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System Safety Study of Minimum TCAS II for Instrument Weather Conditions

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<p>16. Abstract</p> <p>An analysis of the air traffic environment in Instrument Meteorological Conditions (IMC) was conducted to identify those characteristics that have an impact on the level of safety provided by the Traffic Alert and Collision Avoidance System (Minimum TCAS II), and that differ from those characteristics under the more predominant visual conditions. The characteristics assessed include the fraction of aircraft equipped with altitude reporting transponders, the proximity of aircraft operating in these conditions, and the nature of the aircraft maneuvers. The study also extends the analysis of the level of safety provided by TCAS to include interactions with the air traffic control system. Interactions assessed include the compatibility of TCAS maneuvers with the ATC system and the potential for a "domino effect" wherein a TCAS advisory might create a new conflict.</p>			
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EXECUTIVE SUMMARY

1. Introduction

This report documents a study of the Minimum Traffic Alert and Collision Avoidance System (Minimum TCAS II, or simply "TCAS") for Instrument Meteorological Conditions (IMC). The study examines TCAS effectiveness specifically in the IMC environment; also, since air traffic control in IMC relies heavily on Instrument Flight Rules (IFR) procedures, it examines TCAS interactions with the IFR system. The study is a follow-up to the System Safety Study of Minimum TCAS II (Reference 1), which examined the effectiveness of TCAS in all weather conditions as they occur, which turns out to be mostly Visual Meteorological Conditions (VMC).

The overall System Safety Study showed that with today's level of transponder and Mode C equipment, TCAS would reduce the rate of critical near-midair collisions (critical NMACs) to about 42 percent of the existing level (a Risk Ratio of .42). A small fraction of this, equal to 1.1 percent of the existing level, would be caused by the system itself inducing an NMAC. A key assumption in the study was that if the pilot visually acquires a conflicting aircraft in time (even after a Resolution Advisory (RA) had been issued), he would avoid colliding with it even if the RA were incorrect. This visual acquisition has a major effect on the possibility of TCAS inducing an NMAC; it reduces that risk by about 50 percent. In IMC, two major changes occur: visual acquisition is practically impossible (we assume its likelihood to be zero), and the aircraft environment (types of aircraft encountered, fraction that have Mode C, etc.) is quite different. These differences can be expected to have a substantial impact on both the number of NMACs that can be resolved and the number that might be induced.

Another concern addressed in this study is the interaction of TCAS with the ATC system, and whether the use of TCAS would be disruptive. Several situations have been postulated as having a potential for causing disruption. Among these is a situation termed a "domino effect," in which displacement of an aircraft as a result of an RA leads the TCAS-equipped aircraft into a conflict with another aircraft. Also of concern are independent parallel approaches conducted in IMC; TCAS alerts in this situation might be disruptive.

Two principal methods are used to evaluate TCAS System Safety in IMC. The first is a fault tree analysis, which was used in the previous Safety Study. The failure rates that were applied to the fault tree and to the computation of the Risk Ratio in that study represent a numerical average over all weather conditions in the proportions that they occur. New failure rates must be estimated for IMC, leading to the computation of a new Risk Ratio.

The second method involves an examination of the day-to-day workings of TCAS in an ATC environment where it is expected to have the greatest impact. Data obtained from extractor tapes of the Automated Radar Terminal System (ARTS) at Chicago O'Hare airport in IMC was processed to allow simulation of the TCAS logic on individual aircraft pairs to identify the effects of TCAS in a high-density terminal area.

2. Data Sources

Chicago ARTS Data

Over 11 hours of radar data was obtained from ARTS III extractor tapes recorded at Chicago O'Hare airport in IMC during April 1980 (pre-strike). The tapes had been pre-processed to produce files containing data for about 4000 pairs of aircraft potentially in conflict. This large number of potential conflict pairs was reduced to aircraft pairs that would receive TCAS advisories. Each aircraft that would receive an RA was then modeled as responding to its advisory to estimate the displacement from its actual flight path and to determine the effects of this displacement on any aircraft that were in the surrounding airspace.

Critical NMAC Data Bases

FAA incident reports on NMACs involving air carriers were surveyed. An eight year interval of data collected and maintained by the FAA Office of Aviation Safety was used to obtain information on altitudes of the encounters, nature of the intruders, flight plans of the intruders (if any), and visibility conditions when the encounters occurred. A cross-check was made with data from the NASA Aviation Safety Reporting Service (ASRS). The NASA ASRS provides a confidential reporting service for incidents involving safety in the National Airspace System, and contains information similar to the FAA data base.

Flight Progress Strips Data Base

Flight progress strips were examined to identify the transponder equipage and types of aircraft flying on IFR (Instrument Flight Rules) flight plans in IMC. For this study, flight strips were collected at a Terminal Control Area (Philadelphia, PA); a lower density Terminal Radar Surveillance Area (Albany, NY); and several sectors in the Washington Air Route Traffic Control Center. A check of the results was obtained by comparison with another flight strip data collection done for all weather conditions.

3. The IMC Environment

The IMC environment is characterized from the data sources just discussed; these data sources give information on encounter statistics and geometries, and are used as inputs to calculations of the effects of altimetry errors and maneuvering intruders. This information is also used in the quantitative analysis (Section 4).

Encounter Statistics

Table 1 shows the number of critical NMACs involving IFR air carriers during the years 1973 to 1980. For IMC, all encounters involving at least one air carrier aircraft in visibility of 5 miles or less were counted. The number of incidents in IMC appears to be fairly constant at about 2 per year.

Reference 6 gives the numbers of hours air carriers fly per year, which was 8×10^6 for 1979 and 1980 (pre-strike). Airline representatives consulted for this study stated that, based on pilot logbooks, about 5 percent of the flight time is in low visibility conditions (typically less than one mile). From this, it is estimated there were 4×10^5 flight hours per year in visibility less than one mile. From the FAA NMAC data base, there were 8 IFR air carriers involved in NMACs during the 8 year period 1973-1980 in which visibility was less than one mile, or one per year. The risk of a critical NMAC in the lowest visibility conditions is thus computed to be 2.5×10^{-6} per flight hour, which is about the same as the average for all conditions.

A comparison of the distributions of altitudes at which NMACs occur demonstrates one difference between IMC and overall conditions: no incidents were reported in IMC at altitudes over 15,000 ft. The NASA ASRS data supports this, with only

TABLE 1
 CRITICAL NEAR MIDAIR COLLISIONS
 INVOLVING AIR CARRIERS
 1973-1980

Year	IMC (Visibility of 5 miles or less)		ALL CONDITIONS	
	No. of Incidents	No. of IFR Air Carriers	No. of Incidents	No. of IFR Air Carriers
1973	2	3	9	12
1974	3	3	11	12
1975	2	3	6	7
1976	1	2	15	17
1977	2	2	13	14
1978	2	2	14	15
1979	0	0	20	20
1980	2	2	17	17
TOTAL	14 (2 per yr)	17 (2 per yr)	105 (13 per yr)	114 (14 per yr)

Source: FAA Reports of Near Midair Collisions 1973-1980

one observation over 15,000 ft. This is attributed to the nature of IMC, which is usually encountered at low altitudes; most low altitude flying by air carriers (less than 15,000 ft) occurs when they are arriving or departing terminal areas. An examination of the IMC environment for air carriers is thus restricted to terminal areas, which are busier environments than an average mix of terminal and en route areas. This provides an explanation of why the risk in IMC is as high as in overall conditions: even though a direct comparison of an IMC environment and an equivalent Visual Meteorological Conditions (VMC) environment--in this case, terminal only--would show greater risk in VMC, IMC flying time for air carriers is essentially only in terminal areas; VMC includes an average of terminal areas (high risk) and en route areas (low risk).

A breakdown of the operators of aircraft encountered in NMACs in IMC shows that the fraction of air carriers is double the fraction in overall conditions. While the fraction of General Aviation (GA) aircraft decreases, it is still 64 percent of the aircraft encountered. From this, it is assumed that there are still a large number of aircraft encountered in IMC that have the uncorrected altimetry systems typical of GA aircraft.

Examining the data base of flight progress strips shows that virtually all aircraft flying on an IFR flight plan in IMC have Mode C transponders even in a terminal area such as Albany, New York, where a large fraction of the aircraft are GA. However, the FAA NMAC data base shows that only about half the aircraft encountered in IMC NMACs are on an IFR flight plan. As a result, the following method is used to estimate the fraction of aircraft that are Mode C-equipped: all aircraft encountered that were flying on an IFR flight plan are assumed to have Mode C transponders; the likelihood that the remaining aircraft are Mode C-equipped is estimated from the 1981 General Aviation Avionics survey. By this means, it is estimated that 84 percent of intruders in IMC are expected to be Mode C equipped; this is a substantial increase from overall conditions (61 percent). This increase in Mode C equipage has two principal effects: while it increases the effectiveness of TCAS in resolving NMACs, it also increases exposure to the individual failure modes (e.g., altimetry error and maneuvering intruders).

A key result of the System Safety Study was that in overall conditions the distribution of altitude separation at closest point of approach (CPA) is substantially uniform out to 1000 ft. This enters into the calculation of the risk of TCAS inducing an NMAC because of erroneous altimetry or sudden intruder maneuvers, since the principal danger zone for these

phenomena is the range of vertical separations from 300 to 700 ft. The vertical distribution for IMC was analyzed from the Chicago ARTS data base, and is shown in Figure 1. It shows peaks at zero and 1000 ft separation, and a "valley" in the 400 to 600 ft range where Visual Flight Rules (VFR) traffic would normally be encountered in visual conditions. An encounter in IMC with separation in the critical zone of 300 to 700 ft is found to be half as likely as one with 100 ft separation; this reduces the induced NMAC risk proportionally.

Impact of Altimetry Errors

As was the case in overall conditions, it is assumed that TCAS encounters aircraft with two different levels of altimetry: high-quality altimetry which includes corrections such as that provided by air data computers, and is typically found on commercial air carriers; and lower-quality altimetry without such corrections, as would be found in most lower-cost GA aircraft. Each class of system is assumed to have the same error distributions and magnitudes as in overall conditions. Three factors which determine TCAS exposure to altimetry errors change: 1) the mix of high-quality to low-quality altimetry; 2) the altitudes at which encounters occur; and 3) the probability that the intruder has Mode C.

The fraction of aircraft encountered in critical NMACs in IMC that are GA (and are assumed to have uncorrected systems) is .64. This is a decrease from overall conditions, which reduces both the unresolved and induced Risk Ratios. The altitudes at which critical NMACs occur affect risk by only a small amount. The fraction of aircraft that are Mode C-equipped increases from .61 in overall conditions to .84 in IMC, and increases both the unresolved and induced Risk Ratios accordingly.

Taking into account the effect of these changes, the unresolved Risk Ratio due to altimetry error is .010 in IMC. This represents an increase from .003 in overall conditions; the improvement in the unresolved Risk Ratio due to the greater numbers of corrected altimetry systems in IMC does not compensate for the greater exposure to uncorrected systems (higher Mode C equipage) and lack of visual acquisition.

While the factors cited above have the same effect on the induced Risk Ratio as on the unresolved Risk Ratio, there is one additional factor which has an effect on the induced Risk Ratio: the distribution of altitude separation at closest approach. In IMC, the change in the vertical separation distribution (Figure 1) means that the likelihood of an

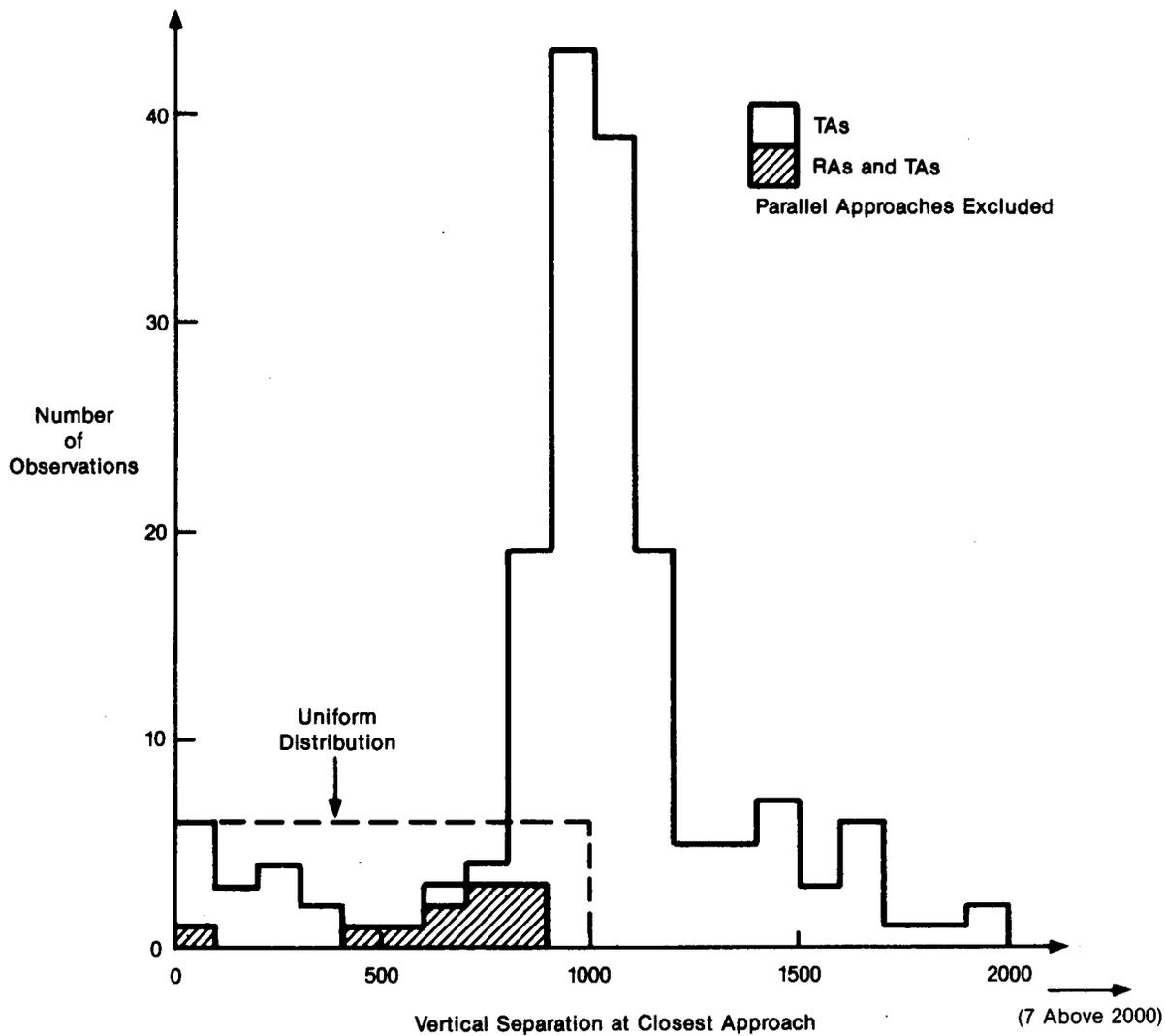


FIGURE 1
DISTRIBUTION OF VERTICAL SEPARATION AT CLOSEST APPROACH
FOR ADVISORY-PRODUCING ENCOUNTERS IN THE
CHICAGO TERMINAL AIRSPACE IN IMC

encounter with 100 to 700 ft of separation shows a decrease of about 50 percent. Risk of an induced NMAC is reduced proportionally. Taking all these factors into account, the Risk Ratio for induced critical NMACs caused by altimetry errors in IMC is .0044. This is about the same as for overall conditions (.0047); in IMC, the greater numbers of corrected altimetry systems and the larger IFR separations used effectively compensate for the higher exposure to uncorrected altimetry systems (higher Mode C equipage) and lack of visual acquisition.

