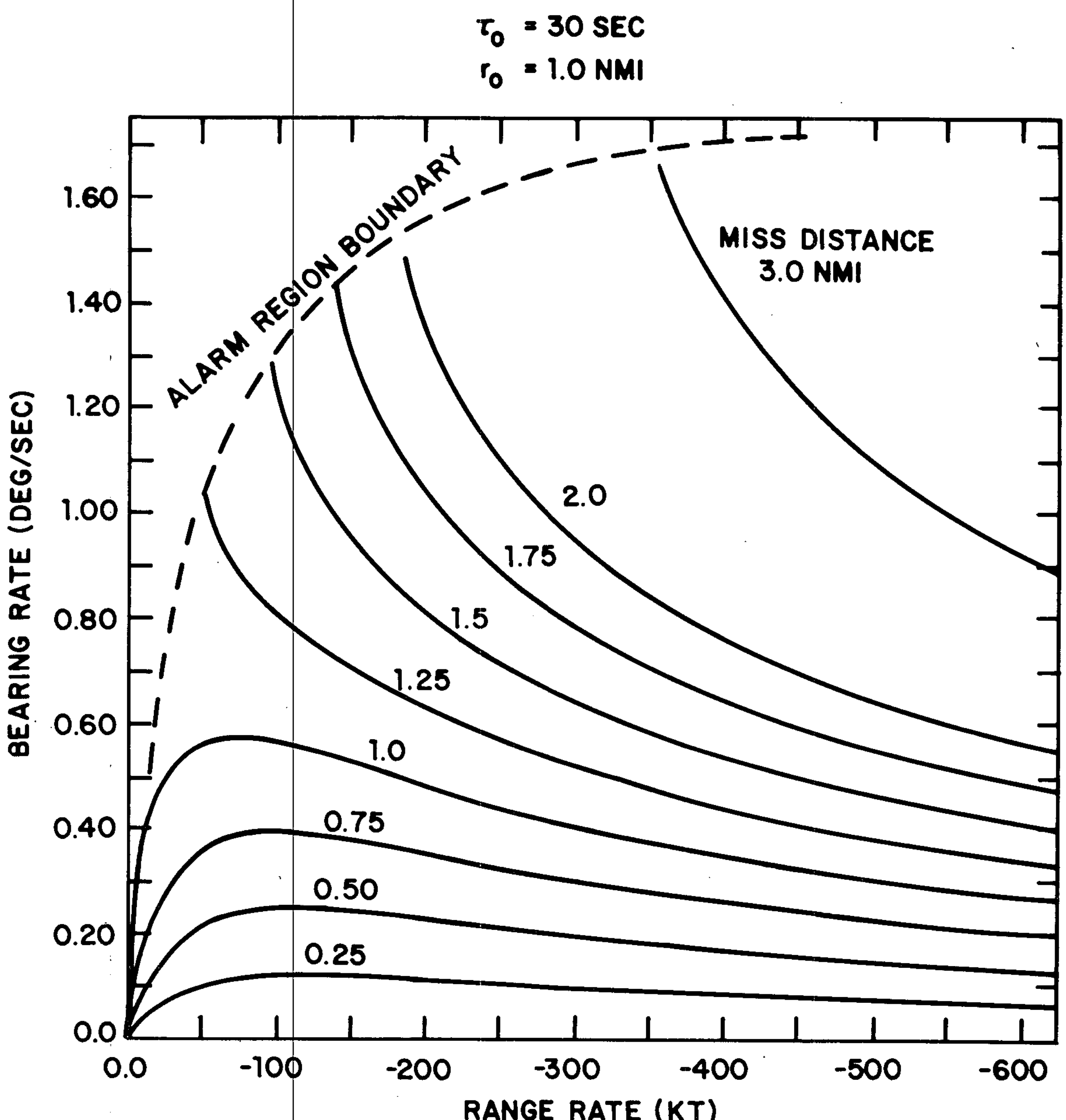


Fig. A.3. Bearing rate at time of detection versus range rate at time of detection.

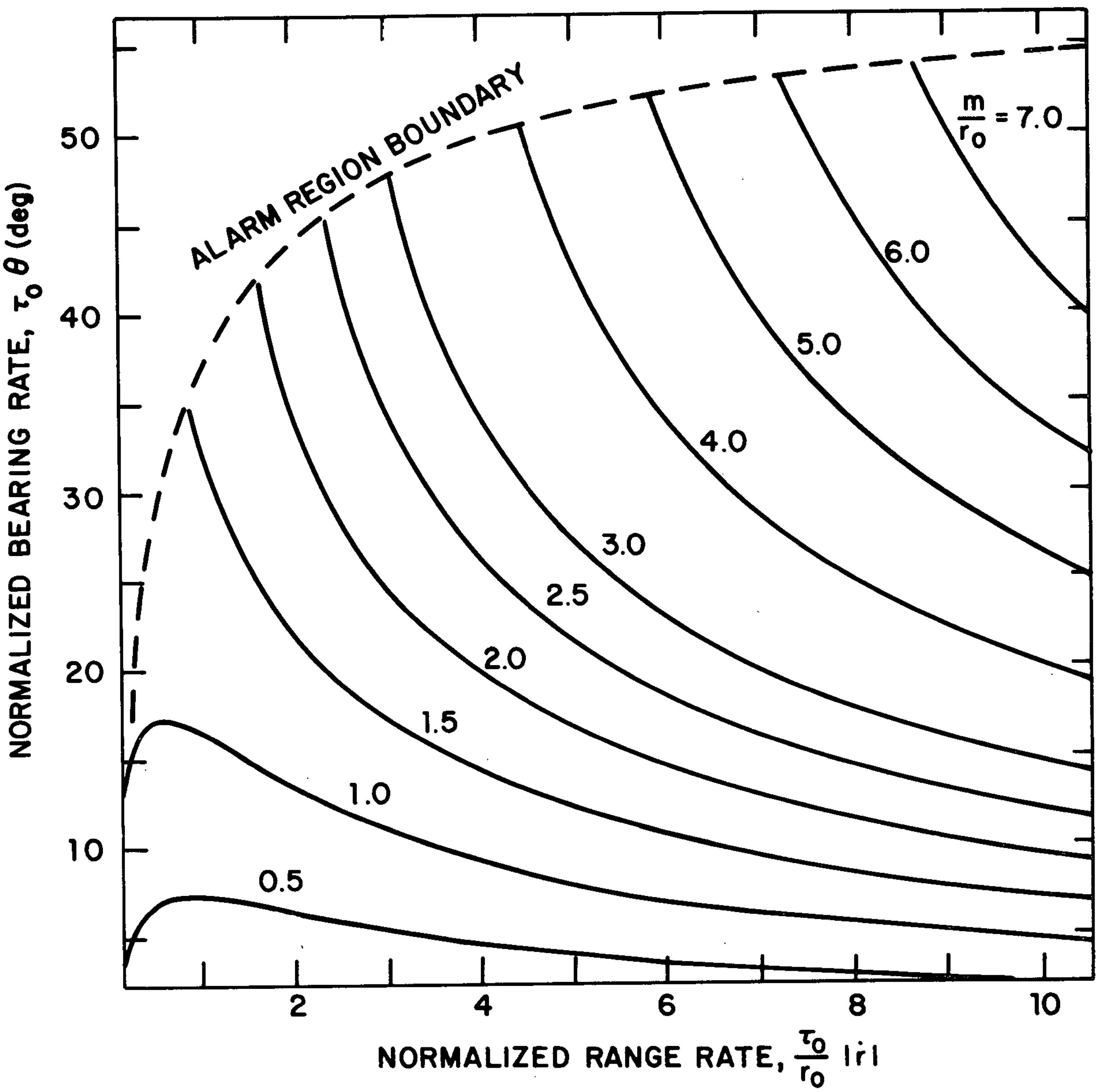


Fig. A.4. Bearing rate versus range rate at time of modified tau detection for various values of the miss distance. All variables are normalized according to the modified tau parameters r_o and τ_o in order to produce a figure valid for any choice of threshold values.

parameter, r_o, to be invalid alarms. It is reasonable to assume that the miss, m, is uniformly distributed. Therefore, the percentage of invalid alarms ($m > r_o$) for each value or range-rate is given by the ratio of the miss at the alarm boundary minus the miss which defines the invalid-alarm criterion, all divided by the miss at the alarm boundary. This plot has been included as the uppermost curve Figure A.5. It can be interpreted as the percentage of tau alarms which could be filtered assuming perfect knowledge of bearing rate. Similar plots can be generated from the fundamental information for other definitions of what constitues an invalid alarm.

When the bearing rate information is not perfect it is appropriate to increase the invalid alarm threshold to provide a margin for error in the determination of the bearing rate. Figure A.5 provides curves for which the invalid-alarm criteria has been relaxed to tolerate various normalized bearing-rate errors.

Bearing Rate Estimation Error

If bearing rate is to be determined by estimation (tracking) based upon the time history of bearing measurement, then a requirement on bearing rate accuracy should be equivalent to some requirement on bearing measurement accuracy. But a number of assumptions and complications arise in translating antenna characteristics into system bearing rate accuracy. One must define

- the ability of the aircraft to compensate for slight rotations of the antenna during the tracking period
- the correlation between measurement errors
- the effect of accelerations of the aircraft in changing the encounter geometry
- the performance of bearing tracking algorithms
- the confidence level required in order to delete an alarm

A lower bound on the error can be attained by making the following optimistic assumptions:

1. The aircraft knows own heading well enough to perfectly compensate for any rotations of the antenna
2. There is zero correlation between measurement errors

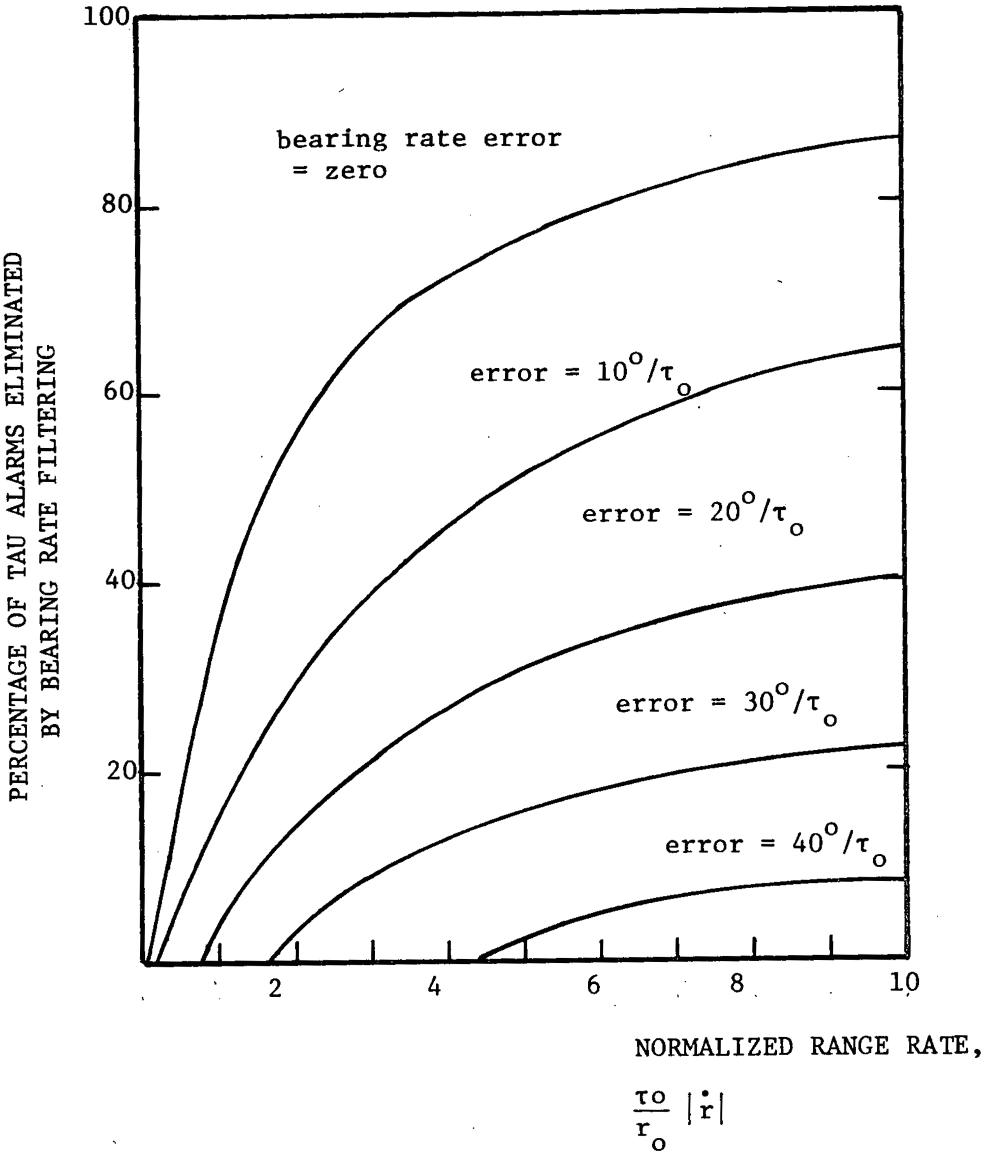


Fig. A.5. Percentage of tau alarms which can be eliminated by bearing rate filtering. These curves assume that alarms with miss distance greater than r_o are deleted.

3. There is no acceleration

4. Tracking algorithms remove all biases and achieve least-square error.

In such a case the bearing rate error would be given by the equation:

$$\sigma_{\dot{\theta}}^2 = \frac{1}{N(N^2-1)} \frac{12\sigma_{\theta}^2}{T^2}$$

Where $\sigma_{\dot{\theta}}^2$ = Variance of bearing rate error

σ_{θ}^2 = Variance of bearing error

N = Number of measurement points in track history

T = Time between measurements

This relationship is plotted in Figure A.6 for a 1 second update rate and several values of N which probably bound the reasonable range of values.

Accuracy Requirements for Traffic Advisories

Bearing measurement requirements are less severe for the provision of traffic advisories to assist in visual acquisition. NAFEC simulation results by Rich, Crook, et al* (Reference A.1) state:

> "Using a practical panel indicator, there is no gain in reducing the warning sector to less than 30 degrees azimuth."

The ATARS (IPC) flight tests at Lincoln Laboratory had success with 30 degree display resolution, even with crab angle and tracking lag errors. Hence traffic advisories are supportable with measurement errors less than 30°, an accuracy which is within the range of airborne measurement systems.