Intruder Maneuvers

An intruder aircraft can cause an induced critical NMAC by making a sudden vertical maneuver just after the time TCAS selects an RA. The probability that this could occur is estimated using the tracks of aircraft that would produce TAs and RAs in the Chicago ARTS data base. The method used in this study directly examines aircraft tracks to locate those with the potential to induce a critical NMAC, using the difference between the intruder's altitude projection when the advisory is issued and the intruder's actual altitude at CPA. The probability that TCAS would encounter the aircraft at the relative altitudes and vertical rates that would result in an NMAC are computed from the appropriate distributions.

The Risk Ratio for an intruder maneuver in IMC was calculated, using the process just described, to be .0016. This result takes into account the higher levels of Mode C equipage in IMC. Even though the benefits of visual acquisition are not available, this Risk Ratio is still substantially lower (by a factor of 4) than in overall conditions (.007); low vertical rates and use of IFR separations that are characteristic of the IMC environment more than compensate for the lack of visual acquisition.

Other Factors

There are three other failure modes judged to have significance in the fault tree analysis: altitude encoder errors, non-acquisition by TCAS surveillance, and avionics critical failures.

The risk of an unresolved NMAC because of B-bit and C-bit errors increases slightly because of higher Mode C equipage, but remains an order of magnitude below other factors that cause unresolved NMACs. The Risk Ratio for induced NMAC because of C-bit errors increases from .0004 in overall

conditions to .0014 in IMC. The Risk Ratio for induced NMAC because of B-bit errors, which was an order or magnitude lower than in overall conditions, decreases further.

The only form of surveillance failure judged to have significant impact in the previous Safety Study is multipath, which results in missed Resolution Advisories. This is not expected to change in IMC.

In order for undetected critical avionics failures (which would cause incorrect Resolution Advisories to be issued) not to contribute significantly to the rate of induced NMACs, they must occur at a rate one order of magnitude lower than any other factor judged significant in the induced Risk Ratio, or 10^{-4} per critical NMAC occurring today. This is the same level estimated in the original System Safety Study for overall conditions.

4. Re-evaluation of Fault Tree for Instrument Conditions

The fault tree constructed for the previous System Safety Study covers all failure mechanisms--including those that occur in IMC--so it is not necessary to construct a new fault tree for this study. Instead, visual acquisition is assumed to be impossible and the new Risk Ratios just computed must be applied.

The failure probabilities used in quantifying the fault tree are summarized in Table 2. The table also provides, for comparison, the probabilities for overall conditions. All these Risk Ratios take into account the fraction of aircraft that have Mode C transponders and the likelihood that surveillance acquires the track. The hourly risk conversion factors, which are the risk of a critical NMAC in today's system without TCAS, are provided also. These conversion factors for both IMC and overall conditions are the same since the risk of a critical NMAC per flight hour was observed to be the same in both IMC and overall conditions.

In IMC, nominal conditions assumed when computing the Risk Ratios for unresolved and induced NMACs are the following:

- Visual acquisition is assumed to be ineffective for the purpose of "see-and-avoid."
- As there is no visual acquisition, the pilot follows the Resolution Advisory.

TABLE 2
SUMMARY OF FAILURE PROBABILITIES USED IN
FAULT TREE EVALUATION

DESCRIPTION OF EVENT	PROBABILITY	
	IMC	OVERALL
UNRESOLVED		
1. No RA is displayed	.185	.41
1.a Encounter is with non-Mode C aircraft	.16	.39
1.b Surveillance fails to acquire aircraft	.025	.018
2. Inadequate RA is displayed	.010	.003
INDUCED		
3. TCAS displays RA which will lead to NMAC		
3.a Intruder maneuvers	.0016	.016
3.b Altimetry error	.0044	.0081
3.c C-bit errors	.0014	.001
HOURLY RISK CONVERSION FACTOR		
4. Risk of critical NMAC (Section 3.1.1, p. 3-1)	$1 \times 10^{-5}/\text{hr}$	$1 \times 10^{-5}/\text{hr}$

- Airborne traffic encountered by TCAS has the level of Mode C transponder equipage of today's IMC environment.
- The intruder is not TCAS-equipped.
- The pilot follows the nominal procedures involved in the use of TCAS; there are no "false moves" based on Traffic Advisory information only.

The only means by which an NMAC can be resolved in IMC is by a correct and timely RA, as visual acquisition is assumed to be ineffective. The Risk Ratio for an unresolved NMAC is thus the probability that an RA is not issued in a timely fashion or is inadequate to resolve the NMAC, and is computed to be .195. Thus, TCAS is expected to resolve more than 80 percent of critical NMACs in IMC. Most of the residue (.16 of the .195) is a result of the intruder not having a Mode C transponder.

The Risk Ratio for an induced NMAC, which is the probability of an induced NMAC expressed as a fraction of the probability of a pre-existing NMAC, is the probability that TCAS displays an RA which leads to an NMAC. This is the joint probability of an incorrect RA because of altimetry errors, intruder maneuvers, and C-bit errors: .007. The induced Risk Ratio for IMC is less than that for overall conditions.

The effects of using TCAS in both overall conditions and IMC are illustrated in Figure 2. The left-most set of bars indicates today's condition--no use of TCAS in IMC or VMC, with 100 percent of current NMACs. With the use of TCAS (the second set of bars), the number of NMACs is reduced, with a larger fraction eliminated in IMC. As the environment approaches full Mode C equipage, TCAS benefits approach 95 percent in resolving NMACs. Accompanying this will be slight increases in induced risk compared with today's level. However, in both today's environment and the future, induced risk in IMC will be less than in overall conditions.

5. TCAS Interactions With the ATC System

In this study, the analysis of the level of safety provided by the use of TCAS is extended to include factors external to those which determine whether TCAS will resolve an individual encounter. An IMC terminal area environment is examined to determine if there are interactions between the operation of TCAS and ATC operation of IFR airspace. First, a description of ATC procedures in the Chicago terminal areas is provided;

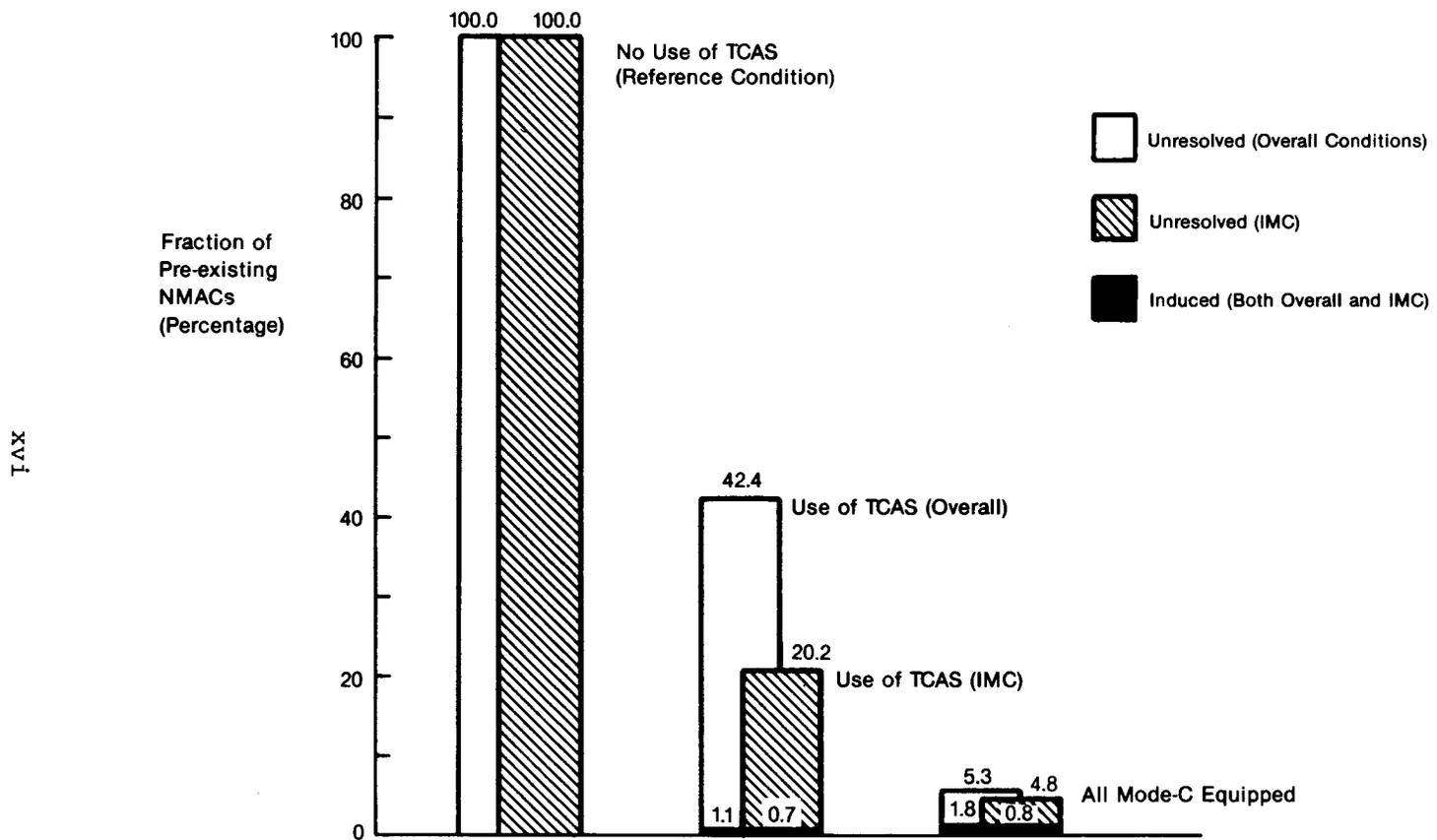


FIGURE 2
RELATIVE TCAS EFFECTS

then the issues are defined; finally, the results of the analysis of a new data base are presented.

Chicago Terminal Area ATC Practices

Inference of pilot and controller intent is made from actual flight paths combined with knowledge of ATC practices in the Chicago terminal area. This information is used as a basis for making judgments about the compatibility of TCAS with ATC practices.

Chicago O'Hare airport has three sets of parallel runways; centerline separations support the operation of independent parallel approaches in IMC. Table 3 lists the runway configurations in use during each data collection period; parallel approaches were observed in operation during some of the periods. An estimate of the number of arrivals and departures at O'Hare is also included in the table, and indicates the large volume of traffic handled by Chicago terminal controllers, even in IMC.

Traffic patterns are set up according to a "four corner post" operation, as illustrated in Figure 3. By letter of agreement, arrival aircraft are handed to the terminal at the four fixes and follow the indicated paths, descending to 7000 ft and then to 4000 ft before turning onto final approach. Departures are cleared through the gaps between the four corners, with intermediate clearances of 5000 ft until they have passed under the arrivals. Aircraft transiting the area use 6000 ft.

Sectors are created by dividing the airspace between arrival runways (for arrivals) and departure runways (for departures). Two controllers are assigned to each arrival stream, one to each departure stream. If independent parallel approaches are in operation, a radar controller monitors the area between the localizers. There may be additional controllers to handle overflights and satellite airports.

Issues

The broad range of issues dealing with TCAS-ATC interactions is divided into three categories: those issues dealing with safety, with controller workload, and with capacity.

Safety-related results of the Chicago ARTS analysis address the following issues:

TABLE 3
 RUNWAY CONFIGURATIONS AND ARRIVAL/DEPARTURE RATES
 AT CHICAGO O'HARE DURING DATA COLLECTION PERIODS

DATE	DAY	Local Time	RUNWAY CONFIGURATIONS IN USE		NUMBER OF	
			Arrivals	Departures	Arrivals	Departures
4/09/80	Wednesday	0919-1100	14R,L	(unknown)	149	109
4/09/80	Wednesday	1210-1654	22R,27L	22L,32L	257	216
4/11/80	Friday	1401-1605	4R,9L	4L,9R	154	160
4/11/80	Friday	1605-2005	9R,L	4R,L	<u>323</u>	<u>309</u>
					883 (78.6/hr)	794 (70.6/hr)

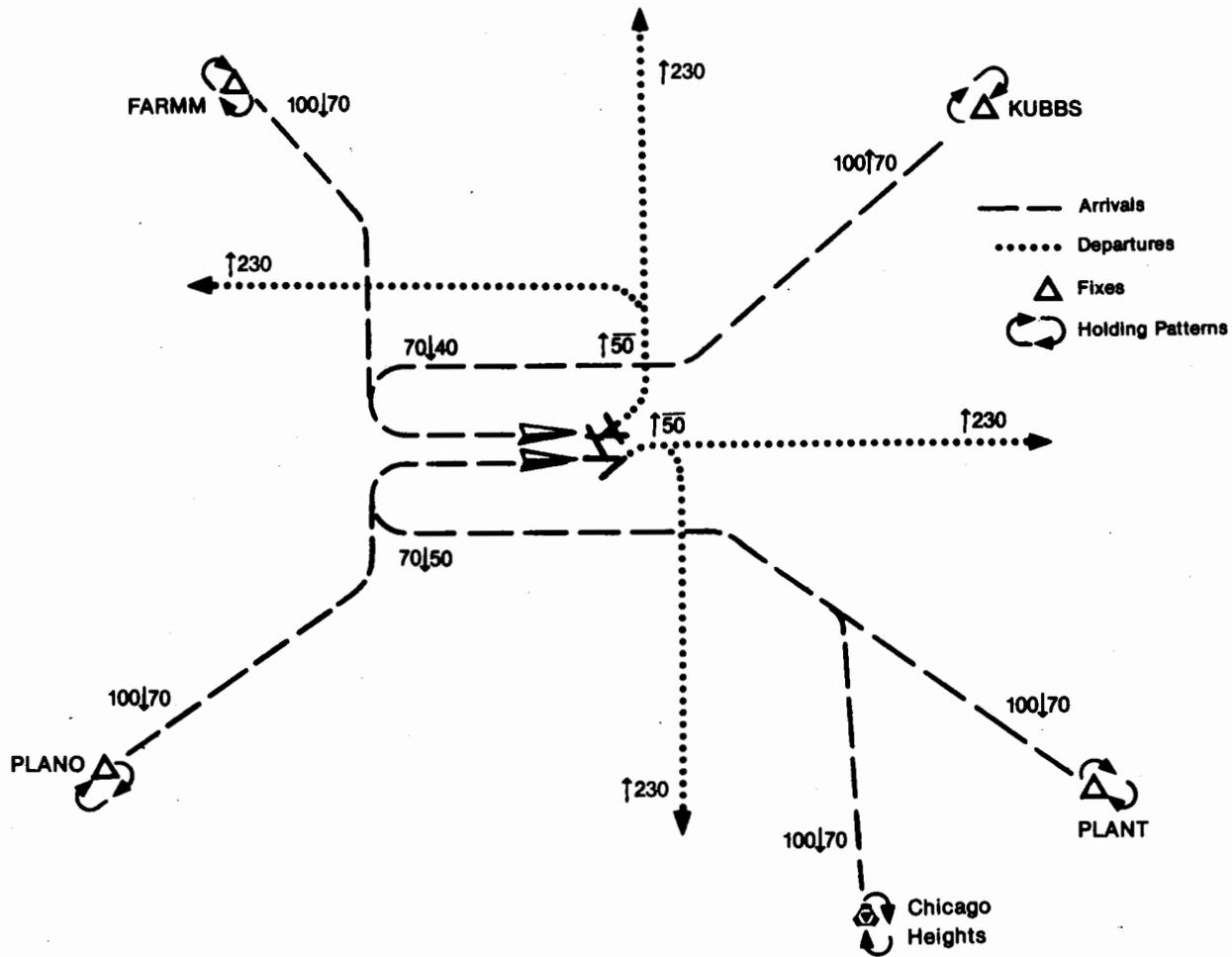


FIGURE 3
EXAMPLE OF PATTERN USED FOR CHICAGO O'HARE TRAFFIC

- Is the RA needed or is it a nuisance advisory?
- Is the maneuver resulting from the RA compatible with pilot and controller intent?
- Is there a domino effect? (A domino effect occurs when a TCAS-equipped aircraft, by following an RA against one aircraft, comes into conflict with a second aircraft.)

The purpose of an analysis of controller workload issues is to identify any characteristics of TCAS operations that may generate additional work for the controller. The analysis addresses two main issues:

- How often will a controller see a displacement? (Note: Many TCAS RAs do not cause any displacement, e.g., "Don't Descend" issued to a level aircraft.)
- Are normal ATC operations disrupted? What, if any, restoration actions are required?

Finally, TCAS could have an impact on capacity if following a TCAS advisory necessitates resequencing, causing a gap in the flow of traffic. The locations of all advisories and the displacements involved are evaluated to estimate the impact that TCAS might have on capacity.

Results from TCAS Encounter Processing

Simulating the TCAS logic for the Chicago ARTS data results in 228 pairs of aircraft receiving TAs and 14 pairs receiving RAs. Independent simulation of the 28 aircraft involved in the 14 pairs receiving RAs resulted in 24 RAs being issued. The results of this simulation address the safety, workload, and capacity issues.

Safety. Figure 4 is a plot of the vertical and horizontal separations at closest approach for 11 of the encounters which produced RAs (the 3 RAs on parallel approaches are treated separately). The arrows show the vertical displacement and the resulting separations that would have occurred if the aircraft were to follow the RA. The large dashed box shows the IFR minimum separation standards (3 nmi and 1000 ft). All of the aircraft that would receive RAs were observed to pass within the IFR separation standards. While Encounter 11 shows safe vertical separation at closest approach, earlier in the encounter it was within the minimum separation standards.

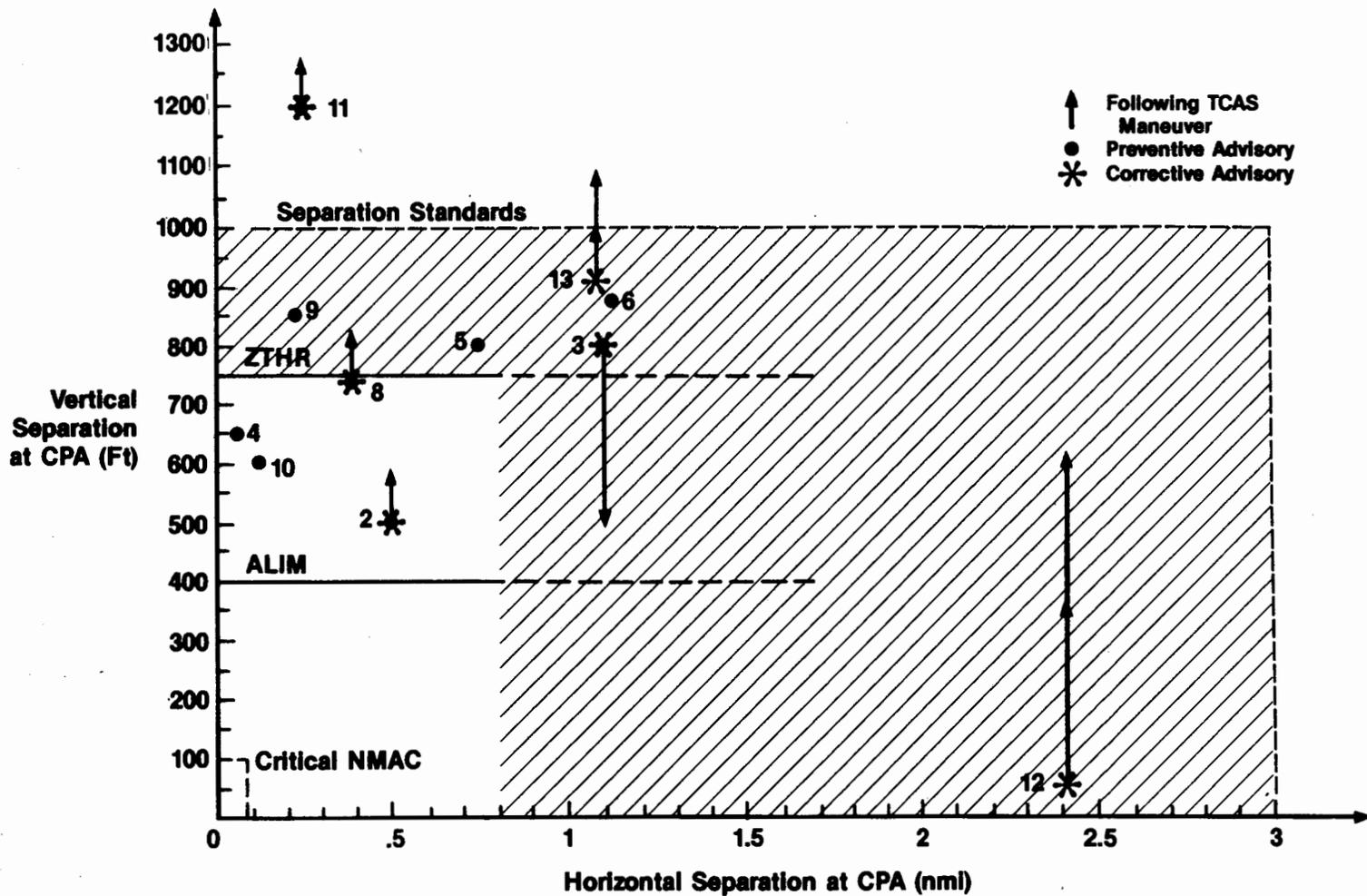


FIGURE 4
VERTICAL AND HORIZONTAL SEPARATION AT CLOSEST APPROACH
(EXCLUDING PARALLEL APPROACHES)

In all of the encounters except Encounter 3, following the RAs would maintain or increase separation. In Encounter 3, TCAS tracked the intruder as having a vertical rate that would result in altitude crossing; however, because of horizontal separation of more than 1 mile, the advisory was removed before separation decreased even to ALIM. While this would be a nuisance advisory, it would not create an unsafe situation.

The aircraft receiving RAs were modeled as following their advisories to determine the resulting displacement. Twelve of the 24 RAs were preventive, requiring no displacement to comply. The 12 remaining RAs called for maneuvers (corrective advisories); however, in four cases this maneuver closely followed the aircraft's observed maneuver, resulting in no displacement from the flight path. Four additional RAs required less than 300 ft of displacement. Only four RAs (out of the 24 total) resulted in displacements of 300 ft or more. In addition, for those aircraft that were observed to maneuver, the RA was in the same direction in all but one case (Encounter 12).

An examination of the location of the next nearest aircraft to each aircraft in an encounter shows that they are all well separated from the TCAS aircraft, and in all but two cases were not closing in both range and relative altitude. Upon simulation of each maneuvering TCAS aircraft with the next nearest aircraft, no advisories (neither TAs nor RAs) were generated. Chicago is a dense traffic environment; this suggests that domino effects may be extremely rare.

One of the RA encounters occurred in a holding pattern. Because of concerns about TCAS effects in holding patterns, this encounter was analyzed in detail. Figure 5 is a diagram of the encounter. Aircraft A is descending rapidly to 9000 ft, causing Aircraft B to receive a "Descend" RA. The displacement resulting from this advisory does not create an RA for Aircraft C, because these aircraft are on opposite legs of the holding pattern. If instead Aircraft C were directly below Aircraft B, the range would be at a minimum but an RA would be generated for Aircraft C only if Aircraft B descends to within 750 ft of Aircraft C; in addition, this RA would be preventive ("Don't Climb"), with no displacement involved. In maneuvers in holding patterns, the TCAS multi-aircraft logic prevents movement from propagating to additional aircraft.