A.3 EXCHANGED HEADING AND AIRSPEED

When heading and airspeed from onboard instruments are exchanged, the miss distance can be determined from the relationship

$$m = r \sin (\gamma - \theta) \qquad (2)$$

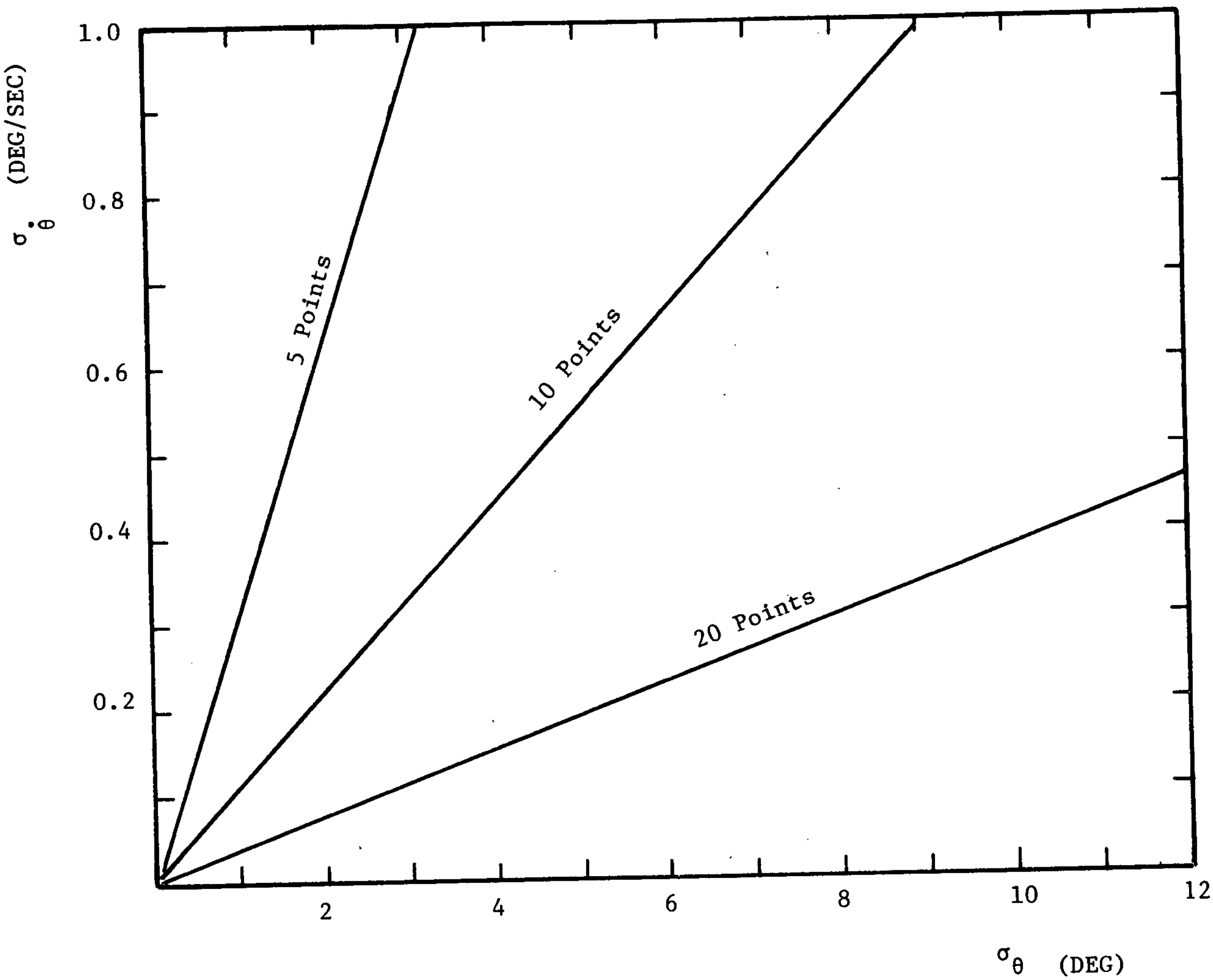


Fig. A.6. Bearing rate estimation error (1 sec. update rate).

The angle γ is determined from a combination of exchanged heading and airspeed data. The bearing, θ, is obtained from angle-of-arrival measurement. Combining (1) and (2)

$$m = \sin(\gamma - \theta) \{r_o + \tau v \cos(\gamma - \theta)\} \quad (3)$$

which is plotted in Fig. A.7 for the case of $r_o = 3$ nmi and $\tau = 60$ sec. To detect that the miss is under 3 nmi with closing speeds up to 250 knots the sensor would have to be able to determine that the angle, $\gamma - \theta$, was under 30 degrees. To determine the miss to a precision of 0.5 nmi at closing speeds up to 250 knots a bearing precision of about 5 degrees is required. This level of precision is probably achievable from the exchanged heading and airspeed data and is conceivable from the antenna being considered. A precision of 15 degrees or better is required to permit the use of negative horizontal commands to protect existing horizontal miss. There are operational drawbacks since both aircraft must be equipped with accurate readout of both airspeed and heading in order for this approach to succeed.

A.4 CONCLUSIONS

The bearing measurement accuracies which can be expected from angle-of-arrival antennas is not sufficient to support horizontal resolution. It is sufficient to provide traffic advisory information to pilots. Exchange of heading and airspeed between aircraft would relax accuracy requirements, but the need for both aircraft in a conflict to be equipped with additional avionics makes such an approach unattractive for EFR applications. For purposes of this study, EFR systems which rely on air-derived surveillance data are limited to vertical resolution only. Consequences of this limitation are discussed in section 6.1.1.

Reference

A.1 Rich, P.H., Crook, W.G., Sulzer, R.L., and Hill, P.R., Reactions of Pilots to Warning Systems for Visual Collision Avoidance, National Aviation Facilities Experimental Center (FAA), FAA-NA-71-54, December 1971.

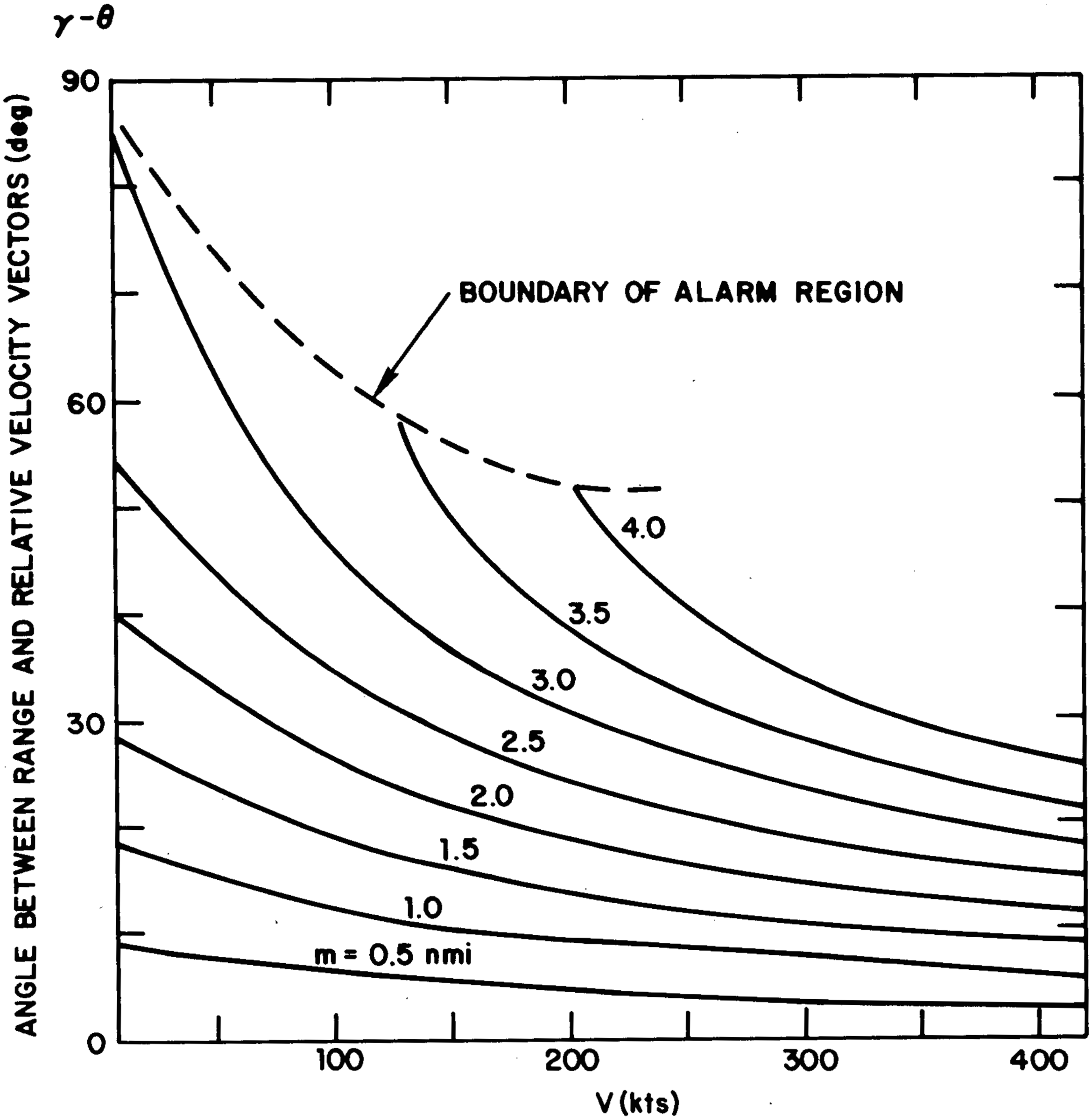


Fig. A.7. Angle between range and relative velocity vectors at time modified tau criterion is violated for tau = 60 seconds, r_o = 3.0 nmi.

APPENDIX B

RADAR COVERAGE

This appendix presents the results of a study of ATC radar coverage. The principal analysis tool used in the study is a software package which draws maps of coverage areas at specified flight altitudes. Several simplifying approximation have been made in deriving these maps. The principal limitation introduced into the model is the use of a smooth earth model which does not take the obstructions of terrain or man-made structures into account. Fig. B.1 provides a plot of the coverage altitude at a given range from a sensor for various values of the elevation cut-off angle. A cut-off angle of 0.25° is utilized in the maps which follow.

Refinement of this model to account for man-made obstructions would require data which is currently unavailable for all but a handful of sites. The effect of obstructions depends upon the location of a sensor upon the airport surface, the antenna pedestal height, and the current location and size of buildings. A statistical model of obstructions would be a logical refinement of this model, but for purpose of the current study this was not deemed necessary.

Terrain obstruction is highly significant for many sites in the western United States. But a previous study (Reference B.1) indicates that few cases of significant terrain obstruction are encountered east of the Rocky Mountains. Thus the coverage maps produced will be most accurate for the East, and will present a quite optimistic upper bound for coverage in the West.

Radar site locations were obtained from a list of 379 current and potential ATC radar sites as compiled by the Electromagnetic Compatibility Analysis Center. The data provided for each site include location (to the nearest minute of latitude or longitude), height above sea level, and type of current or proposed radar (ASR or ARSR).

In order to identify sites for a limited EFR radar deployment, each site was tagged according to the following "traffic priorities":

Current TCA's
Large Traffic Hubs
Proposed Future TCA's
Medium Traffic Hubs
Small Traffic Hubs
All other sites

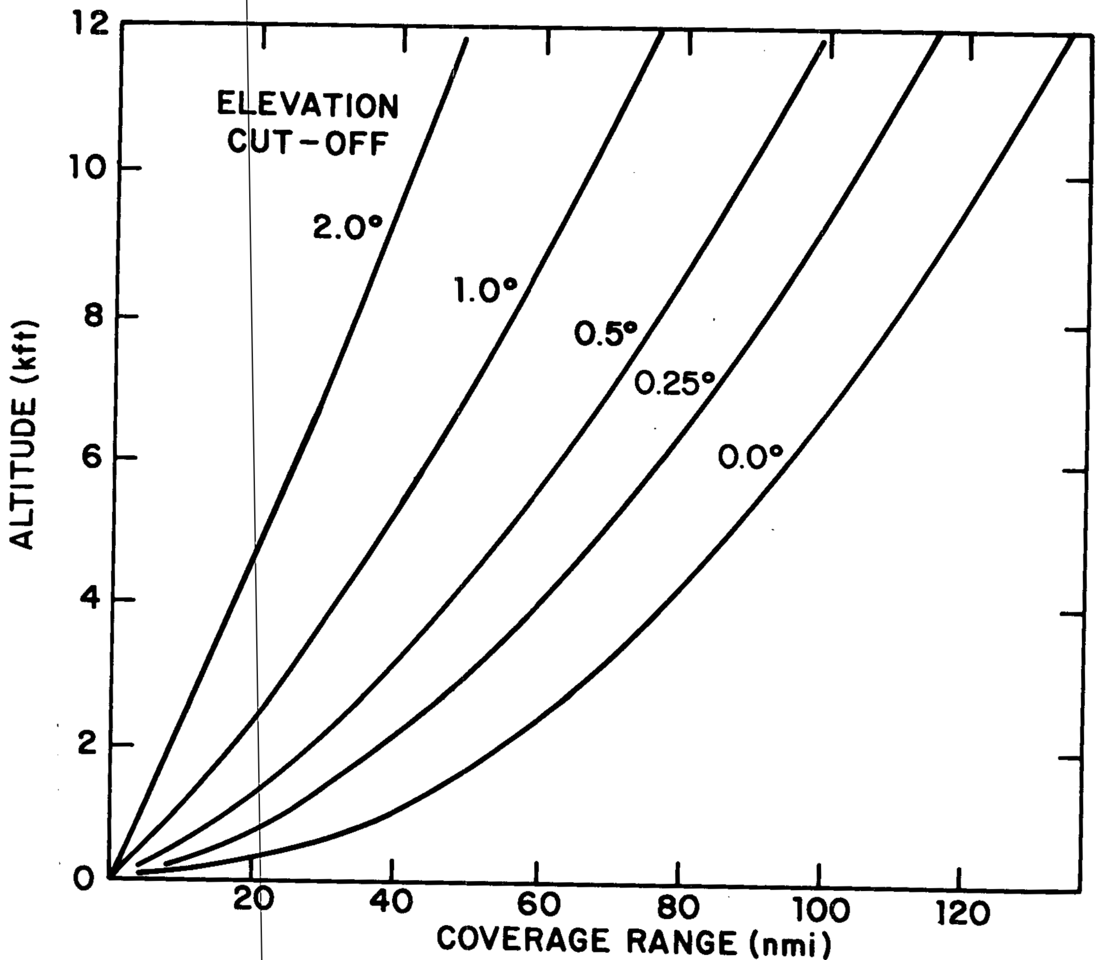


Fig. B.1. Radar coverage altitude versus range from sensor. An elevation cut-off angle of 0.25° was selected for purposes of coverage analysis.