Workload. Advisory rates for aircraft were computed based on an estimate of track-hours of aircraft in the Chicago ARTS data base. The RA rate for aircraft in IMC was found to be half

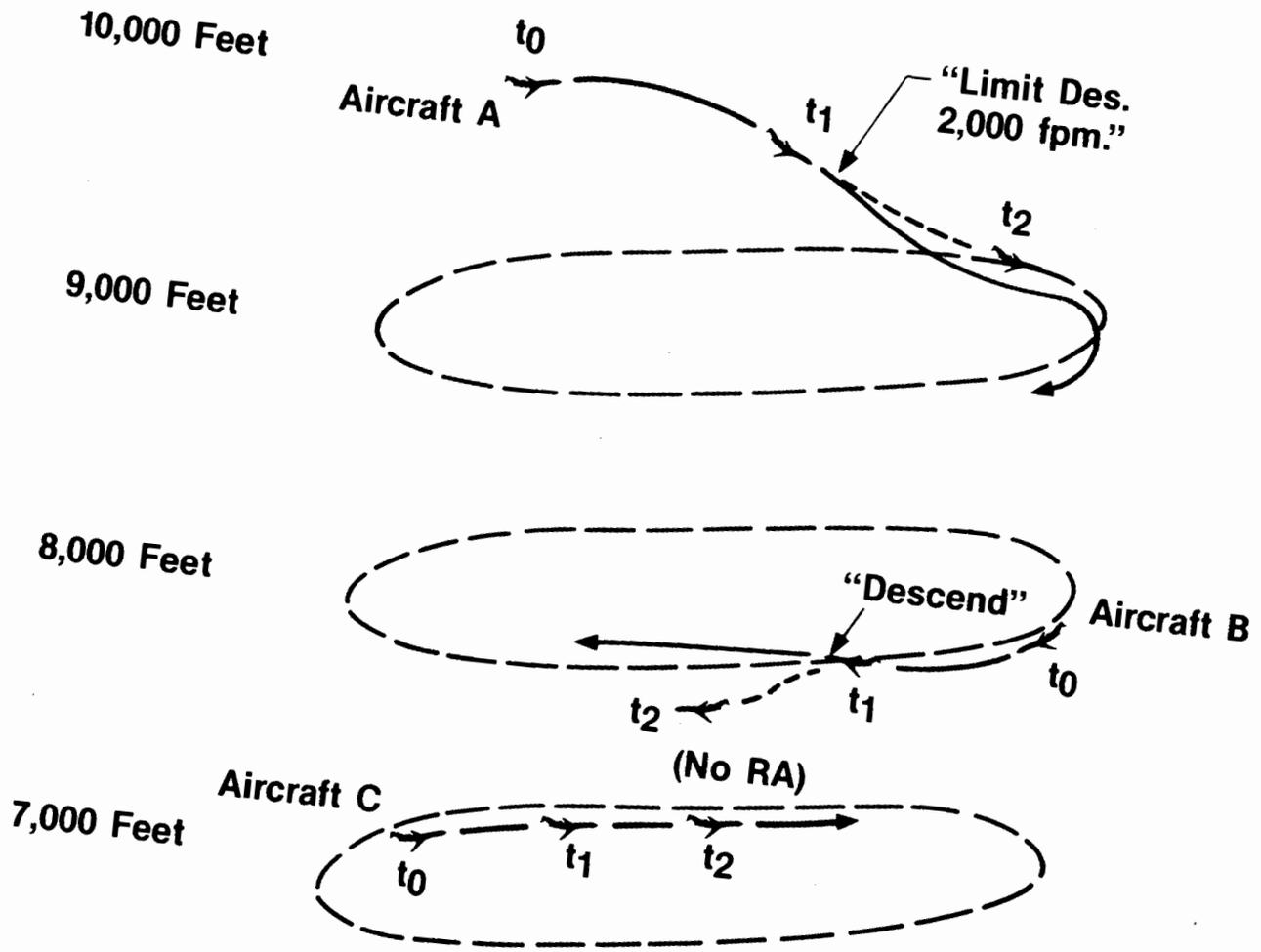


FIGURE 5
HOLDING PATTERN ADVISORY

that observed in overall conditions in terminal areas, because of the larger vertical separations and lower vertical rates of the more structured airspace in IMC. (Eighty percent of tracks were found to be level in IMC, compared with 60 percent in overall conditions.) The TA rate, however, increased; this is attributed to the large number of parallel approach encounters contained in the Chicago data base. It was also found that RAs are less likely to require displacement; only 50 percent of RAs in IMC were corrective, compared with 82 percent in overall conditions. The structure of the airspace in IMC reduces both the frequency of RAs and the amount of maneuvering required to comply with them. The altitudes and locations of RAs were examined to identify any concentration of advisories. With the exception of the three parallel approach encounters (out of an estimated 472 aircraft making parallel approaches) no concentration of RAs was found.

Rates at which aircraft would receive RAs were computed for the entire Chicago terminal area airspace and on a per-controller basis. On the average, RAs were issued to aircraft once every 28 minutes (corrective RAs, once every 56 minutes). Rates were seen to vary, however, from a low of 0 over a two-hour period (Friday 2-4 p.m.) to a high of 14 over a four-hour period (Friday 4-8 p.m.). On a per-controller basis, the average rate at which aircraft controlled by a Chicago terminal controller would receive an RA is once every three hours. RAs causing displacements of 300 ft or more, however, would occur on average only once every 19 hours.

Capacity. Examination of the locations at which RAs occur shows that in most cases, sequencing had not yet been established at the time of the RA and there is time for recovery from any displacement from the flight path. In these cases, there is little potential for advisories to affect capacity. Locations where RAs were observed that could potentially affect capacity are independent parallel approaches, because sequencing and spacing have already occurred. Interruption of this process may cause a reduction in runway utilization.

Three parallel approach encounters were observed to generate RAs because of altitude separation of less than 750 ft (1000 ft is required). The displacements generated are small, however, and no aircraft would be required to deviate from its clearance. During the 5.7 hours in which parallel approaches were in operation, there were an estimated 472 arrivals at O'Hare. The three parallel approach encounters thus correspond to a rate of 1 encounter every 1.91 hours of parallel approach

operations, or 1 aircraft making a maneuver as a result of an RA for every 157 executing a parallel approach. While this rate is low, an investigation was made to see if it could be further reduced. It was found that because of the nature of parallel approach operations, the TCAS range test for RAs would almost always be passed; however, the procedure of providing 1000 ft altitude separation eliminates RAs in more than 99 percent of encounters. Close monitoring of altitude separation thus appears to offer the best means to prevent unwanted RAs.

6. Findings and Recommendations

System Safety Findings

1. The original System Safety Study found that only 14 percent of critical NMAC incidents involving air carriers in today's system occur in IMC; however, given that an air carrier is in IMC, the risk of a critical NMAC (measured on a per-flight hour basis) is approximately the same as in overall conditions. This is attributed to the fact that air carriers are more likely to experience IMC at low altitudes, where they will typically be in the terminal areas with the associated greater numbers of surrounding aircraft.
2. In IMC, the fraction of aircraft encountered that are Mode C equipped is higher by one-third, and the fraction that are air carriers (and carry high-quality altimetry) doubles. The higher Mode C equipage increases the proportion of critical NMAC encounters that TCAS will resolve; however, it will also increase exposure to those aircraft with altimetry errors and to those that may maneuver to defeat a TCAS Resolution Advisory. The larger number of air carriers reduces the effect of altimetry errors.
3. The relative altitudes of encounters in IMC are larger than those in overall conditions (primarily VMC) due to the use of IFR separation standards, and the vertical rates are lower. These characteristics reduce the susceptibility of TCAS to the predominant failure modes that can cause induced NMACs.
4. TCAS is expected to show a greater effectiveness in resolving critical NMAC encounters in IMC than in overall conditions. The proportion of encounters it will resolve increases from 60 percent to 80 percent, primarily as a result of increased Mode C equipage.

5. A basic assumption in the original System Safety Study is that visual acquisition, aided by the display of a Traffic Advisory, enables the pilot to avoid an intruder even if an incorrect Resolution Advisory were issued due to altimetry error or other causes. The effect of this is to reduce the induced component of the Risk Ratio in overall conditions by more than 50 percent. However, the characteristics of encounter geometries in IMC (IFR separations and low vertical rates) compensates for this factor; thus, following Resolution Advisories in IMC is expected to be even safer than following Resolution Advisories in VMC after clearing the airspace.

TCAS-ATC Interactions Findings

1. The possibility of a domino effect is extremely remote. The orderly nature of the IFR system ensures that aircraft are well separated. Examination of locations in which aircraft are placed in close proximity also demonstrates reasons why domino effects are not expected to occur. In a holding pattern, no set of conditions has been uncovered that would cause more than two aircraft in the pattern to be displaced from their altitudes.
2. It is unlikely that TCAS will be considered disruptive to ATC. In IMC, the rate at which Resolution Advisories occur is low. While some advisories do occur which can be classified as nuisance alerts because of large horizontal miss distances (1 mile or more), all aircraft pairs receiving advisories were observed to pass within 3 miles and 1000 ft (IFR separation standards).
3. Resolution Advisories, when they occur, are compatible with ATC intent; no recovery action is seen to be needed. Altitude displacements are small. When aircraft that would receive RAs were observed to maneuver, all but one maneuvered in the same direction as that called for by TCAS.
4. No major increase in pilot-controller communications workload is likely because of the low rates of advisories, the small displacements, and compatibility of TCAS advisories with ATC intent.
5. No severe capacity impacts are foreseen. The only place where Resolution Advisories occur after aircraft have been sequenced for approach is on parallel approaches; TCAS would affect less than 1 percent of them. This is because TCAS alarm thresholds are highly compatible with ATC

procedures. Traffic Advisories, however, will be provided on most parallel approaches; the effect of providing this additional traffic information is expected to be beneficial.

Recommendations

1. No changes in the TCAS logic or parameters were found to be necessary to introduce Minimum TCAS II to the IMC environment for the following reasons:
 - TCAS shows a greater effectiveness in resolving critical NMACs in IMC than in overall conditions with a decrease in the risk of an induced NMAC.
 - TCAS alert rates in IMC are low and the resulting displacements are small; no lowering of sensitivity is warranted.
 - Special situations, such as holding patterns and parallel approaches, were analyzed. It was found that it would not be useful to invoke a special logic (by means of a pilot switch, for example) in any of these situations.
2. Several factors which should be addressed in a pilot training program were discussed in the System Safety Study for overall conditions. Based on the analysis of the IMC environment, two of these require re-emphasis:
 - Premature maneuvering based on the Traffic Advisory alone could be self-defeating. There is a greater susceptibility to this in IMC, since visual acquisition is not likely to occur.
 - The previous System Safety Study showed that the pilot is better off trusting the displayed advisory than ignoring it, with a ratio of resolved NMACs to induced NMACs in overall conditions of 23:1 (58:1 if visual acquisition aided by the TA is taken into account). In IMC, this is even more the case; the ratio of resolved to induced NMACs is 115:1.
3. Critical avionics failures, namely those which could cause a critical NMAC and for which the performance monitor does not shut off the system, must occur at the rate of 10^{-4} or less per critical NMAC to be negligible relative to other factors that could induce a critical NMAC. This is the same level as for overall conditions.

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1. INTRODUCTION

This report documents a study of the Minimum Traffic Alert and Collision Avoidance System (Minimum TCAS II, or simply "TCAS") for Instrument Meteorological Conditions (IMC). The study examines TCAS effectiveness specifically in the IMC environment; also, since air traffic control in IMC relies heavily on Instrument Flight Rules (IFR) procedures, it examines TCAS interactions with the IFR system. The study is a follow-up to the System Safety Study of Minimum TCAS II (Reference 1), which examined the effectiveness of TCAS in all weather conditions as they occur, which turns out to be mostly Visual Meteorological Conditions (VMC).

1.1 Background

1.1.1 Description of Minimum TCAS II

The Minimum TCAS II interrogates ATC transponders to track nearby aircraft in slant range and relative altitude; it uses these to assess the collision threat potential and to generate appropriate collision avoidance advisories. Two types of advisories are provided to the pilot: Traffic Advisories (TAs), which indicate the threat's position; and Resolution Advisories (RAs), which provide vertical escape maneuvers. In collision encounters, the system is designed so that the TA normally is issued approximately 15 seconds before the RA. The TA can convey information such as the range, bearing, and relative altitude of the potential threat.

An aircraft is declared to be a collision threat to the TCAS aircraft if its current position, or its projected position, simultaneously violate range and relative altitude criteria. Generally, an aircraft will be declared to be a collision threat 20-30 seconds before closest approach, at which time an RA is displayed. This provides time for the escape maneuver by the pilot. The RA (e.g., Climb, Descend, Don't Climb, etc.) is chosen to provide a specific margin of separation with a minimum change in the existing flight path of the TCAS aircraft. Minimum TCAS II utilizes maneuvers in the vertical plane only.

Reference 2 provides a more detailed description of the TCAS system.

1.1.2 The TCAS System Safety Study

The overall System Safety Study of Minimum TCAS II was conducted to assess the safety characteristics associated with the use of TCAS by air carrier aircraft in all conditions. This study used the fault tree technique to provide an overall assessment of the interrelation of avionics, pilots, and the air traffic control system, in all conditions under which the TCAS system is expected to be used. Principal basic limitations and failure modes of TCAS included the following:

- lack of universal Mode C equipage
- errors in transponder-reported altimetry
- susceptibility to being deceived by an intruder's sudden maneuver
- bit errors in an intruder's reported altitude code
- TCAS surveillance failure
- avionics failures

Failure rates, when combined within the fault tree framework, were used to calculate the probability that a critical near-midair collision (critical NMAC, or simply "NMAC") would occur for air carrier aircraft equipped with TCAS.

This study showed that, with today's level of transponder and Mode C equipage, TCAS would reduce the rate of critical NMACs to about 42 percent of the existing level. This figure will continue to drop as the trend to greater equipage continues. Of the remaining NMACs, most would have occurred without TCAS; TCAS simply does not resolve them. However, a number equal to 1.1 percent of the pre-existing rate would be due to the system inducing an NMAC. The factors that make TCAS susceptible to inducing an NMAC are sudden maneuvers by the intruder, errors in the intruder's Mode C altitude report, and bit errors in the altitude report. This estimate of the risk of TCAS inducing an NMAC includes a reduction due to the pilot's visual acquisition of the threatening aircraft; that is, in the Safety Study, it is assumed that if the pilot, aided by the Traffic Advisory, visually acquires the threat by a certain time he can avoid an NMAC even if an incorrect RA were to be issued. This has the effect of reducing the induced risk by about 50 percent. Several human factor failure modes were also examined; the

most severe postulated is one in which the pilot uses the TA inappropriately, in the absence of visual acquisition, to make an incorrect maneuver intended to avoid the threat.

1.2 Need for the Instrument Weather Conditions Safety Study

The results of the overall Safety Study point to the need for a more detailed examination of the IMC environment. Two specific concerns have been raised:

- Extreme difficulty of visual acquisition in IMC
- Interaction of TCAS with the structured IFR system

Each will be discussed in turn.

1.2.1 Visual Acquisition

A key assumption in the overall Safety Study is that if a pilot visually acquires a conflicting aircraft in time (even after an RA has been issued) he will avoid colliding with it, even if the RA is incorrect (the type that would induce an NMAC). Such timely, effective visual acquisition was assumed to be possible only under good visual conditions (bright daylight) to be conservative; other conditions (e.g. haze, glaring sun, and night) were not considered to support effective visual acquisition. Visual acquisition in IMC, for the purpose of achieving the benefits described, was assumed not possible.

In VMC, visual acquisition aided by the TA resolves some NMACs and TCAS RAs resolve some NMACs; the remainder are unresolved. In IMC, only TCAS RAs are available to resolve NMACs; however, the effect on the number of unresolved that remain is small, since in those cases where a TA is received it is followed almost always by a correct and timely RA.

Visual acquisition has a major effect on induced NMACs. In contrast, TCAS will generate RAs for a large number of proximate aircraft; only a few of these will be incorrect and may potentially induce an NMAC. In VMC, visual acquisition will enable a pilot to recognize an incorrect RA, and he is expected to use see-and-avoid procedures to resolve the situation. In IMC, visual acquisition is assumed not to be possible, and thus all potential induced NMACs would occur.

The effectiveness of TCAS in IMC is changed, however, not only by the mode of operation but also by the characteristics of the environment. These characteristics include the operators and types of aircraft, the fraction that are Mode C equipped, and the geometries of the encounters. The differences in IMC can be expected to have a substantial impact on both the number of NMACs that can be resolved and the number that might be induced.

1.2.2 ATC Interactions

In Instrument Meteorological Conditions, virtually all aircraft fly on IFR flight plans. The IFR system is a highly structured one; use of TCAS in IMC leads to the question of whether the use of TCAS would be disruptive. TCAS may cause aircraft to move off their clearances in situations where the controller might not be expecting it.

Several situations in particular have been postulated as having potential for causing disruption. Primary among these is a situation termed a "domino effect," in which displacement of an aircraft resulting from a TCAS RA leads the TCAS-equipped aircraft into a conflict with another aircraft (other than the one the RA is displayed for). If the new threat is also TCAS-equipped, it too may receive an RA causing a maneuver. The possibility that this effect may occur is of particular concern in holding patterns, where aircraft are in close proximity.

Another situation of concern for potential interactions is the operation of independent parallel approaches in IMC. Characteristic of such approaches is that aircraft are placed in close proximity, closing in range, under the supervision of a monitoring radar controller. Because of the level of supervision and the critical nature of approach and landing, TCAS RAs in this safe situation would be extremely disruptive. Further examination of data may provide more examples of situations where the TCAS displacements may not be desirable.

1.3 Approach

As indicated by the two-part nature of this study, two principal methods are used to evaluate TCAS System Safety in IMC. The first is a fault tree analysis, which is used to estimate the risk of a critical NMAC in IMC. The second is the processing of 11 hours of ARTS extractor data, which is used to determine TCAS-ATC interactions.

1.3.1 TCAS Safety Analysis for IMC

The original TCAS System Safety Study involved the development of a fault tree which described all possible means by which failure (a critical NMAC) could occur. A quantitative cut was made of those failure modes which would be significant and those which were less important. The probability of occurrence of the significant failure modes were then calculated relative to the rate at which critical NMACs occur in today's system. This relative rate is termed a "Risk Ratio," and is the basis for evaluating TCAS System Safety in both overall and instrument weather conditions.

The original study was structured so as to be applicable to all traffic situations and environmental conditions expected in normal flight. Thus, for the purposes of this study, the fault tree definition as provided in the overall Safety Study is complete. No new branches or events exist for the IMC case. The failure rates applied to the fault tree and computation of the Risk Ratio, however, represent a numerical average over all conditions in the proportions they occur. New failure rates must be estimated for Instrument Conditions, leading to the computation of a new Risk Ratio given IMC. The FAA historical data base is reviewed; a new source of historical data, the NASA Aviation Safety Reporting Service, is examined; and new probabilities for the significant failure modes are computed. These probabilities are combined using the fault tree structure to obtain a new risk estimate for a critical NMAC in IMC.

1.3.2 Study of TCAS Interactions with the ATC System

A complete study of TCAS interactions with the air traffic control system requires not just an analysis of isolated and rare NMAC events, but also an examination of the day-to-day workings of TCAS in an ATC environment where it is expected to have the greatest impact. To this end, a new major data source was examined.

Data obtained from ARTS extractor tapes recorded at Chicago O'Hare airport in IMC was processed to allow simulation of the TCAS logic on individual aircraft pairs. A complete record of TCAS performance during two peak time periods representing approximately 11 hours was compiled. This provides a basis for identifying the effects of TCAS in normal, day-to-day IFR operations at a major airport terminal area.

1.4 Study Assumptions and Limitations

This study of the use of TCAS in IMC involves the study of an environment that constitutes a small proportion of possible conditions. It is recognized that the data bases are small; the total of all critical NMACs, an already low number, is reduced even further when restricted to IMC. As in the overall Safety Study, conservative assumptions are used and the sensitivity of the results to all input parameters is tested.

While in this analysis the distinction between IMC-only and overall conditions (VMC and IMC, in the proportions found in the overall Safety Study) is frequently made, it is hard to draw a sharp dividing line between IMC and non-IMC conditions. The distinctions are more a matter of the degree to which the prevailing conditions represent an all-IFR environment. It is common to refer to conditions in an area as "an IFR day," since the visibility conditions for an aircraft depend on where the aircraft is in that area. However, it is possible to determine whether conditions are such that everyone should be flying IFR. When collecting data one can ascertain what the weather is at one location (for the Chicago extractor tapes the weather reported at O'Hare is used), which will be indicative of what the weather generally is like in the area but does not necessarily apply everywhere.

Ideally, one would like to derive data from various locations using flight test recordings, as was done in the overall Safety Study. However, at the time this report was prepared no flight test data has been collected that can be specifically identified as IMC. Where data of this nature is required, the Chicago ARTS extractor data is used: characteristics such as large traffic volumes and a great degree of maneuvering make the Chicago terminal area a worst-case environment, and thus an effective substitute for flight data. Also, IMC is typically a low-altitude phenomenon (for air carriers).

1.5 Structure of this Report

Section 2 of this report discusses in detail the data sources used, including the means by which the data is analyzed. Section 3 presents the data taken from these sources, after reduction, that is used in Section 4 to quantify the fault tree. Section 4 also includes analysis of the sensitivity of the results to key assumptions and failure rate estimates. Section 5 will discuss the TCAS interactions with air traffic control, and Section 6 presents the key findings and recommendations.

2. DATA SOURCES

Several data sources were used to characterize the operation of TCAS in IMC. Primary among these is data obtained from Automated Radar Terminal System (ARTS) extractor tapes recorded in the Chicago terminal area. The process used to construct and simulate TCAS encounters from the ARTS tracks is described below. Other data sources include the NMAC historical data bases maintained by the FAA and the NASA Aviation Safety Reporting Service (ASRS). These data bases are examined for information concerning reported critical NMACs in IMC. Finally, a data base of flight progress strips collected in IMC from various locations is examined to identify the characteristics of IFR aircraft flying in IMC.

2.1 Chicago ARTS Data Base

To study the everyday operation of TCAS in the IFR system, radar data was obtained from ARTS III extractor tapes recorded at Chicago O'Hare airport. Air carriers encounter instrument weather conditions principally at low altitudes, and the effects of TCAS can best be seen in high density traffic. The Chicago terminal area, therefore, provides an ideal environment for studying the effects of TCAS in IMC because it has such a high rate of terminal operations. The details of the Chicago Terminal operations are discussed in Section 5.3.1. This data permits the simulation of TCAS encounters using recorded actual traffic movements to examine the interactions of TCAS with the highly structured air traffic control system in IMC.

2.1.1 Available Data

ARTS extractor tapes contain Secondary Surveillance Radar (SSR) data for all aircraft tracked by the Chicago terminal area radar. The tapes analyzed here were recorded during April 1980, and therefore represent pre-strike traffic levels. Thirty tapes were recorded over a nine-day period and contain about 71 hours of radar data. Two of the days experienced instrument weather conditions, in which 11.24 hours of radar data was collected. Fortunately, much of this IMC data was recorded during peak traffic periods: a Wednesday (April 9) morning and afternoon, and a Friday (April 11) afternoon and evening.

The data obtained from the extractor tapes had been pre-processed during an earlier study of the Beacon Collision Avoidance System (BCAS) to produce files containing pairs of

aircraft potentially in conflict. The range and altitude filters used for this preliminary reduction are much larger than the TCAS advisory thresholds and therefore would not eliminate any pairs of aircraft that could receive TCAS advisories if equipped. Approximately four thousand potential conflict pairs were generated for the IMC data processed, although most of these "potential conflicts" actually do not come close to meeting the criteria for TCAS advisories. The files contain the following information for each aircraft in a potential conflict pair for every radar scan passed by the preliminary filter:

- assigned beacon code (Mode A)
- reported altitude (Mode C)
- x and y positions referenced to radar location
- tracked vertical and horizontal rates
- system time

Additional information is available on the airport operations and the weather details at the time the extractor tapes were recorded. The arrival and departure runway configurations and the times of the configuration changes are included. This information, supplemented by knowledge of typical control procedures in use for given runway configurations, is important for analyzing any effects TCAS may have on the IFR system. The weather details include the winds, ceilings, and visibility during the two days studied. The weather conditions, which consist primarily of light rain and snow showers, are IMC or marginally VMC due to low cloud ceilings.

2.1.2 TCAS Encounter Processing

To effectively analyze TCAS encounters using the actual traffic recorded in IMC, the large number of "potential" conflict pairs must be reduced to aircraft pairs which receive TCAS advisories. The obvious non-TCAS conflicts are eliminated by an additional filtering program to isolate the pairs of aircraft that may generate TCAS advisories if equipped. Then, by simulating all these aircraft as TCAS-equipped, the operation of TCAS in IMC can be examined, both collectively and on an aircraft-by-aircraft basis. This additional filtering of the ARTS data and the TCAS encounter processing is briefly discussed here; further details are given in Reference 10.

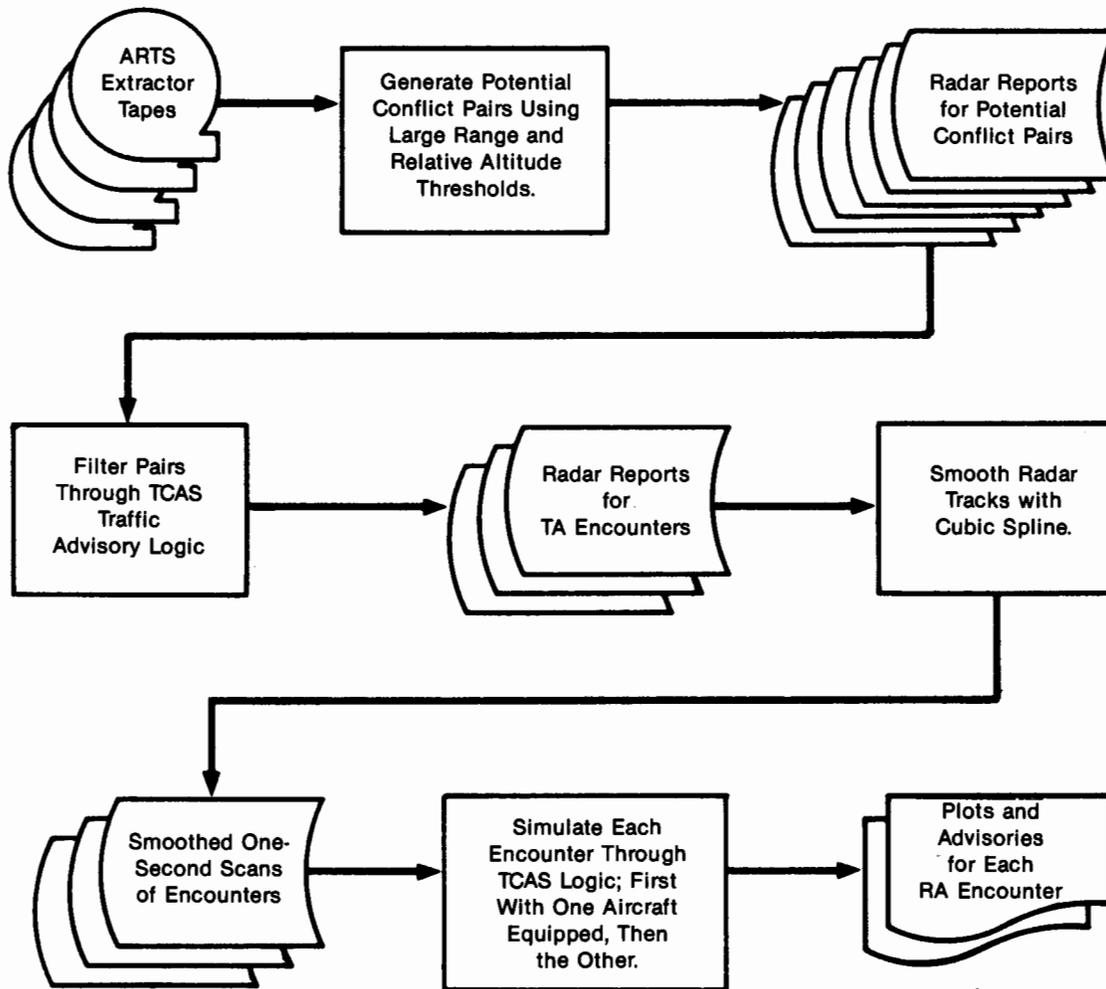
Filtering of Aircraft Tracks. Figure 2-1 summarizes the ARTS data reduction and TCAS encounter processing done for this study. The first part of the process (described in Reference 9) generated potential conflict pairs from the original ARTS tapes. The potential conflict pairs were then run through the TCAS Traffic Advisory logic to eliminate those encounters not likely to generate any advisories. This traffic filter eliminated all but 275 of the original 4000 potential conflict pairs. This large reduction is not surprising since many of the potential conflict pairs are very short, false encounters created by garbled or noisy radar reports.