The most extensive coverage level considered involves provision of EFR service by sensors at all 243 current sites in the data base. Figures B.2 through B.5 provide radar coverage maps at altitudes of 4, 6, 8 and 10 kilofeet above ground level (AGL) for such a sensor network. It can be seen that fairly continuous coverage over the eastern United States is achieved for altitudes above approximately 6000 feet. Continuous coverage in southern California is achieved somewhat below 6000 feet. No large regions of continuity are evident for the rest of the country until altitudes of 10000 feet are reached. However it should be recalled that these coverage maps are overly optimistic for the mountainous western areas where terrain blockage has a significant impact upon coverage. Furthermore altitudes of 10000 feet AGL in such regions often correspond to altitudes of 15000 feet MSL or greater. Such flight altitudes are not feasible for most potential EFR aircraft. Hence it appears that EFR service in the mountainous western regions will be impractical using current radar sites.

Because the upgrading of sites for provision of EFR service would probably occur gradually, the coverage provided by smaller numbers of sensors is of interest. In the case of DABS-based EFR service, it is anticipated that EFR would have little influence upon the sites selected for DABS deployment. It is quite possible that the initial deployment of DABS sensors would occur primarily in air traffic hubs in order to provide DABS data link services in the terminal area and in areas of high density. Such terminal sensors would have extensive coverage in en route airspace and could therefore provide EFR services as well. In order to evaluate the coverage of such a network, coverage maps were drawn using sensors located at all 132 small, medium, and large traffic hubs in the data base. It can be seen from Fig. B.6 that at 6000 feet AGL, continuous coverage is provided only along the eastern seaboard and in the mid-west. At an altitude of 8000 feet AGL (Fig. B.7) coverage begins to approach continuity over the eastern United States.

In order to determine the minimum number of sensors required under optimal site selection, a radar network was defined by hand selection from existing sensor sites for maximum coverage without overlap. Approximately 82 sensors were required to provide continuous coverage at 6000 feet AGL over the eastern United States (east of the 100° meridian). At 10,000 feet only 63 sites are required.

The coverage maps presented so far give a feel for the area coverage, but an even more important question is the fraction of traffic which is covered by a given network. Since sensors tend to be located in areas where traffic is densest, the fraction of traffic covered tends to be greater than the fraction of continental airspace covered. Using 1974 data on en route operations, it is estimated that the eastern United States region covered contains approximately 70 per cent of the national en route traffic and that southern California contains about 6 percent. Hence a radar network can serve approximately 76 percent of the potential EFR aircraft even if it is unable to provide service in mountainous Western regions.

Reference

B.1 S.I. Krich, "DABS Coverage", ATC-75, M.I.T. Lincoln Laboratory, 16 August 1977.

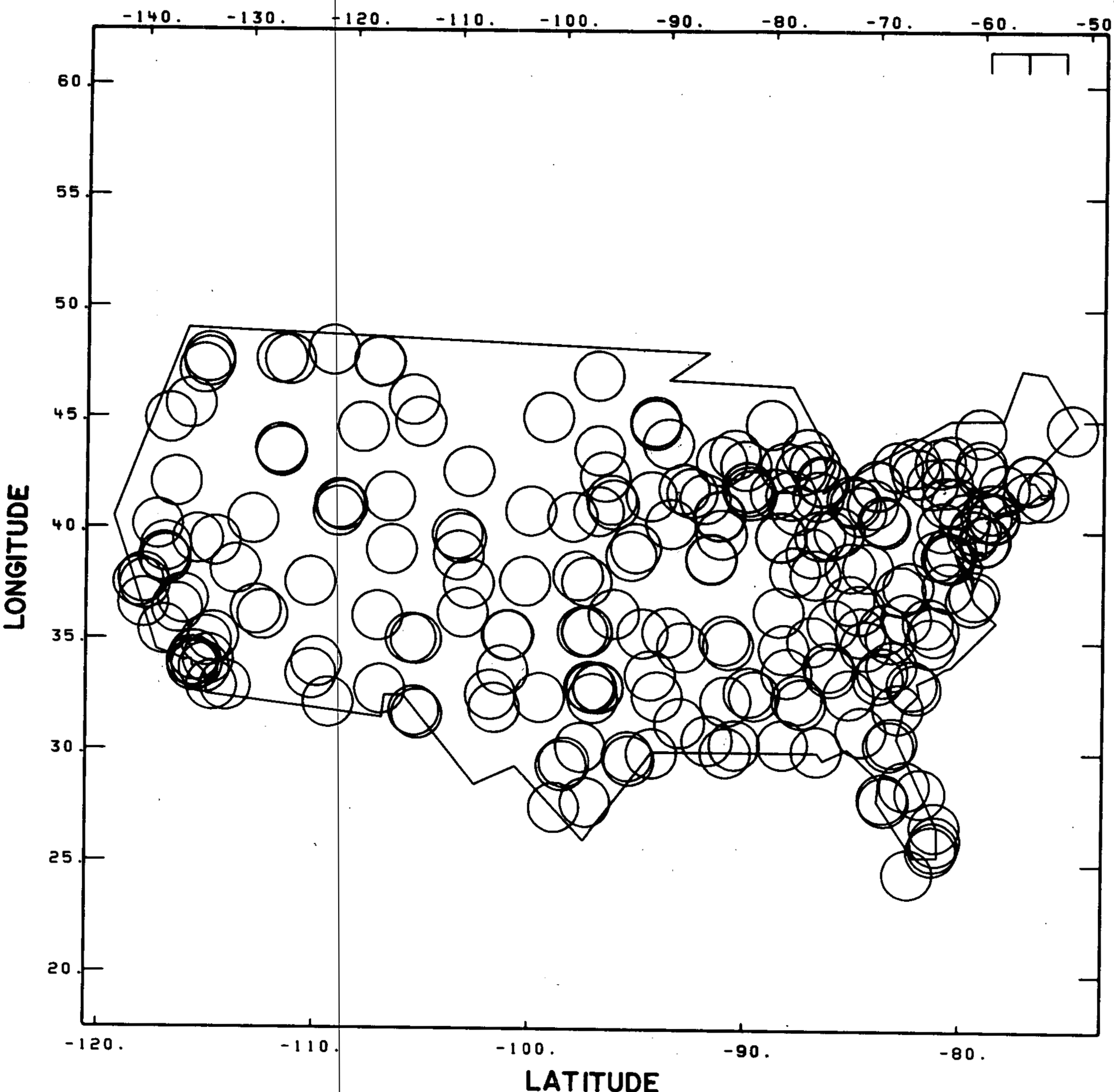


Fig. B.2. Radar coverage at 4000 feet AGL for 243 sensor retwork.

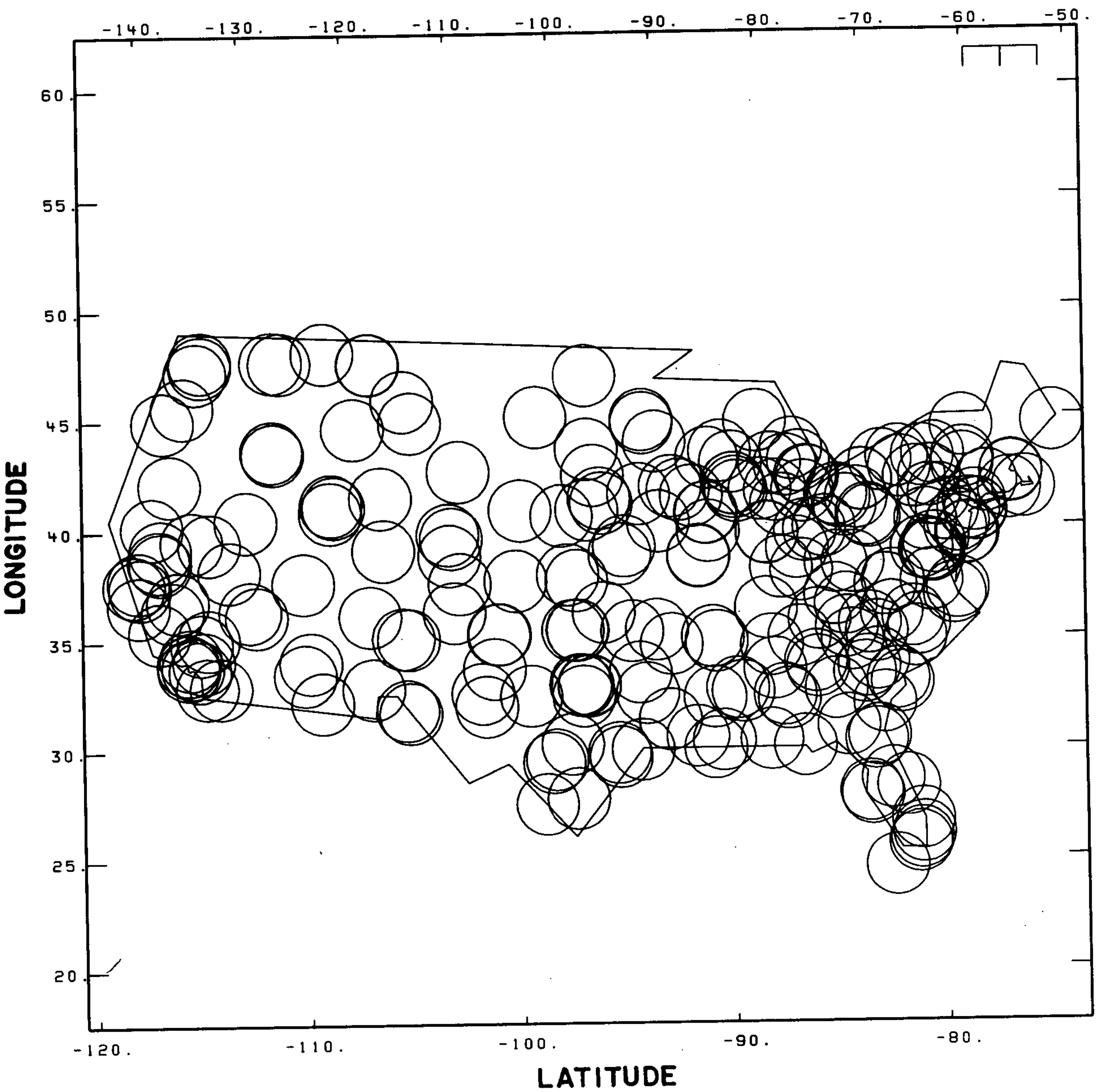


Fig. B.3. Radar coverage at 6000 feet AGL for 243 sensor network.

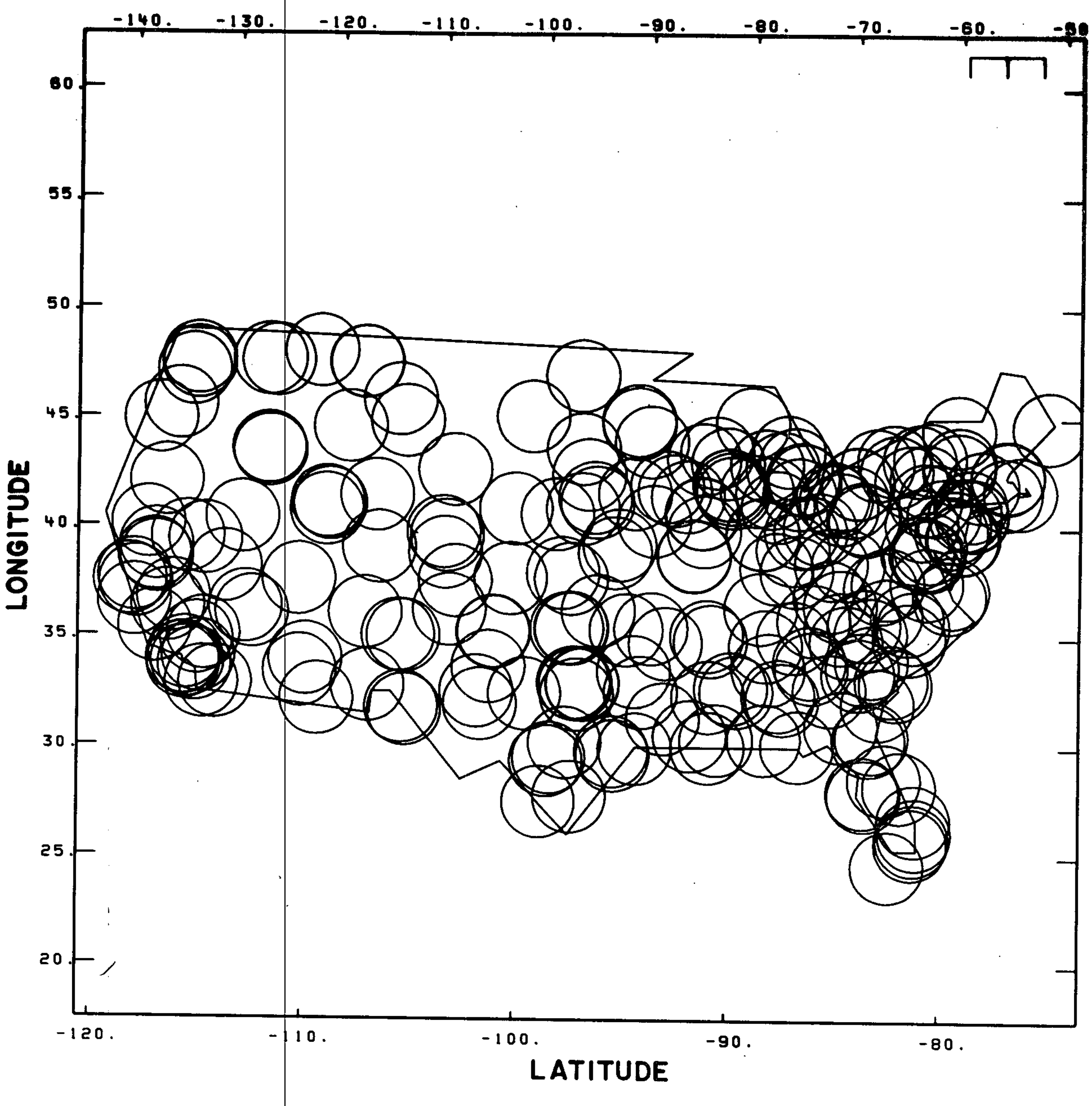


Fig. B.4. Radar coverage at 8000 feet AGL for 243 sensor network.