Smoothing of Tracks. The filtered pairs need to have any garbled position and altitude reports removed and the tracks smoothed to minimize noise introduced by the radar. Such noise would not be contained in the range measurements of an airborne TCAS. Each aircraft track from the 275 filtered pairs is individually examined for garble and noise. After manually deleting any garbled reports, each track is smoothed with a cubic spline function. The amount of smoothing required is based on the amount of radar noise observed and the curvature of each track. This "customization" of each track is necessary to construct a realistic aircraft track for the TCAS simulation. Figure 2-2 shows a plan-view plot of the original ARTS tracks for an example conflict pair, and Figure 2-3 shows the same pair after being smoothed.

The Mode C altitude reports, however, are not smoothed. One-second reports for the TCAS simulation are created by linear interpolation of the non-garbled Mode C reports. The reports are then requantized to 100 ft increments.

Simulation Through the TCAS Logic. Once the aircraft tracks are smoothed, the simulation programs developed for the analysis of TCAS II flight tests (Reference 11) are used to simulate the encounters and generate plots and statistics for analysis. Each aircraft in a pair is separately simulated as the TCAS-equipped aircraft, with the other aircraft acting as an unequipped intruder. Therefore, each encounter is simulated twice. Advisories and statistics generated by the TCAS logic are printed for every second of each encounter. Plots are also generated to show the plan-view and vertical profile of each encounter, as illustrated by another example in Figure 2-4.

Additional Processing. To further characterize TCAS interactions with ATC, additional processing was done for the 14 encounter pairs that generated RAs. To estimate the



**FIGURE 2-1
ARTS DATA REDUCTION AND TCAS SIMULATION PROCESS**

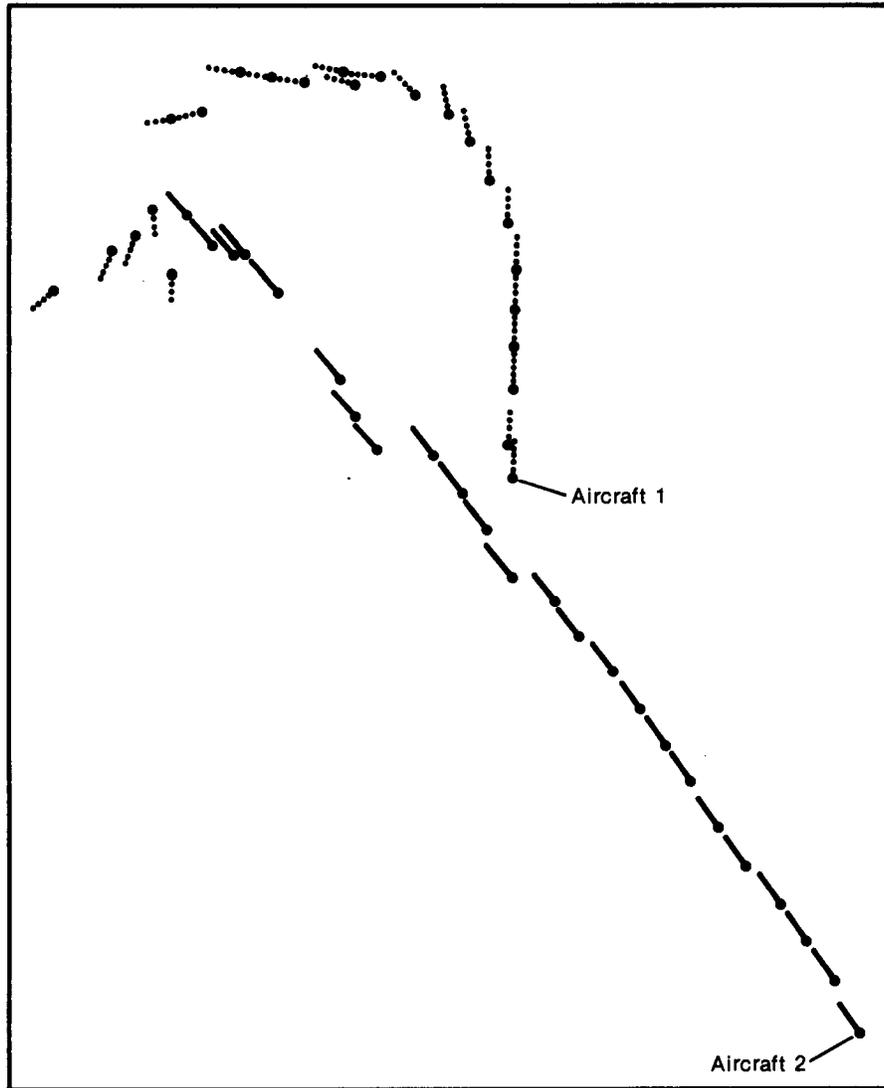


FIGURE 2-2
EXAMPLE PLOT OF UNSMOOTHED ARTS TRACKS

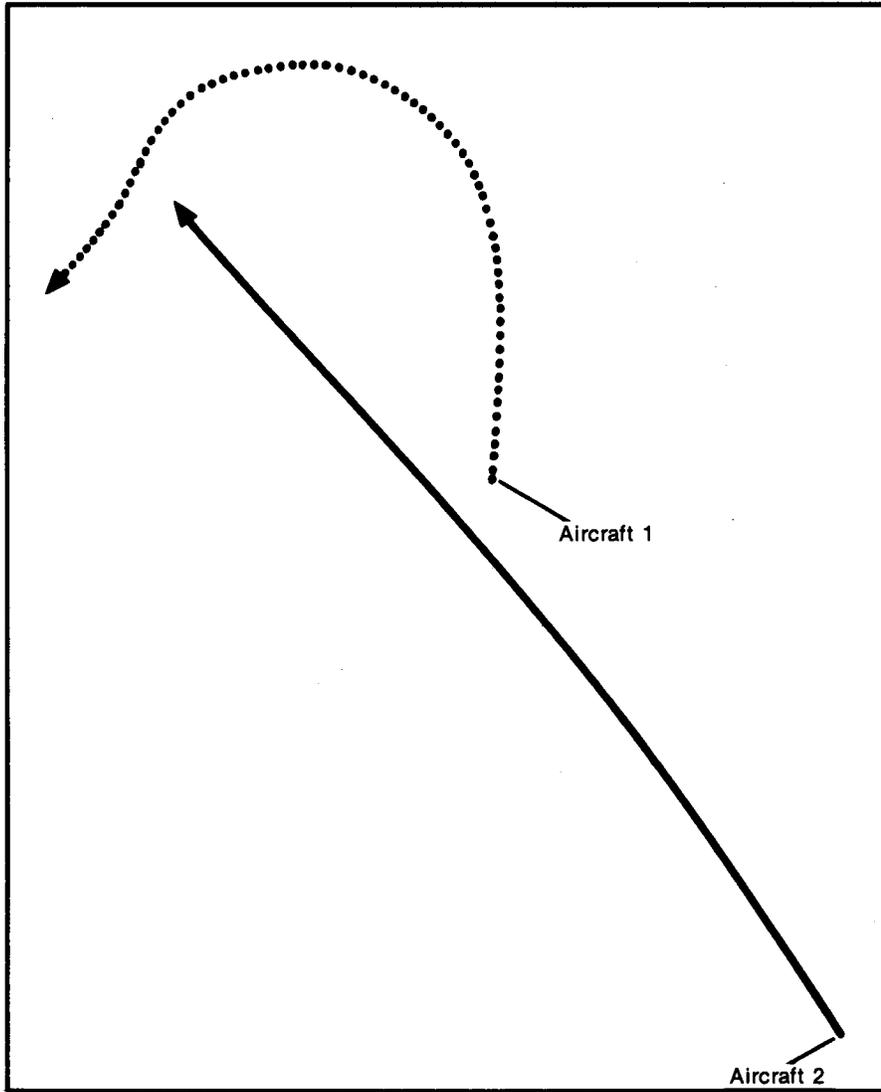


FIGURE 2-3
EXAMPLE PLOT OF SMOOTHED ARTS TRACKS

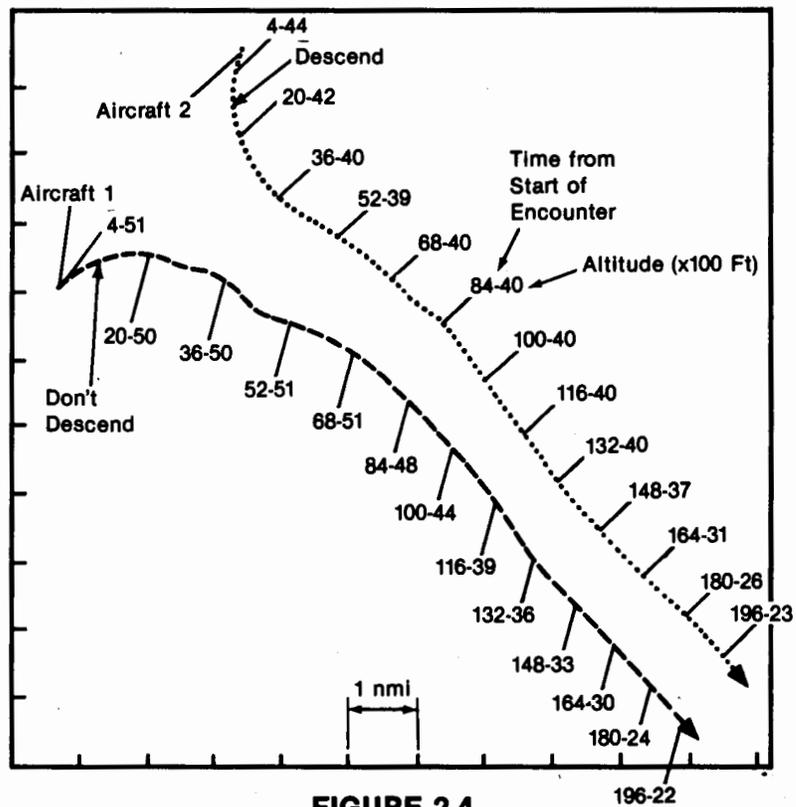
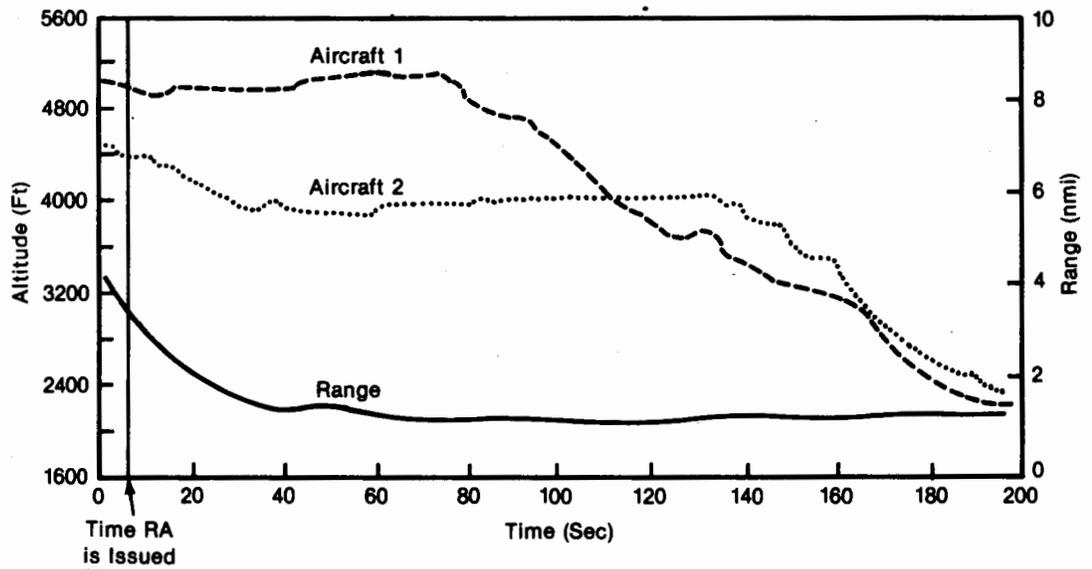


FIGURE 2-4
EXAMPLE OF VERTICAL AND HORIZONTAL PLOTS
FOR A SIMULATED ENCOUNTER

displacement from the flight path that would result from using TCAS, each aircraft is modeled as responding to its TCAS advisory. The following assumptions are made: a 5-second pilot delay occurs after the RA is issued; the aircraft accelerates at 1/4 g to the appropriate vertical rate (1500 fpm for "climb" or "descend"); this rate continues for 5 seconds after the RA is removed; and, finally, the aircraft accelerates at 1/4 g to level flight. This modeling is used to evaluate the compatibility of the RA with the intended flight path, which is obtained from the complete tracks of both aircraft.

Locating other traffic that is in the vicinity of the RA encounters from the original pair files provides the opportunity to examine the relationship of the TCAS maneuvers with the next nearest aircraft, and thus determine whether a "domino effect" would result. Special control situations such as parallel approaches or holding patterns are also studied as they are locations where TCAS-ATC interactions can result from an unplanned maneuver. Finally, the ARTS data provides information used in the risk analysis: tracks which produce RAs and TAs are examined to identify any geometries susceptible to a critical NMAC caused by an intruder maneuver.

2.2 Critical NMAC Data Bases

The critical NMAC data bases are used to determine the geometries and locations of NMAC encounters that air carrier aircraft are involved in and the nature of the intruder aircraft. Two principal data bases are used in this study: the FAA incident reports and the NASA Aviation Safety Reporting Service data base.

2.2.1 FAA Incident Reports on Near-Midair Collisions

This data base (Reference 3), collected and maintained by the FAA Office of Aviation Safety (ASF-200), was used to characterize the TCAS environment in the overall Safety Study. It provides information on NMACs such as the following:

- altitude of the encounter
- operator of the other aircraft
- type of aircraft

- flight plan of the aircraft, if known
- visibility conditions when the encounter occurred

The visibility conditions allow the extraction of IMC encounters. However, the data does not have a 3 mile visibility category; visibility is reported in categories of less than 1 mile, 1 to 5 miles, or higher categories. Throughout this study, in general we include the data up to 5 miles visibility, since visibility of less than that may not support effective use of visual acquisition.