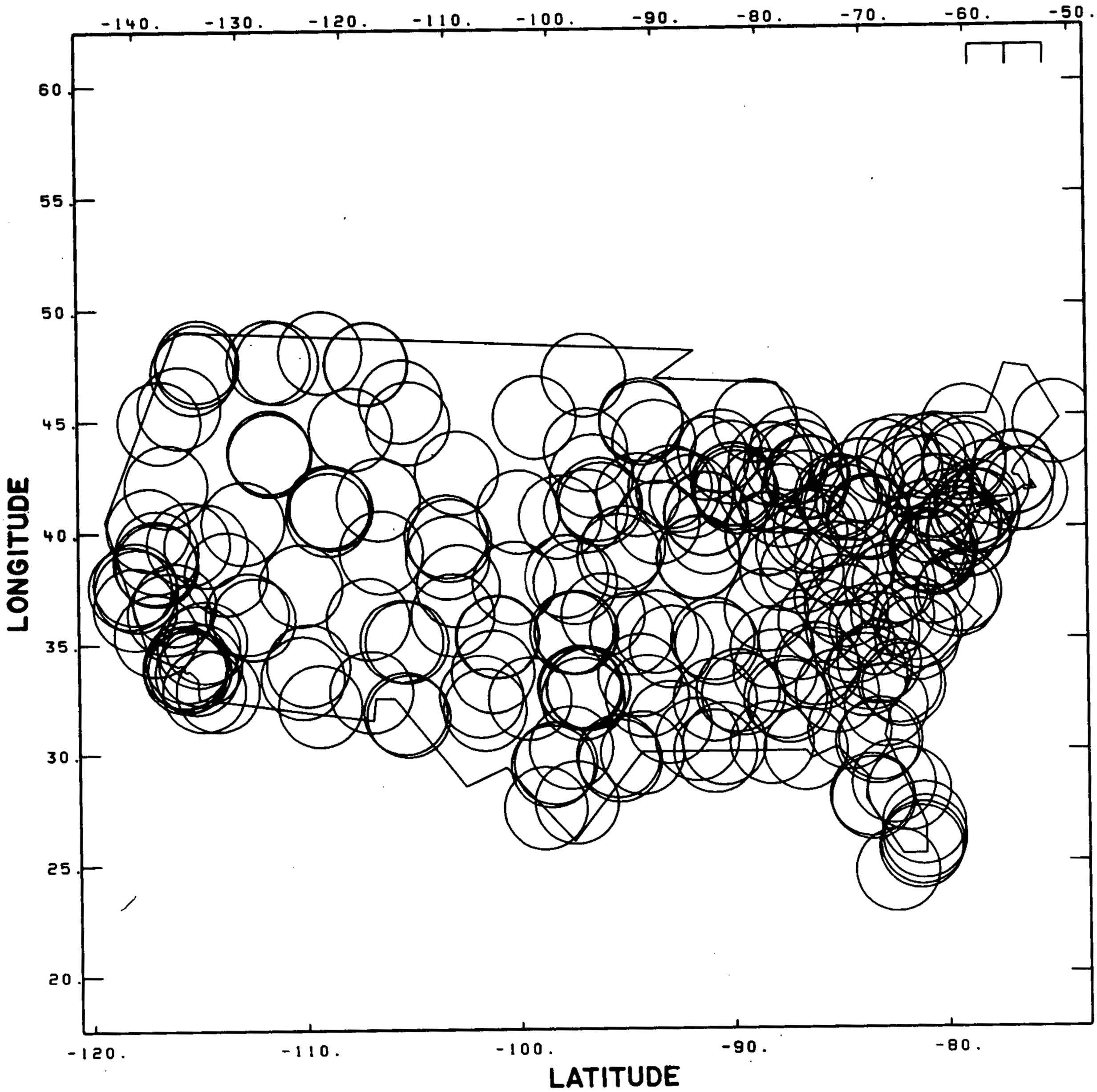


Fig. B.5. Radar coverage at 10000 feet AGL for 243 sensor nerwork.

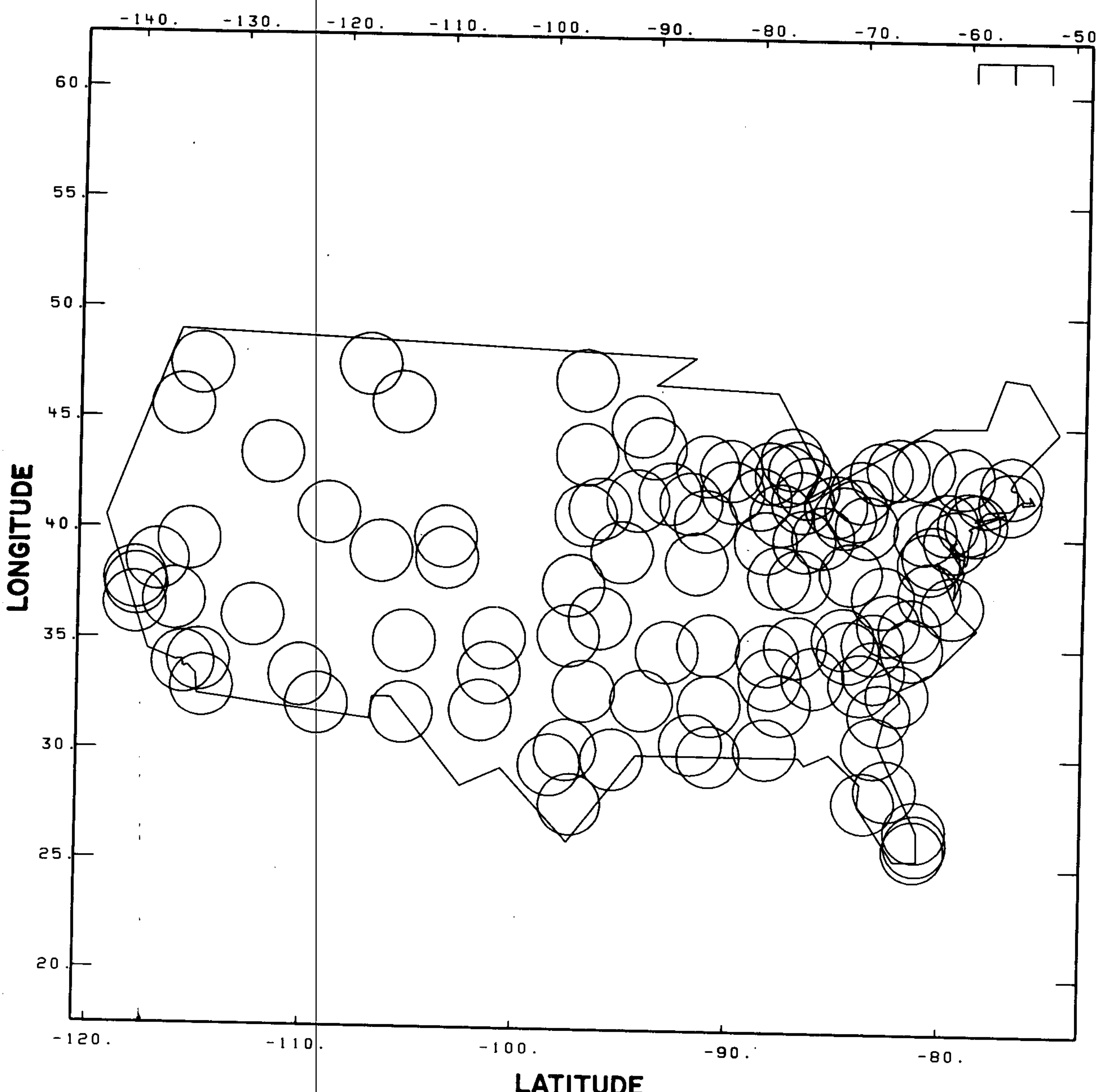


Fig. B.6. Radar coverage at 6000 feet AGL for 113 sensor nerwork.

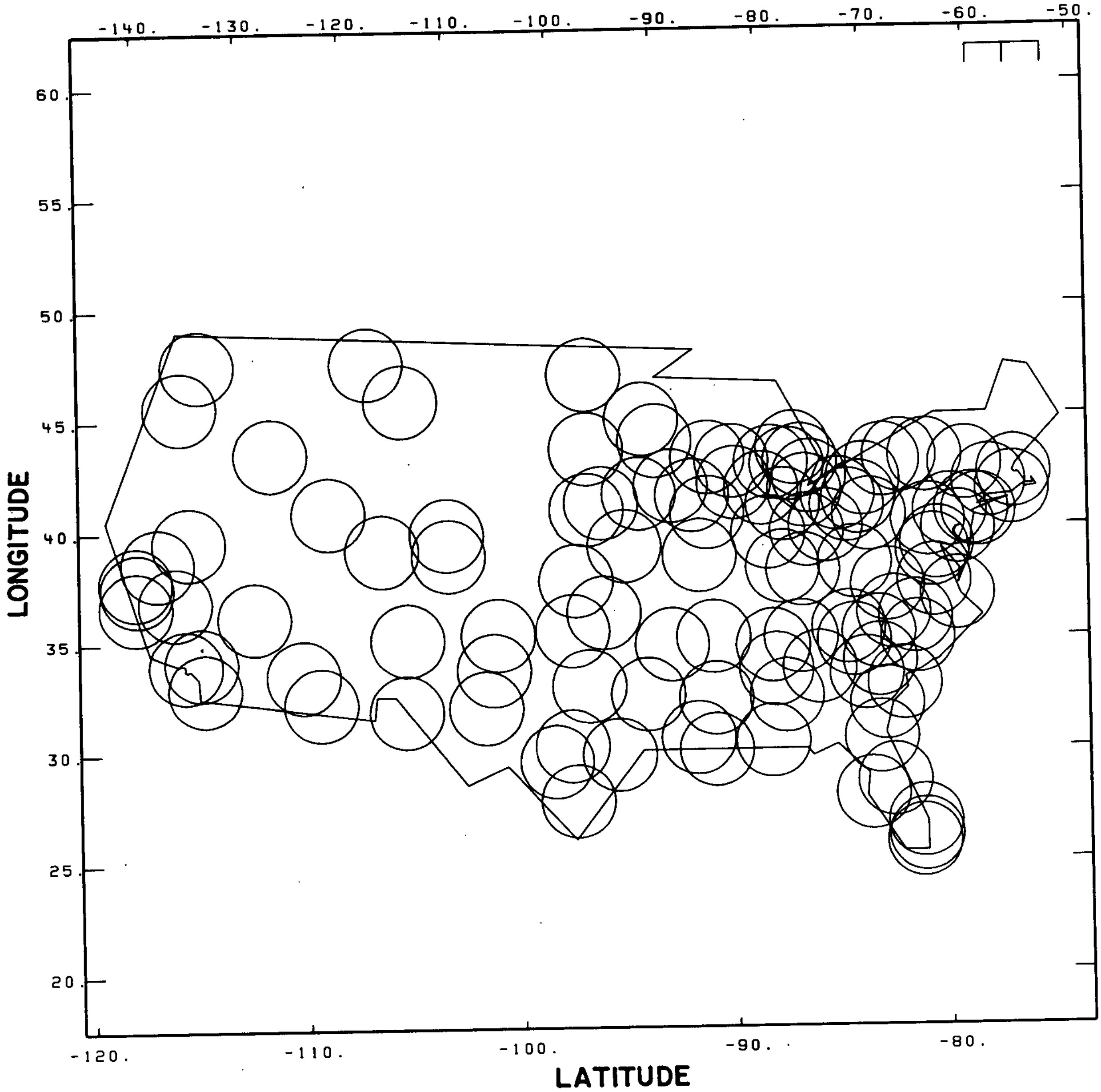


Fig. B.7. Radar coverage at 8000 feet AGL for 113 sensor network.

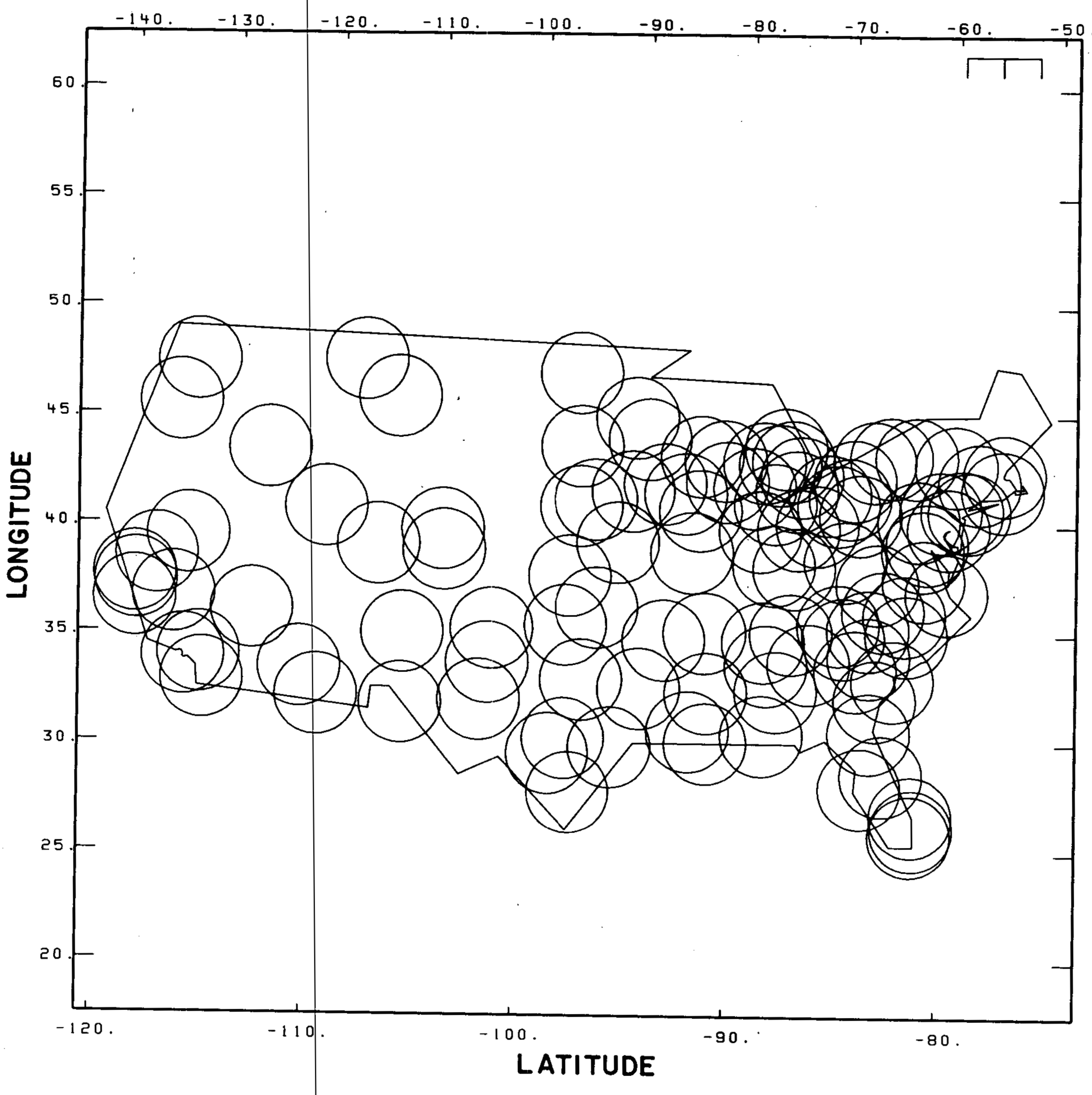


Fig. B.8. Radar coverage at 10000 feet AGL for 113 sensor nerwork.

APPENDIX C

TRAFFIC ENVIRONMENT ANALYSIS

This appendix provides additional data which supplements the traffic environment analysis discussed in section 7.0.

Characteristics of Air Traffic

An understanding of the traffic environment within which an EFR system would operate was pursued in several ways. Traffic data and traffic models from previous studies were reviewed. To provide more detailed data a set of routines were written which produced traffic "snapshots" based upon data recorded by the Transportable Measurement Facility (TMF) at various field sites. Each snapshot contained all available information on each tracked aircraft at a specific instant. Traffic characteristics were analyzed by selecting a large number of tracks and tabulating the distributions of certain track variables. Among the characteristics tabulated were traffic density, ground speeds, altitudes, and altitude rates. Examples of the data output are shown in Figures C.1 through C.7. Figure C.1 is a scatter plot of altitude versus ground speed for 10 different snapshots. An interesting aspect of this plot is the clear speed separation of jet traffic and reciprocating traffic above 7000 feet. The greatest density is at low altitude and low airspeed. Fig. C.2 is a scatter plot of altitude rate versus ground speed. Again there is a clear separation into two speed classes with the greater number at slow speed. The low speed group shows altitude rates that are generally less than 15 fps. The higher speed aircraft show greater altitude rates associated with their higher performance capability. The ratio of altitude rate to ground speed shows that aircraft flight path angles are generally under 6 degrees. Fig. C.3 is a scatter plot of altitude vs. altitude rate. Again it can be seen that the majority of the traffic is at low altitude. A large fraction of the aircraft are climbing and descending at typical rates less than 15 fps.

Observed Densities at Los Angeles

Figure C.4 is a geographic plot of the time-averaged aircraft density observed in square blocks of airspace which measure 5 nmi on a side. The outline approximates the boundary of the Los Angeles TCA at 3000 feet. Los Angeles International Airport lies between the two TCA segments. It can be seen the highest aircraft densities lie outside the TCA. It is generally observed that peak densities occur near busy general aviation airports situated along the edge and under the floor of the TCA. The majority of these aircraft are operating VFR. In Fig. C.4 the highest densities are along the southern border of the TCA with peaks near Compton and Long Beach Airports. The density can be seen to fall off rapidly with distance away from the peak areas.

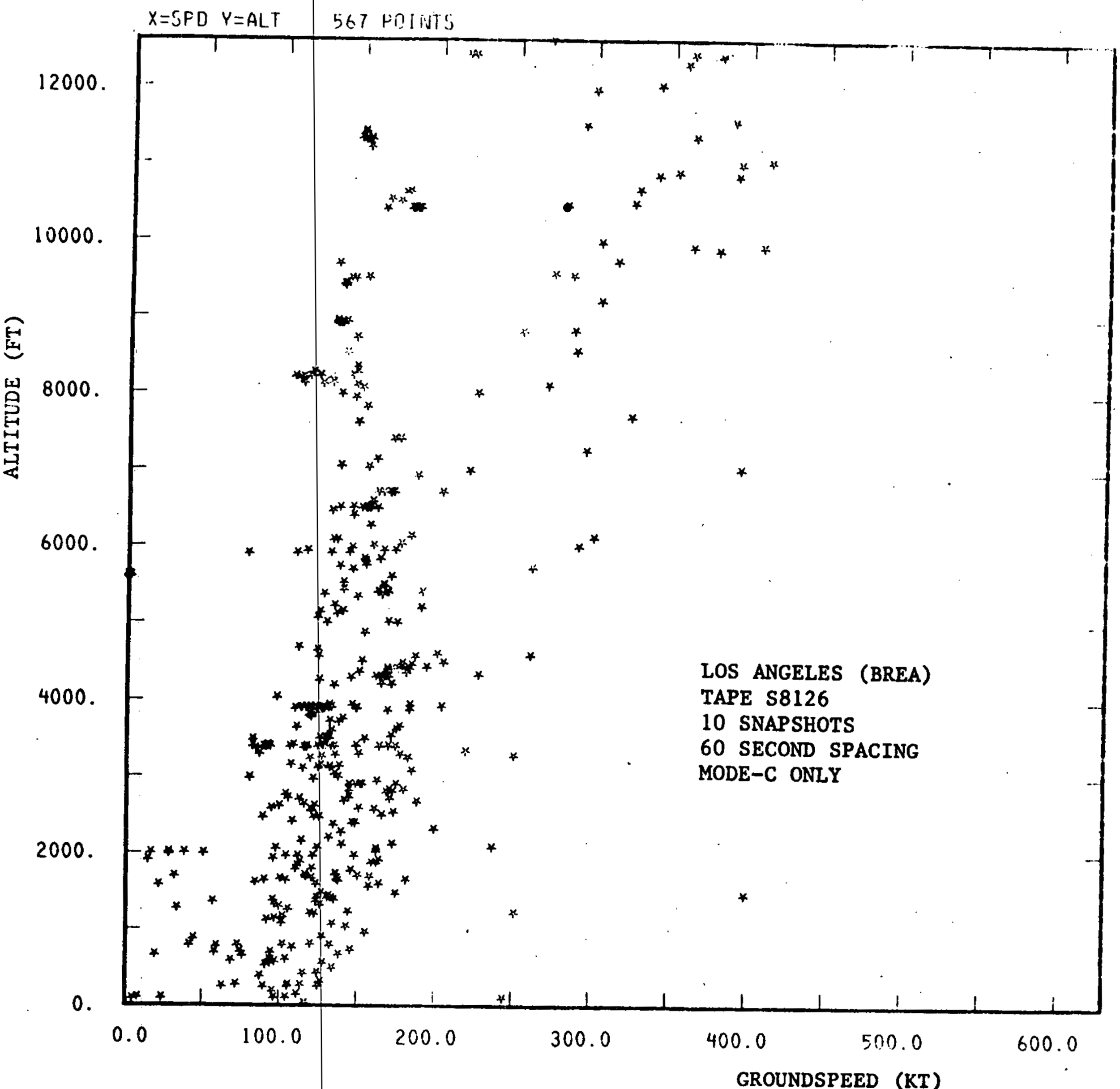


Fig. C.1. Altitude versus groundspeed for mode-C reporting aircraft observed by sensor near Los Angeles (Brea). The plot combines data from 10 snapshots spaced at 60 second intervals.

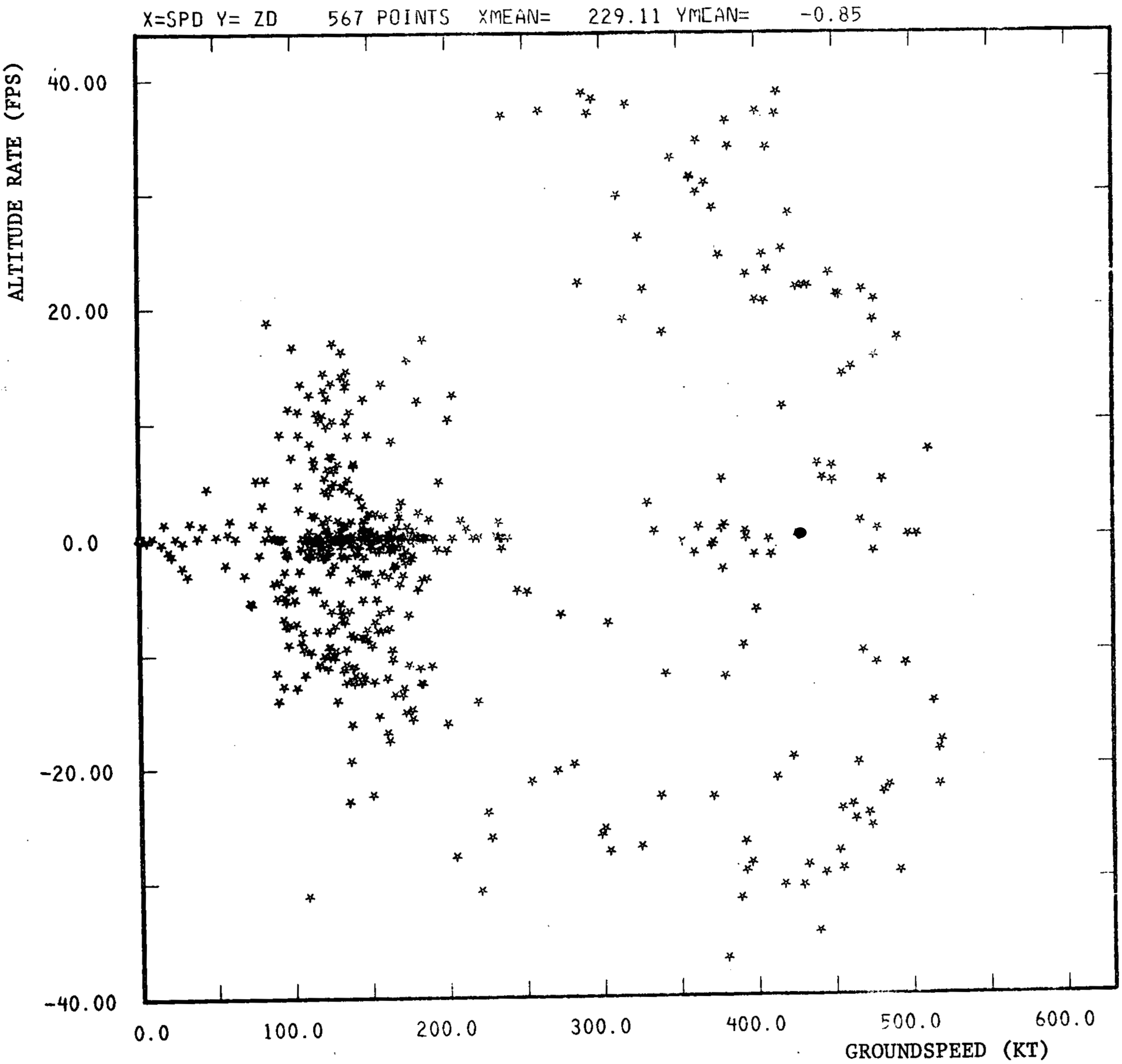


Fig. C.2. Altitude rate versus groundspeed for Mode-C reporting aircraft observed by sensor near Los Angeles (Brea). The plot combines data from 10 snapshots spaced at 60 second intervals.

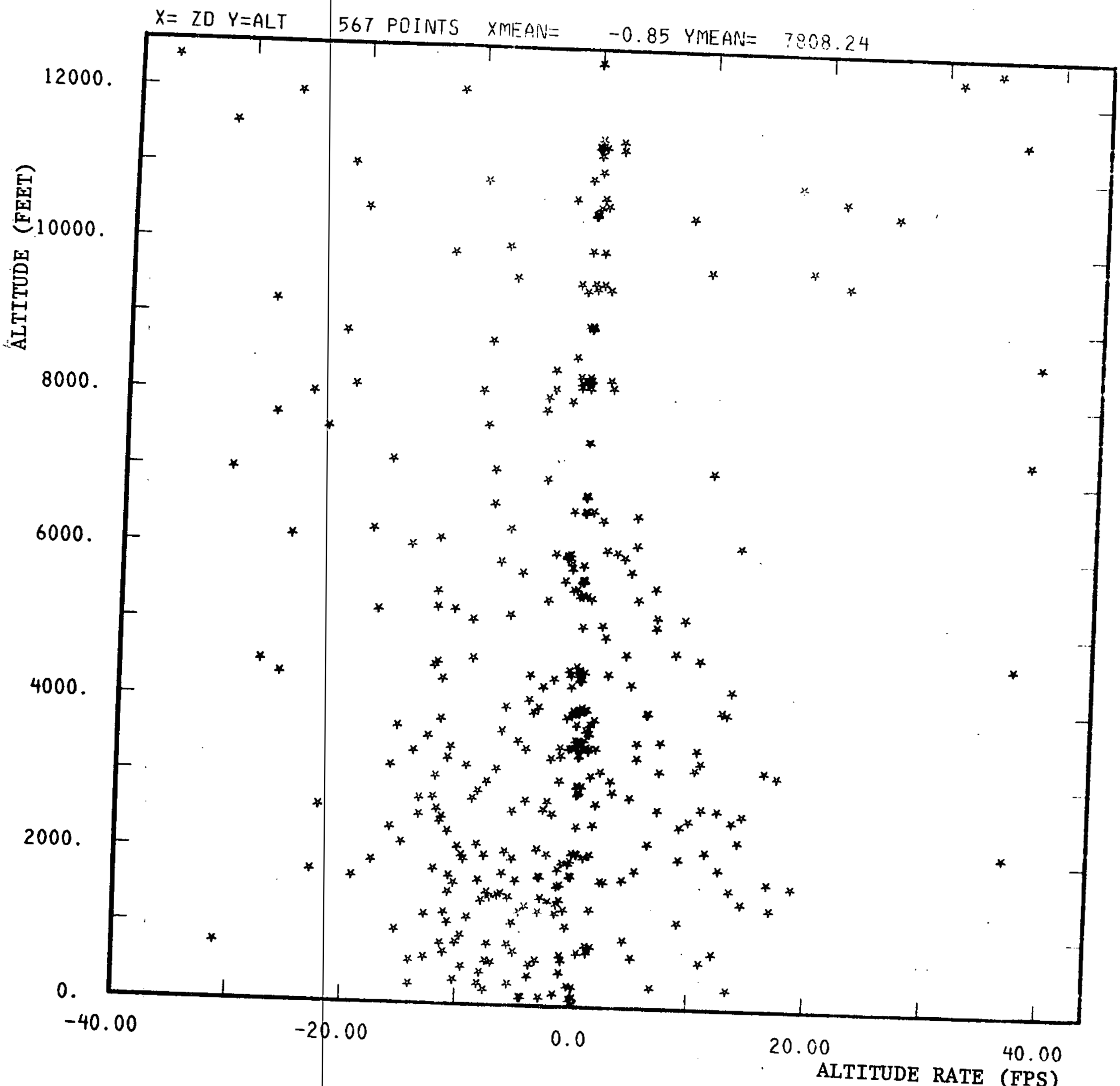


Fig. C.3. Altitude versus altitude rate for Mode-C reporting aircraft observed by sensor near Los Angeles (Brea). The plot combines data from 10 snapshots spaced at 60 second intervals.