When supplemented with other data, this data base can be used to determine the following:

- the risk of encountering an NMAC in IMC
- the transponder equipage of the aircraft encountered

The number of incidents reported in IMC is small; in the 5 miles or less category there are only 14 reported incidents over 8 years. Because of this, a cross check with the NASA Aviation Safety Reporting Service was sought.

2.2.2 NASA Aviation Safety Reporting Service

A description of the purpose and nature of the NASA Aviation Safety Reporting Service (NASA ASRS) can be found in Reference 5. The NASA ASRS grew out of an FAA Aviation Safety Reporting Program that was established in May 1975 to improve the flow of safety information for the purpose of aiding FAA safety investigations and research. A key provision of the program was the offer of a limited waiver of disciplinary action to those reporting and to those involved in the incidents. In spite of this immunity, it was apparent there were misgivings in the aviation community about reporting to the FAA; consequently, the FAA asked NASA to act as a "third party" in handling the program for them. The NASA ASRS began operating in April 1976.

The NASA ASRS provides a confidential reporting service for incidents involving safety in the National Airspace System. Part of its data collection effort includes the collection and maintenance of reports of NMACs. These are received and "de-identified," a process that involves removing references in the report of an incident that could be used to identify either the reporter, another person, an airline, or any other entity.

Together with the FAA offer of immunity, this provides for the perception of a higher likelihood that an incident will be reported.

The ASRS NMAC data base contains information similar to the FAA data base, such as altitude, type of aircraft, operator, and weather conditions. It differs in some respects, however. The FAA investigates all reported incidents; the ASRS may contact a reporter for more information before de-identification, but are not permitted to verify any information through other contacts. ASRS resources do not provide for investigation.

Examination of the ASRS data shows an extreme fluctuation in the rate of reports of critical NMACs in which air carriers were involved in IMC. The data base started in mid-1978, and for the remainder of that year reports came in at a slow rate (2 in an 8-month period). In early 1979, the rate increased, averaging 1 a month through the end of 1979. After that, the rate slowed to approximately the same as in the FAA data base, about 2 incidents per year involving air carriers. (There are no reports at all for the first 4 months of 1984.)

Given the voluntary nature of the ASRS data base, this study uses the FAA reports of NMACs to establish the approximate level of risk of a critical NMAC in IMC. As will be seen, even use of the highest rate seen in the ASRS data base results in an estimate of today's level of risk that is within an order of magnitude of the estimate based on the FAA data base.

2.3 Flight Progress Strips Data Base

One means of identifying the types and transponder equipage of IFR aircraft flying in IMC is by examination of the flight progress strips used by controllers. Flight progress strips for three aircraft are illustrated in Figure 2-5. The operator can be identified through the call sign, printed at the upper left-hand side. The "EA630" on the flight strip in (a) indicates Eastern Airlines flight 630; the "AGAR17" in (b) indicates a military flight; and the "N" followed by a series of numbers in (c), a general aviation flight. The aircraft type and equipage are indicated on the line below the call sign, separated by a slash. EA630 is a McDonnell-Douglas DC-9; AGAR17 is a C135 transport; and N777MC is a Lear Model 55. All three are equipped with altitude-encoding transponders, as indicated by codes following the aircraft type ("A", "P", "R", or "U" indicate altitude-encoding transponders).

EA630 DC9/A T439 G404 257 ²⁰ 03	RDU 041 041 1542	15 46	330 270 280 290	RDU LVL RIC J40 MARBY J150 OOD PROUD4 LGA	0537
		LVL			

a) Airline Aircraft

AGAR17 C135/A T420 G380 271 ²⁰ 06	MODEL 1553	15 56	250 240 225	ADW./V33 HCM ORF SWL/D2+00 SWL	4713
		HCM		O DELAY AT SWL FOR H OLDING TEST ORBITS	

b) Military Aircraft

N777MC LR55/R T440 G351 149 ²⁰ 04	RIC 1548	15 57	390 270 170 110	TEB./RIC J14 V3 STEMM-RDU	1510
		NUTTS			

c) General Aviation Aircraft

2-11

FIGURE 2-5
EXAMPLES OF FLIGHT PROGRESS STRIPS

For the purposes of this study, flight strips were collected in varying environments:

- a high density Terminal Control Area (TCA):
Philadelphia, PA
- a lower density Terminal Radar Service Area (TRSA):
Albany, NY
- several sectors in an Air Route Traffic Control Center (ARTCC): one low, one intermediate, and one high sector in the Washington Center

Flight strips were collected for two peak hours in IMC on two days for the center and one day for each of the terminals. A format was devised for entry of the data contained on the strips into a computer for analysis using the Statistical Analysis System. A check of these results was obtained by comparing these results with a separate flight strip data collection done for all conditions (Reference 18).

3. THE IMC ENVIRONMENT

As noted in the overall System Safety Study, the performance of TCAS depends on the environment in which it is used. IMC presents a significant change in environment: aircraft are not operating under visual flight rules, as was largely the case in overall conditions. Consequently, changes are expected in the frequency and geometries of the encounters and in the nature of the intruders. These factors affect the rates of occurrence of the failure modes, which are dependent on the environment. For example, the degree to which an error in reported altitude can induce a critical NMAC is dependent on the geometry of an encounter.

This section characterizes the IMC environment from the NMAC data bases, flight progress strips, and ARTS extractor data. These characteristics are then applied to the calculation of the effects of the failure modes, particularly altimetry errors and maneuvering intruders. Section 4 incorporates these results into the fault tree calculations.

3.1 Encounter Statistics

3.1.1 Critical NMAC Risk in IMC

Table 3-1 shows the number of critical NMACs involving IFR air carriers during the years 1973 to 1980 for both IMC and overall conditions. For IMC, all encounters involving at least one air carrier aircraft in five miles visibility or less were counted. The "number of incidents" represents the number of critical NMAC reports. In some instances, both aircraft involved in the NMAC are air carriers; the "number of IFR air carriers" represents the total number of airline aircraft involved in the incidents, and is the basis for evaluating the risk of a critical NMAC for air carrier aircraft. The number of incidents in IMC appears fairly constant at less than 2 per year; IFR air carriers are involved in these at a rate of about 2 per year. The number of incidents and air carriers in all conditions is provided for comparison.

Table 3-2 shows the comparison between the FAA NMAC data for air carrier aircraft in IMC and that received by the NASA ASRS. Data in the NASA data base runs from May 1978 through May of 1984. There is a sharp peak in the data for 1979 and 1980, with 12 and 9 incidents reported in each of those years; however, after 1980 the rate settles down to 2 or 3 per year, similar to the FAA rate. The peak during 1979-80 provides an indication of the under-reporting of these events.

TABLE 3-1
 CRITICAL NEAR MIDAIR COLLISIONS
 INVOLVING AIR CARRIERS
 1973-1980

IMC (Visibility of 5 miles or less)			ALL CONDITIONS	
Year	No. of Incidents	No. of IFR Air Carriers	No. of Incidents	No. of IFR Air Carriers
1973	2	3	9	12
1974	3	3	11	12
1975	2	3	6	7
1976	1	2	15	17
1977	2	2	13	14
1978	2	2	14	15
1979	0	0	20	20
1980	2	2	17	17
TOTAL	14 (2 per yr)	17 (2 per yr)	105 (13 per yr)	114 (14 per yr)

Source: FAA Reports of Near Midair Collisions 1973-1980

TABLE 3-2
 COMPARISON OF FAA NMAC DATA WITH NASA ASRS DATA
 (Instrument Conditions)

FAA			NASA ASRS		
Year	No. of Incidents	No. of IFR Air Carriers	No. of Incidents		No. of IFR Air Carriers
1973	2	3			
1974	3	3			
1975	2	3			
1976	1	2			
1977	2	2			
1978	2	2	1978	2 (8 mo.)	3 (8 mo.)
1979	0	0	1979	12	13
1980	2	2	1980	9	10
Total	14 (2 per yr)	17 (2 per yr)	1981	3	3
			1982	2	2
			1983	3	3
			1984	0 (5 mo.)	0 (5 mo.)
			Total	31 (5 per yr)	34 (5 1/2 per yr)

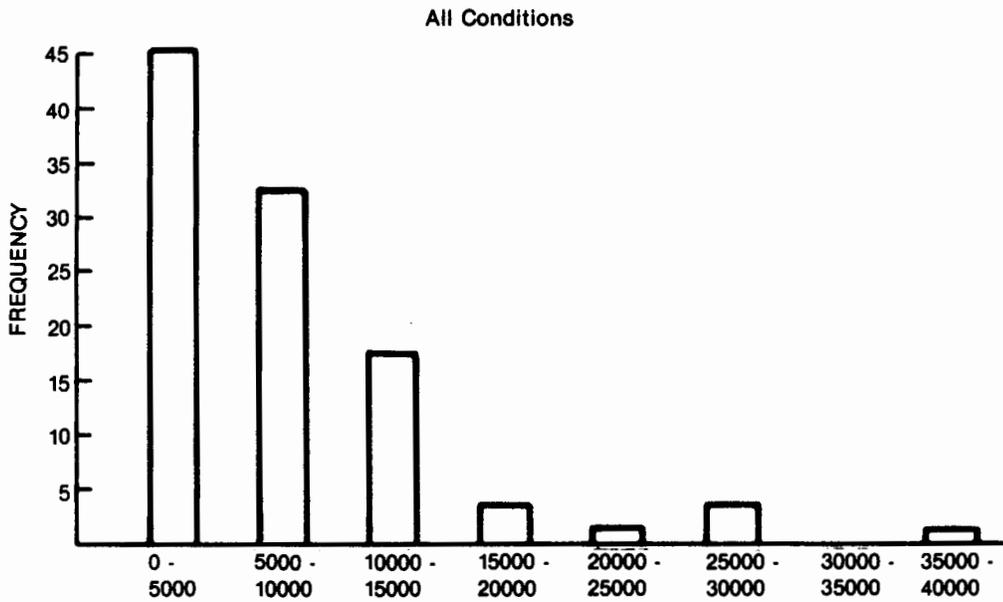
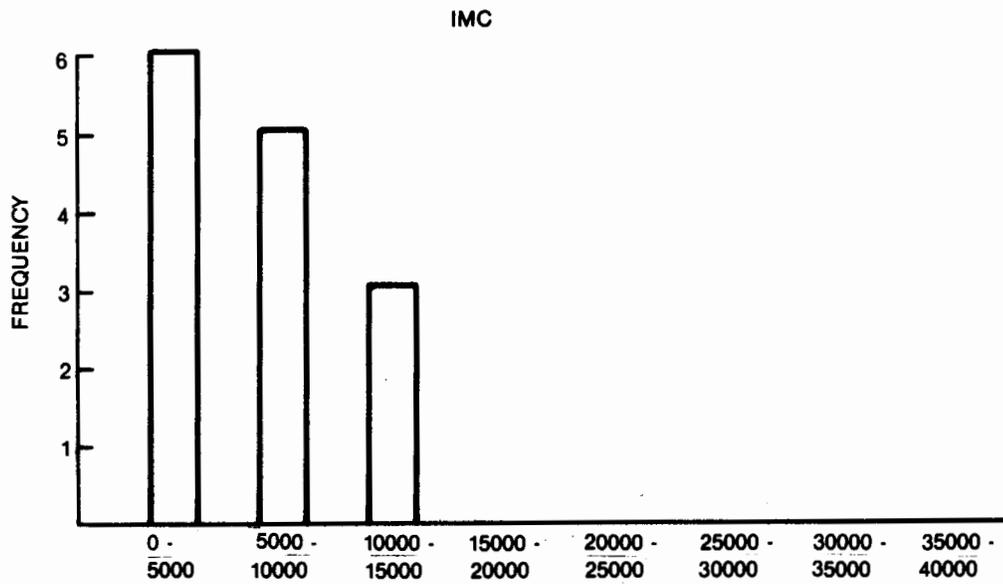
Sources: FAA Reports of Near Midair Collisions 1973-1980
 NASA Aviation Safety Reporting Service

Reference 6 gives the number of hours air carriers fly per year, which was 8×10^6 for 1979 and 1980 (pre-strike). An estimate of air carrier flight hours in IMC is obtained by factoring by the fraction of flight time in IMC. An estimate of this fraction was obtained by consulting airline representatives. These representatives stated that, based on pilot logbooks, air transport pilots generally fly about 5 percent of the time in low visibility conditions, which are defined as those times when the pilot is flying without any outside references--typically less than 1 mile visibility. From this, it is estimated that there were 4×10^5 flight hours per year in visibility less than 1 mile. From the FAA NMAC data base, there were 8 IFR air carrier aircraft involved in 7 NMACs during the 8 year period 1973-1980 in which visibility was less than 1 mile. The risk of a critical NMAC in the lowest visibility conditions is thus computed to be 2.5×10^{-6} per flight hour. This is quite similar to the value obtained from the FAA data base for overall conditions, which was 2.8×10^{-6} per flight hour. Based on this estimate for the lowest visibility conditions (less than one mile), it is concluded that in today's ATC environment, the risk in IMC is about the same as that in overall conditions.

The lower density of traffic associated with an all-IFR environment that is characteristic of IMC makes this an unanticipated result. However, the risk represents an average for the environment; one must take into account other characteristics of an IMC environment before interpreting this result. The key factors used to interpret this result are the altitudes and locations of NMACs occurring in IMC.