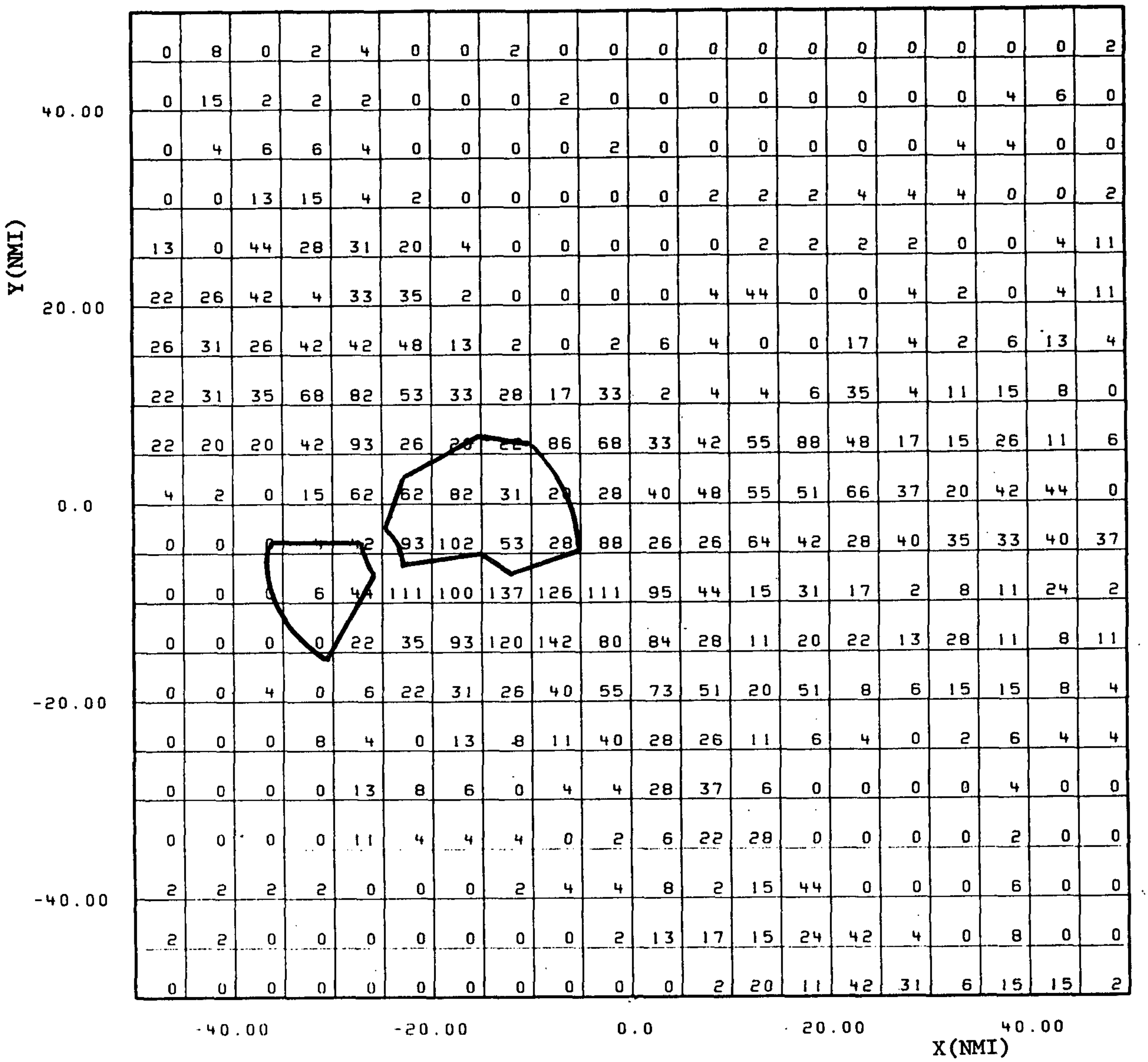


Fig. C.4. Aircraft density (aircraft per 1000 nmi^2) observed by sensor near Los Angeles (Brea). The outline approximates the Los Angeles TCA boundary at 3000 feet.

C.1. Traffic Density Around Hubs

Traffic density is defined to be the number of aircraft per unit area averaged with respect to time during peak traffic conditions. Peak traffic densities normally occur when weather satisfies visual meteorological conditions (VMC). The highest traffic densities are observed around major hubs. The density shows localized peaks in the vicinity of individual airports. The number of secondary airports and the traffic density associated with them tends to fall off as distance from the major airport increases. On a larger scale the traffic density generated by the complex of airports generally fits a model for which density decreases exponentially with range:

$$\rho = \rho_o \exp[-r/R] \qquad \text{(C.1)}$$

where ρ = aircraft density
ρ_o = aircraft density at major airport
r = radial distance from major airport
R = characteristic distance for exponential distribution

Figure C.5 - C.7 show an exponential fit to TMF data taken in 1976 at Los Angeles, Washington and Philadelphia. The data was obtained by counting the number of aircraft in bins 5 nmi on a side and averaging the density obtained for all bins of a common radial distance. The characteristic distance is between 20 and 30 nmi. Because the data has a reasonable fit to an exponential density model it is worth looking at that model in more detail. The total airborne count, N, inside the radial distance, r, can be found by integrating the density to obtain:

$$N = N_o \left[1 - \left(1 + \frac{r}{R}\right) \exp(-r/R)\right] \qquad \text{(C.2)}$$

where N_o = total airborne count associated with the hub = $2\pi\rho_o R^2$

Fig. C-8 gives a plot of δ, N, and dN/DR for exponental traffic. For those tracks that lead radially in and out of the hub the associated density falls off inversely with the radial distance so long as the number of aircraft on the track remains uniformly distributed. For this kind of track the derivative of the airborne count with respect to radial distance, dN/dr, would be constant. The magnitude of dN/dr can be interpreted as the inverse of the spacing which would result if all the traffic were to be metered for landing on a single runway at the origin.

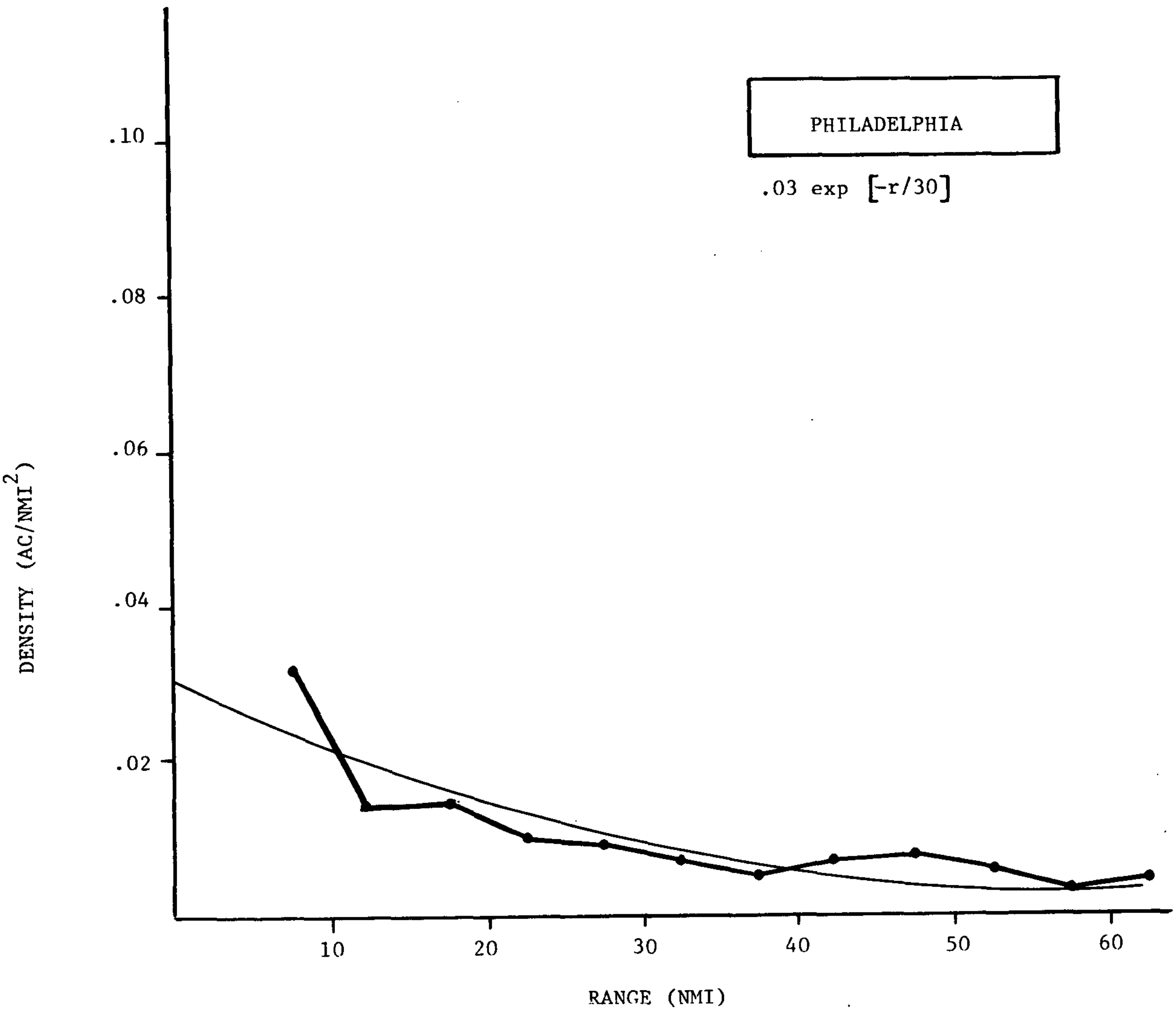


Fig. C.5. Exponential fit to TMF traffic data at Philadelphia.

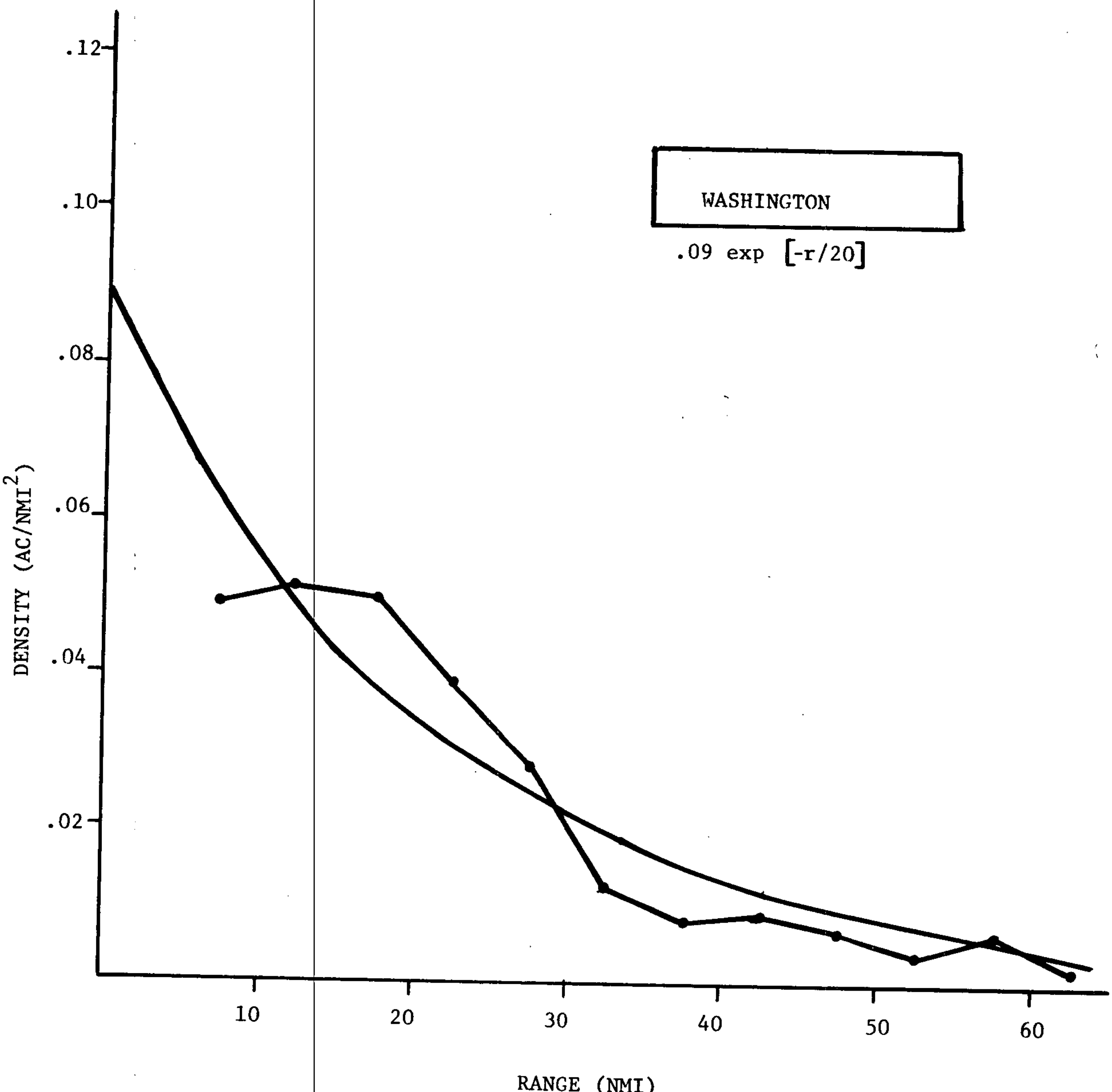


Fig. C.6. Exponential fit to TMF traffic data at Washington.

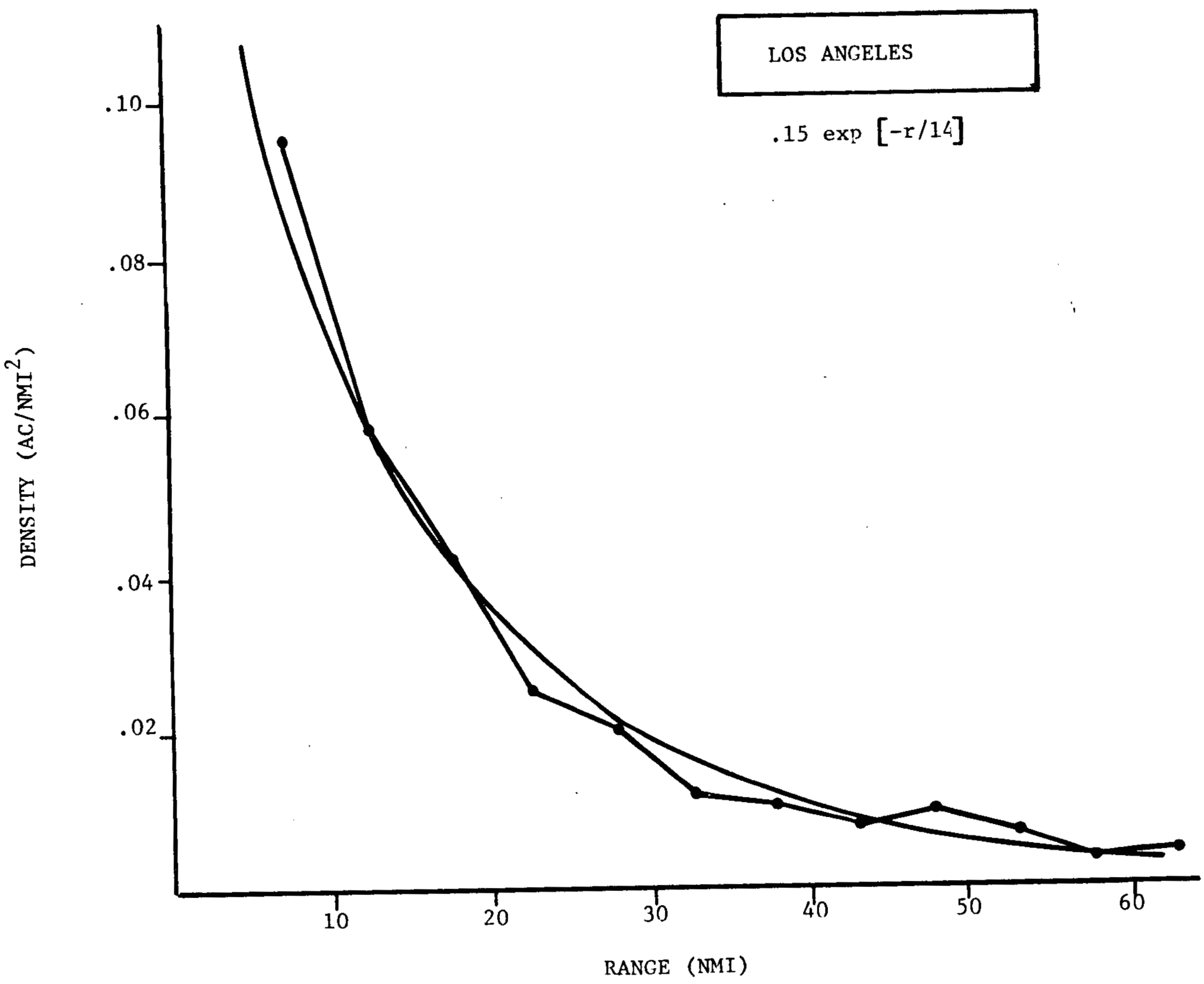


Fig. C.7. Exponential fit to TMF traffic data at Los Angeles.

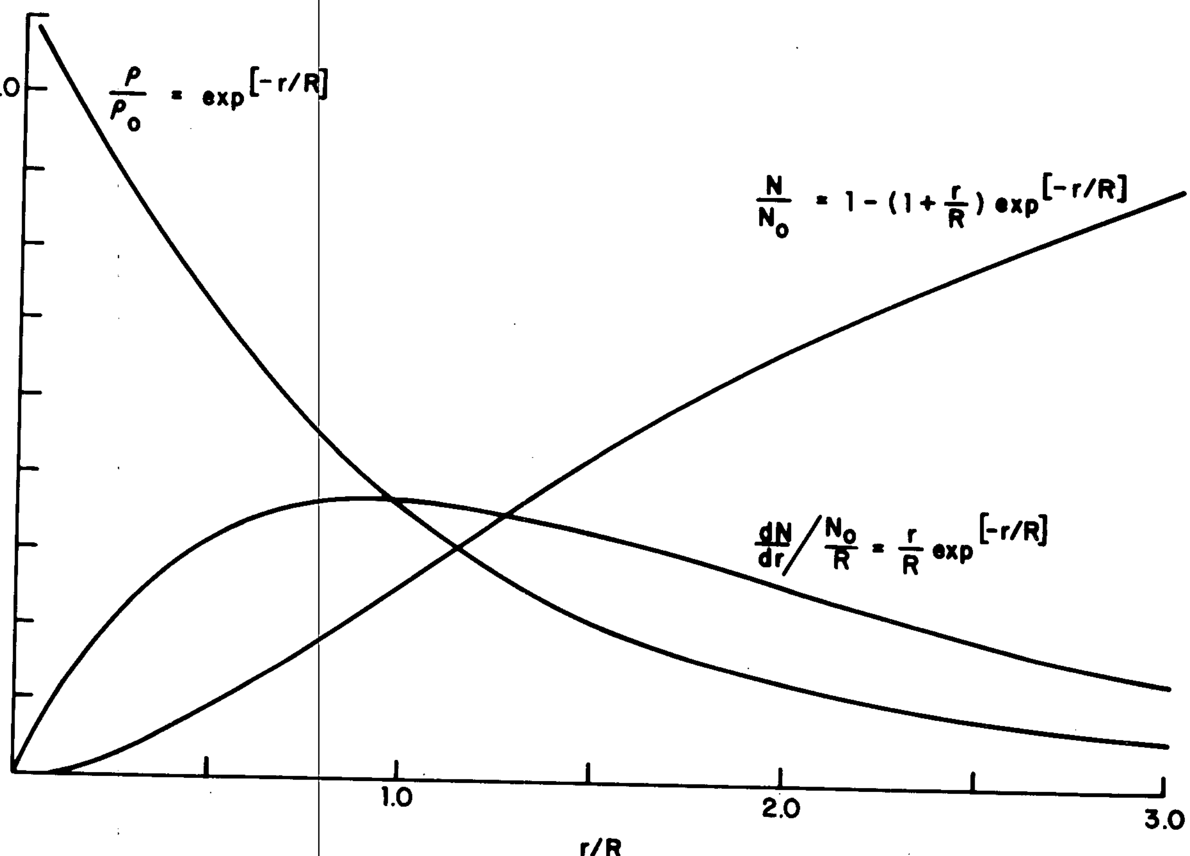


Fig. C.8. Relationship of major parameters characterizing an exponential traffic distribution.

18-4-14808

	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10
10							5	3	3	3	3	3	3	4						
9					3	3	5	3	3	3	4	3	3	5	31	5				
8					3	3	3	5	3	3	3	3	5	33	22	5				
7			3	3	3	3	4	6	3	3	3	5	33	42	33	5	4	4		
6			3	3	5	3	4	5	3	3	3	4	31	33	22	5	4	3		
5		3	3	4	3	3	4	4	4	3	7	17	1	5	5	4	5	3	3	
4	3	3	4	4	3	3	16	22	7	7	1	16	8	11	5	5	4	3	3	4
3	3	4	3	4	3	8	1	13	23	11	14	8	14	2	1	5	5	3	5	4
2	3	4	3	4	3	11	18	12	38	63	27	13	6	6	6	5	5	5	5	4
1	4	4	4	4	4	7	7	49	67	72	59	33	13	13	9	5	5	4	4	3
-1	5	7	7	7	10	13	21	27	21	47	31	0	1	6	3	3	3	3	3	3
-2	5	7	7	7	10	12	18	30	8	19	10	10	6	3	1	3	3	3	3	3
-3	5	7	7	7	5	27	36	27	13	3	17	0	0							
-4	5	5	5	9	5	13	28	26	6	3	8	5	0							
-5		10	18	18	10	41	5	6	1	1	11	11		1						
-6			36	36	18	9	5	4	3	3	2	3			1					
-7			36	36	18	5	4	3	4	3	2	3				0				
-8					10	4	3	4	4	3	2	3								
-9					4	4	3	3	3	3	2	3								
-10							3	4	3	3	2	3								

N

20 NMI

B BOSTON
N NEW YORK
P PHILADELPHIA
W WASHINGTON

Fig. C.9. Predicted distribution of aircraft within 200 nautical miles of New York in 1982. Quantity shown in each 200-nmi square is "peak instantaneous aircraft count" (PIAC).

The contribution, $\Delta\rho$, to the density at distance, r, by itinerant traffic in and out of a runway at the central terminal is given by:

$$\Delta\rho = \frac{1}{2\pi r} \Delta \left(\frac{dN}{dr}\right) \quad \text{(C.3)}$$

As an example, a saturated runway using 3 nmi spacing on landing with equal number of takeoffs contributes:

$$\Delta \frac{dN}{dr} = 0.67 \text{ aircraft/nmi}$$

The contribution to the density at r = 20 nmi is $\Delta\rho$ = 0.005 aircraft/nmi^2. It can be seen that even a very busy airport (about 80 operations/hour for the example above) does not contribute heavily to the density at 20 nmi from that airport.

In summary, for traffic around a typical hub the density tends to fall off exponentially with radial distance. The highest densities near the hub center are due more to the presence of several close-in airports than to the hub terminal itself. VFR aircraft provide the major contribution to density. These densities have their peaks at low altitude near general aviation airports located outside and under the TCA boundaries.

In the real world a single hub is not isolated and other nearby hubs may contribute to the surrounding traffic density. A complete model may also allow for a small, more or less constant background density due to random overflights. Fig. C.9 shows a predicted traffic distribution for the Northeast Corridor in 1982 (Ref. C.1). While each of the major hubs shows approximate exponential density with respect to radius the two dimensional distribution shows the composite effect along the corridor as well as a background density of about 0.007 aircraft/nmi^2.

Reference

C.1 "Development of a Discrete Address Beacon System", Quarterly Technical Summary, FAA-RD-72-117, 1 October 1972.

APPENDIX D

DESCRIPTION OF AN EFR CONTROL ALGORITHM

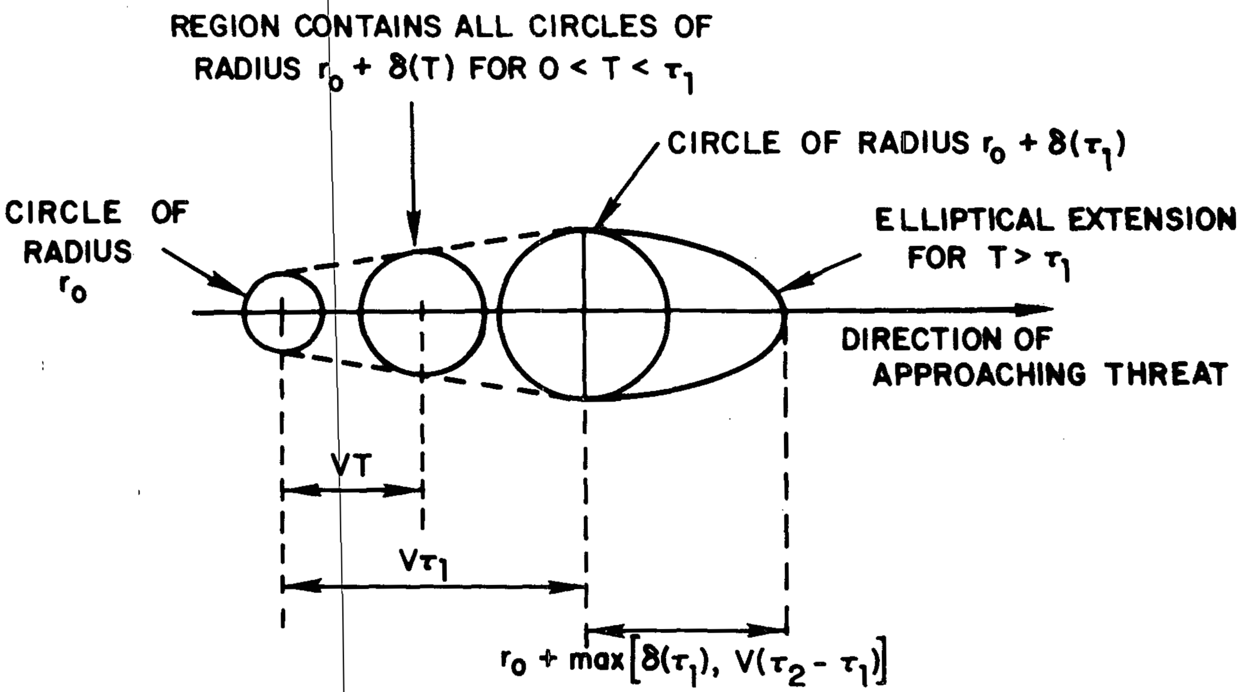
The decision-making process can be divided into the following areas: detection, resolution, monitoring, and termination. Detection involves the decision that some type of resolution instructions should be issued. Resolution involves the initial selection of resolution instructions. Monitoring involves the monitoring of the progress of resolution and the altering, if necessary, of the instructions. Termination involves the decision that control instructions are no longer required. Each of these functional areas is discussed in further detail in the following sections.

D.1 Detection

The goal of the detection logic is to initiate resolution in sufficient time for success, but to avoid, insofar as possible, initiating resolution when separation standards will not be violated. Because future flight paths of aircraft are uncertain, the actual lead times provided by a given detection logic vary from encounter to encounter. In a system such as EFR, longer lead times are desired for purposes of resolution efficiency. It is not necessary to provide this extended lead time under worst case threat accelerations since such accelerations occur with a frequency small enough to have little impact upon average system efficiency. However, worst case accelerations will have a significant impact upon the system safety level if they cannot be accommodated. With these factors in mind, the detection region for the EFR algorithm was "shaped" to meet two lead time threshold requirements. In the event of unaccelerated flight (the expected situation) the detection logic provides a lead time of τ_2 seconds (before violation of separation standards can occur). In the event of worst case acceleration, the detection criteria provides a lead time of τ_1 seconds (where $\tau_1 < \tau_2$). The nominal values of these parameters used in simulation studies were $\tau_1 = 40$ seconds and $\tau_2 = 60$ seconds. The shape of the resulting horizontal detection region is portrayed in Figure D.1.

The alarm rate which results from these criteria is roughly proportional to the width of the alarm region. Hence the alarm rate is dependent primarily upon r_o, τ_1, and the assumed acceleration capability of the aircraft. The τ_2 parameter provides additional resolution time in the nominal (unaccelerated) encounter while contributing little to the total alarm rate.

Vertical detection relied upon a test which determined: 1) if aircraft altitude separation is currently less than parameter z_o, 2) if existing altitude rates will result in altitude separation less than z_o within time τ_2, or 3) if changes in altitude rates of ±1000 fpm for either aircraft could result in an altitude separation of less than z_o within time τ_2.



r_0 = SEPARATION STANDARD (HORIZONTAL)

T = LEAD TIME

V = RELATIVE SPEED OF THREAT

τ_1, τ_2 = LEAD TIME PARAMETERS

$\delta(T)$ = BOUND UPON DEVIATION FROM RECTILINEAR FLIGHT DUE TO ACCELERATION OVER A TIME T

Fig. D.1. Alarm region for detection.

Return-to-Course Provisions. The EFR algorithm shall maneuver aircraft only to the extent necessary to achieve desired separation standards. In many cases it is possible to relax constraints upon aircraft as the encounter progresses toward a successful conclusion. This relaxation minimizes the required deviation from course. In actual systems the desirability of this relaxation must be considered in light of the potential additional workload which would result from altering instructions. In the test algorithm, the logic modifies horizontal commands when it is possible to allow aircraft to return to their original (pre-resolution) headings. The simulated aircraft return to their original headings as soon as it is allowed.

D.2 Resolution

As discussed in section 8.0, the choice of the discrete resolution option to be issued is dependent upon the cost function evaluation. The cost associated with each option is the sum of a number of independent cost terms. The cost term approach to algorithmic design yields a logic structure in which each term evaluation is performed by a separate, independent cost term module. The number of cost terms required depends upon the number of independent considerations which the logic must take into account in order to select the proper resolution option. No significance is attached to the absolute value of cost terms - their values are used only to establish the relative desirability of the command options. The following paragraphs discuss the manner in which specific cost terms were implemented.

a. Separation Hazard Term (Horizontal). The expected separation at closest approach which would result from implementing the option under consideration is determined. An error variance for this separation is derived by assuming linear propagation through time of a normally-distributed velocity error. The probability, PF, that the separation at closest approach will be less than some minimum safe distance AMDMIN is then computed. AMDMIN, the minimum distance which assumes separation, was assigned a value of 1500 feet. The value of the cost term is then defined as:

$$C_1 = 1000 \text{ PF}$$

It should be noted that the resolution option with the greatest projected separation is not necessarily the option which is safest since safety is also influenced by the error in the expected separation. The size of the uncertainty depends upon the time required to reach closest approach. A further refinement might allow the error to depend upon the orientation of the closest approach separation relative to the radar line-of-sight (to account for the non-isotropic nature of radar tracking).

b. Separation Standard Term (Horizontal). This term is intended to penalize options for which the issued instructions are insufficient to achieve the desired separation standard. Let the expected separation at closest approach be CPA. The value of the term is then:

$$
\begin{cases} 0, & CPA \geq r_o \\ 4 + 6\, r_o/CPA, & CPA < r_o \end{cases}
$$

c. Control Cost Term (Horizontal). This control term penalizes options according to the extent to which they are expected to prevent aircraft from following desired flight paths or to intrude upon normal flight conduct. Since such costs accrue independently to each aircraft, the final cost term is a sum of the costs to the individual aircraft. The cost term is defined as a function of two variables which must be computed for each aircraft.

The first variable is related to the required deviation from projected flight path. The projected flight path (based upon continued flight at current heading, speed, and altitude rate) represents the most likely intended path of the aircraft. A resolution option is penalized according to the deviation it requires from this trajectory. The deviation is derived by first computing the projected distance at the time commands will terminate between the aircraft position without resolution and the aircraft position with resolution. This distance is then converted into seconds of flight, t_1, by dividing by the aircraft speed (see Fig. D.2). Note that both longitudinal and lateral deviation contribute to this time.

A second variable is required to account for the fact that the projected flight path may not be the desired one. This is especially significant if an aircraft wishes to make a course change which is precluded by resolution instructions. From the vantage point of the algorithm, course changes are events which occur at random. The longer an aircraft is constrained, the greater is the expected deviation of the projected course from the course actually desired. The expected deviation (in seconds of flight) can be written as a function of the length of time an aircraft is kept under control, t_2. By making the cost term increase with t_2, a resolution option which requires no deviation from projected course (e.g., which involves only a "don't turn" instruction) will still be penalized according to the expected disruption it might cause.

The portion of the control cost term for an aircraft can now be defined as a function of the variables t_1 (deviation from projected course) and t_2 (time under control). In order to provide flexibility in the weighting of these two variables, the expression defining the cost term is written as a general quadratic in t_1 and t_2:

$$
\text{cost} = a_o + a_1 t_1 + a_2 (t_1)^2 + a_3 t_1 t_2 + a_4 (t_2)^2 + a_5 t_2
$$

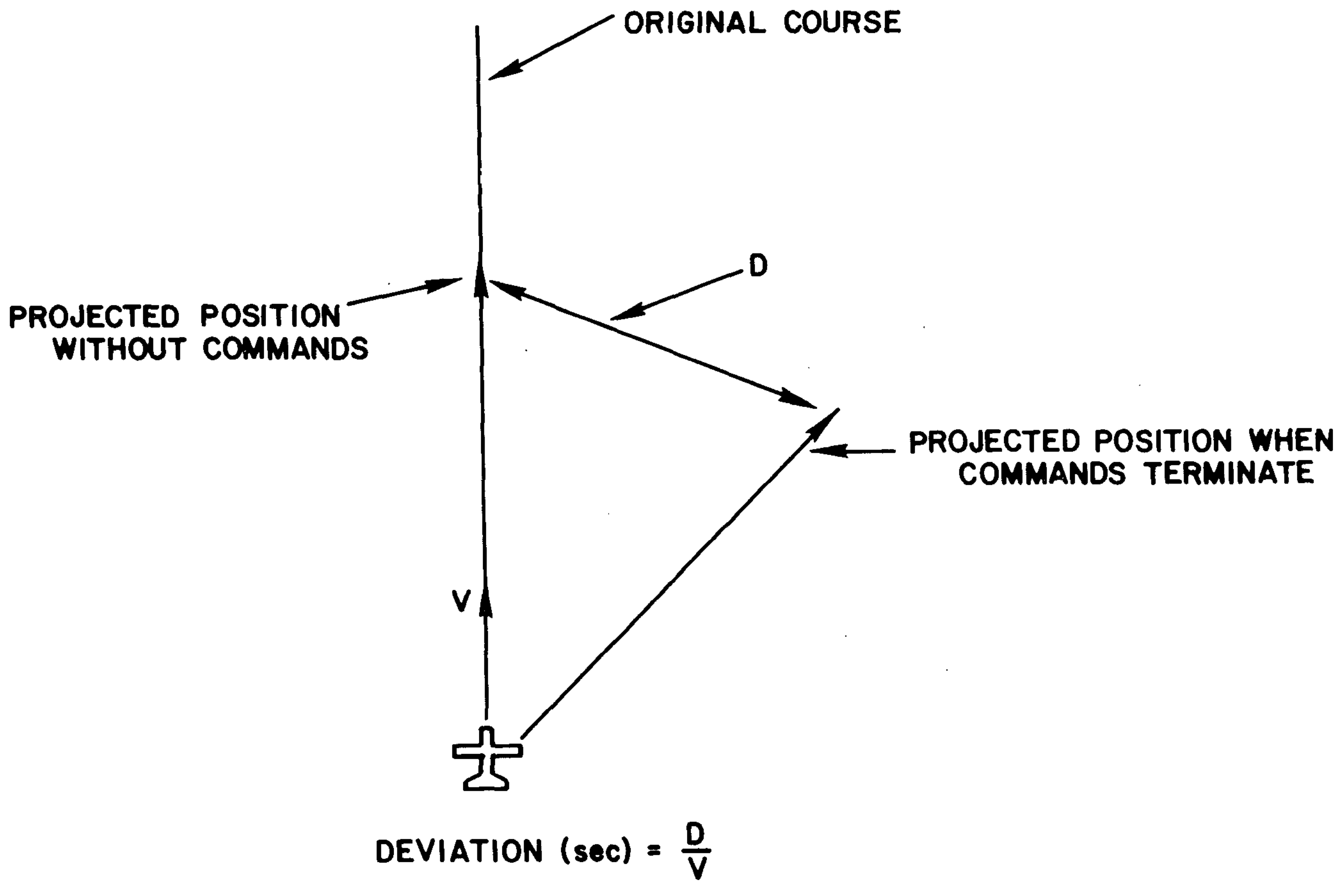


Fig. D.2. Definition of deviation from course.

The term a_o can be set to a non-zero value in order to reflect a cost incurred due to workload involved in reading any command. This would allow a "no command" option to be included as a possibility in the evaluation.

Figure D.3 is a plot of the cost contours for the cost term function utilized in the simulation of the EFR logic. Note that at a typical operating point, $(t_1,t_2) = (20, 75)$, 50 seconds of additional control time is equal in cost to approximately 18 additional seconds of deviation time.

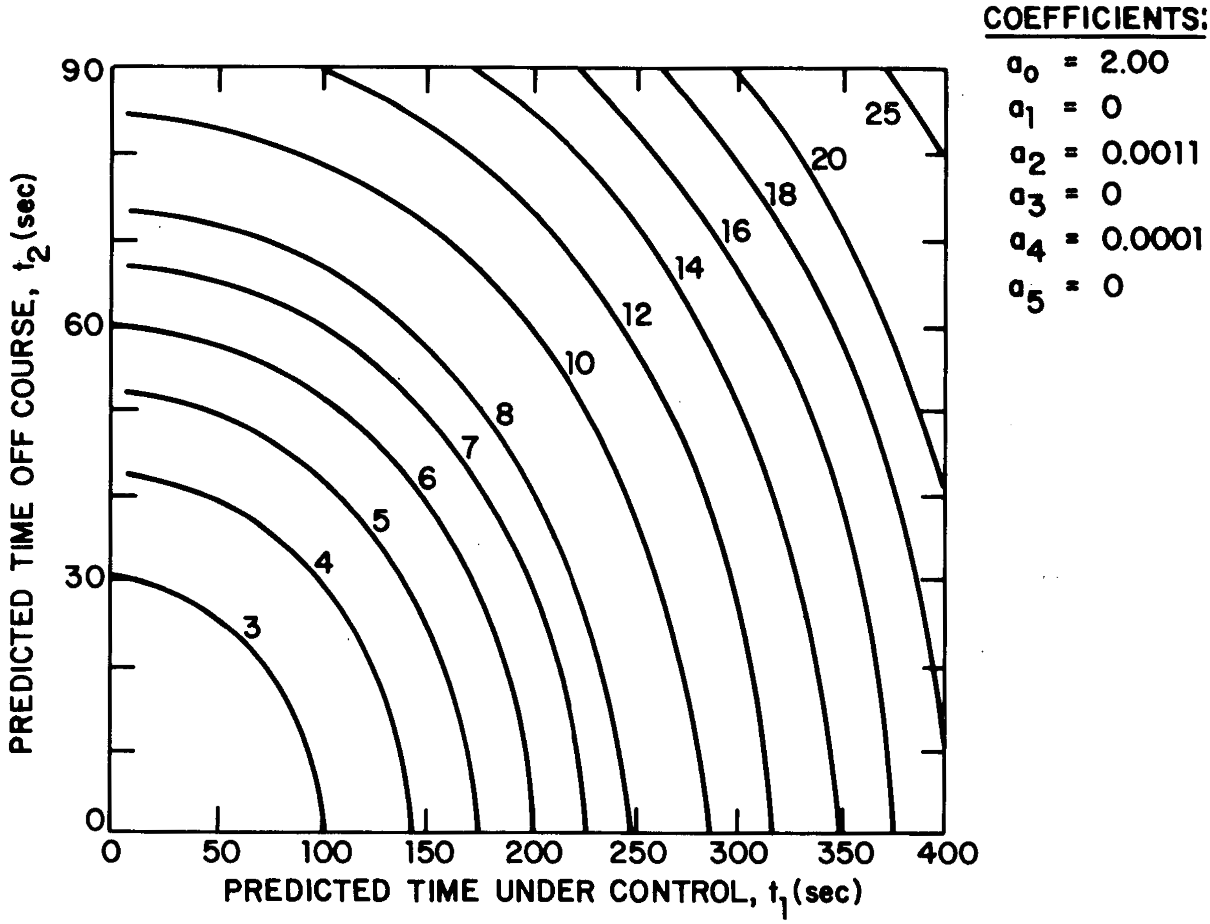


Fig. D.3. Contours of control cost.