3.1.2 Altitudes and Locations of NMACs

The altitude distribution of NMACs is shown in Figure 3-1. The distribution for overall conditions is also provided for comparison. The distributions are similar at the lower altitudes; but there are no reported incidents in IMC above 15,000 ft. The NASA ASRS data supports this, with only 1 incident over 15,000 ft. While most NMACs occur at low altitudes even in VMC, the lack of incidents above 15,000 ft in IMC is considered significant. According to the FAA/National Weather Service publication "Aviation Weather" (Reference 7), the most common "IFR producers" are fog, low clouds, haze, smoke, blowing obstructions to vision, and precipitation. What these weather conditions have in common are that they are low altitude phenomena and not normally encountered at altitudes that air carriers fly en route.



**FIGURE 3-1
ALTITUDE DISTRIBUTION OF NMACs**

When air carrier aircraft are at low altitudes (less than 15,000 ft), it is typically because they are arriving or departing a terminal area. Examination of the locations of IMC NMACs confirms this, and in addition shows that most occurred near high-volume airports:

LOCATIONS OF IMC NMACS

- Chicago
- Atlanta
- Deer Park (Chicago)
- Norfolk
- Philadelphia
- Ontario (Los Angeles)
- Oklahoma City
- Hayward (San Francisco)
- Patchogue (New York)
- San Diego
- Dallas/Ft. Worth
- International Falls
- San Antonio
- La Guardia (New York)

An IMC environment for air carriers is thus a terminal environment as well. This provides an explanation of why the average risk in IMC is as high as the average risk in all conditions: even though a direct comparison of an IMC environment and an equivalent VMC environment--in this case terminal only--would show greater risk in VMC, IMC flying time for air carriers includes terminal areas only; VMC includes an average of terminal areas (high risk) and en route areas (low risk).

3.1.3 Aircraft Encountered

Table 3-3 shows a breakdown of the operators of aircraft encountered in critical NMACs in both IMC and all conditions. The most significant difference for IMC is that the fraction of air carriers has doubled. The fraction of General Aviation and "other" (e.g., air taxi, commuter) aircraft has decreased, but only slightly, to 64 percent of the population in IMC compared with 71 percent in all conditions.

Table 3-4 shows the types of aircraft encountered in NMACs in IMC. Piston-engine aircraft constitute more than half those aircraft encountered. Given that 64 percent of aircraft encountered are General Aviation and these are a large number of piston-engine aircraft, it is assumed there is a large number of aircraft encountered with baseline (uncorrected) altimetry systems in IMC. Consequently, the analysis of the effect of altimetry errors on TCAS will use the same error magnitudes for IMC as for overall conditions.

TABLE 3-3
OPERATORS OF AIRCRAFT ENCOUNTERED IN NMACs

	IMC		ALL CONDITIONS	
	Number	Percent	Number	Percent
Air Carrier	6	36	18	17
General Aviation	9	56	75	69
Military	0	0	13	12
Other	1	8	2	2
TOTAL	16 (1 unk.)		108 (6 unk.)	

Source: FAA Report of Near Midair Collisions 1973-1980

TABLE 3-4
 TYPES OF AIRCRAFT ENCOUNTERED IN NMACs IN IMC

AIRCRAFT TYPE	NUMBER	PERCENT
Air Carrier Turbojet	6	40
Twin Turboprop	1	7
Multiengine Piston	5	33
Single-engine Piston	3	20
TOTAL	15 (2 unk.)	

Source: FAA Reports of Near Midair Collisions 1973-1980

3.1.4 Fraction of Aircraft on IFR Flight Plans

The FAA NMAC data base was examined to determine the fraction of aircraft flying in IMC or marginal VMC that are on an IFR flight plan. Of the 17 aircraft encountered in visibility of 5 miles or less, only 8 were known to be on an IFR flight plan. Five were on VFR or no flight plan, and 4 were unknown. (All 8 aircraft with IFR flight plans were in less than one mile visibility; however, there was one instance of a non-IFR flight plan in visibility this low.) This information will be used to infer the level of transponder equipage.

3.1.5 Fraction of Transponder Equipage

Table 3-5 shows the fraction of aircraft in the IFR flight strip data base that are transponder-equipped and that have altitude-encoding. Since it was shown earlier that IMC NMACs occur below 15,000 ft, flight strips from high sectors in the data base were removed. Virtually all aircraft flying on IFR flight plans were found to be transponder equipped and reporting Mode C, even in a terminal such as Albany, New York, where a large fraction of the aircraft are GA.

This result is supported by a separate analysis of transponder equipage (Reference 18). In this analysis, System Analysis Recording (SAR) tapes were collected from seven Air Route Traffic Control Centers (ARTCCs) without regard to weather conditions. The SAR tapes contain both primary and secondary radar data for controlled aircraft and define precisely the percentage of Mode C, Mode A only, and non-transponder aircraft. This study found that the fraction of Mode C equipped aircraft in the various centers ranged from 92 to 99 percent; of the remainder, in most cases all but 1 percent were Mode A equipped, leaving 0 to 1 percent unequipped with transponders.

However, as seen in the preceding section, not all aircraft encountered in critical NMACs are on flight plans. The following method is used to estimate the fraction of Mode C equipage: all aircraft encountered that were flying on an IFR flight plan are assumed to have Mode C transponders; the likelihood that the remaining aircraft are Mode C equipped is estimated from the type of aircraft, using the 1981 General Aviation Avionics survey.

TABLE 3-5
 PERCENTAGE OF AIRCRAFT FLYING ON IFR FLIGHT
 PLANS ON AN IMC DAY THAT HAVE TRANSPONDERS

LOCATION	TRANSPONDER EQUIPPED	
	Yes	No
Washington ARTCC (low & intermediate sectors)	317 (100%)	0 (0%)
Philadelphia (TCA)	182 (100%)	0 (0%) (8 unk.)
Albany (TRSA)	82 (100%)	0 (0%) (2 unk.)

LOCATION	ALTITUDE ENCODING	
	Yes	No
Washington ARTCC (low & intermediate sectors)	317 (100%)	0 (0%)
Philadelphia (TCA)	173 (98%)	3 (2%) (14 unk.)
Albany (TRSA)	79 (99%)	1 (1%) (4 unk.)

Table 3-6 illustrates the calculation. From the FAA data base, 15 of 17 aircraft encountered were either on an IFR flight plan or the type of aircraft was known. For those not on an IFR flight plan, column A lists the fraction of aircraft of the type that are Mode C equipped. Column B shows the fraction of IMC NMACs with aircraft of this type. The probability of an intruder being Mode C equipped is obtained by summing the products of column A and column B for each type, with the result that 84 percent of intruders in IMC are expected to be Mode C equipped. This represents a substantial increase from overall conditions, where only 61 percent of intruders are expected to be Mode C equipped.

3.1.6 Vertical Distribution

A key result of the overall Safety Study was that in overall conditions the distribution of altitude separation at closest point of approach is substantially uniform over the range 0 to 1000 ft. This result was used in calculating the risk of TCAS inducing an NMAC, either because of erroneous altimetry or because of sudden intruder maneuvers; the principal danger zone for these phenomena occur with actual vertical separations of 300 to 700 ft. The question to be explored is, "Is the vertical distribution of aircraft different in IMC than in overall conditions?"

The vertical distribution for IMC was analyzed from the Chicago ARTS data base. Vertical separation at closest point of approach was noted for all encounters generating TCAS Advisories. Parallel approaches were analyzed separately, since aircraft are placed in intentional close proximity in these circumstances. The resulting distribution of vertical separation is shown in Figure 3-2.

This data is clearly not uniform from 0 to 1000 ft. It shows two peaks, one at 0 and one at 1000 ft separation, and a "valley" in the 400 to 600 ft range, where VFR traffic would normally be encountered in visual conditions. The uniform shape of the distribution observed in overall conditions implies that an encounter with vertical separation of approximately 500 ft is as likely as an encounter with a separation of 100 ft (a critical NMAC). Applying the same reasoning to the distribution observed in IMC, an encounter with about 500 ft separation is found to be less than half as likely as one with 100 ft separation, and the risk of an induced NMAC is reduced accordingly. The following two sections will calculate this risk.

TABLE 3-6
 CALCULATION OF PROBABILITY THAT INTRUDER
 IS MODE C-EQUIPPED

AIRCRAFT TYPE	<u>A</u> MODE C EQUIPAGE (fraction of type)	<u>B</u> FRACTION OF NMACs WITH THIS TYPE	<u>C</u> A x B
Single-Engine Piston			
1-3 seats	.03	1/15	.002
4 + seats	.34	1/15	.023
Two Engine Piston	.82	4/15	.22
Turboprop	.92	1/15	.06
IFR Flight Plan	1.0	8/15	.53
TOTAL			.84

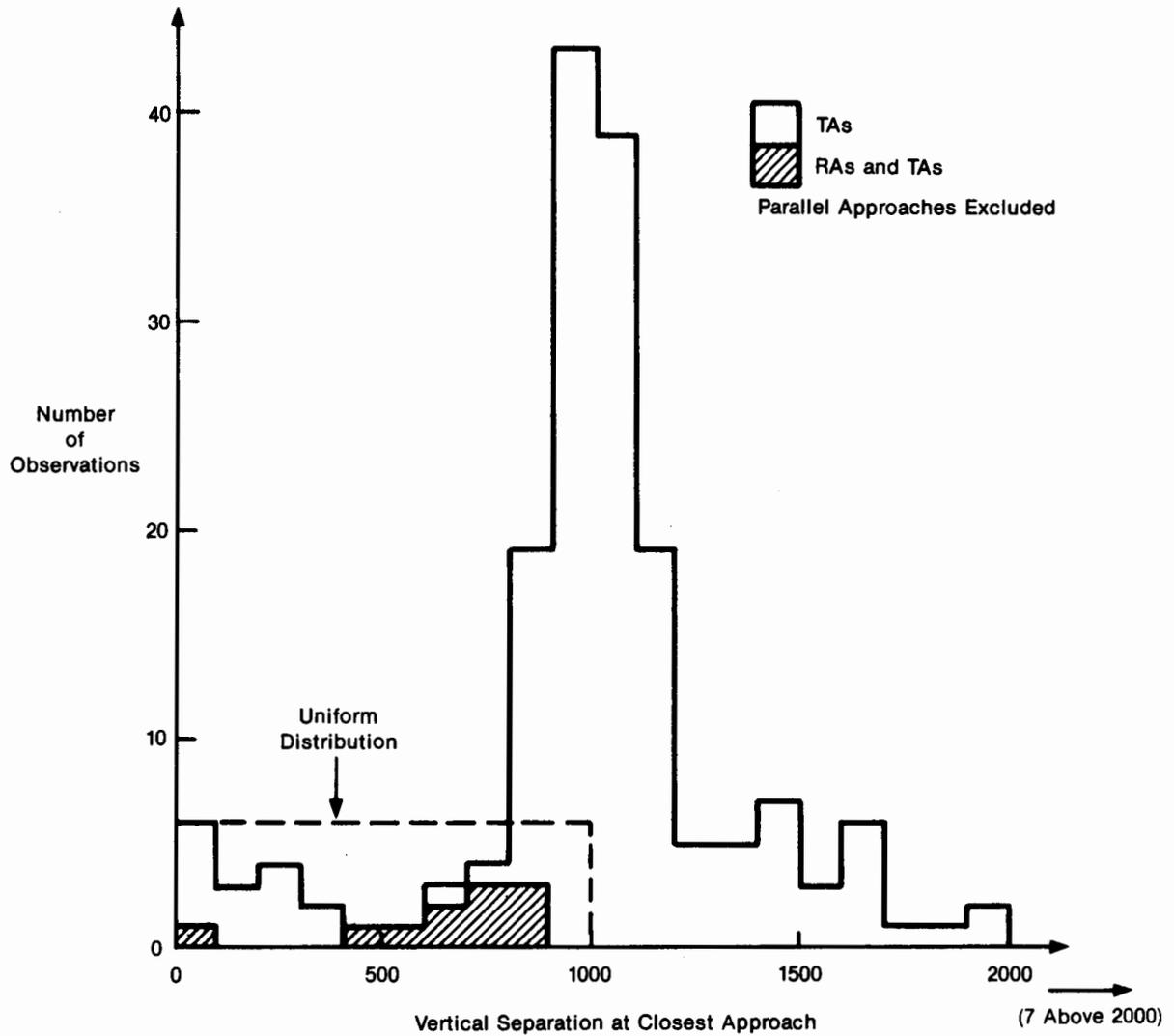


FIGURE 3-2
DISTRIBUTION OF VERTICAL SEPARATION AT CLOSEST APPROACH
FOR ADVISORY-PRODUCING ENCOUNTERS IN THE
CHICAGO TERMINAL AIRSPACE IN IMC

3.2 Impact of Altimetry Errors in IMC

A critical NMAC due to altimetry error can occur with the use of TCAS under two circumstances:

- An encounter that is an NMAC would have occurred without TCAS; altimetry error renders TCAS ineffective (unresolved NMAC).
- An encounter would have occurred that, while close, would not be an NMAC; an error in the intruder's altitude report causes TCAS to generate an RA that results in an NMAC (induced NMAC).

As the descriptions imply, specific combinations of altitude separation and error in reported altitude must exist to result in an NMAC. The nature of these conditions does not change in the IMC environment; what changes is their frequency of occurrence. The factors that change and their impact on the computation of the altimetry error risk ratio are discussed here; details of the computation can be found in Appendix A.

3.2.1 Unresolved NMACs

An unresolved NMAC occurs when a TCAS-equipped aircraft encounters an intruder with less than 100 ft of vertical separation and a TCAS RA (if provided) does not increase separation to more than 100 ft because of an error in the intruder's reported altitude. The Risk Ratio, which is the ratio of the probability of an unresolved NMAC to the rate at which NMACs occur today, is the probability that in a critical NMAC situation an altitude error in an intruder's reported altitude is large enough that the displacement required to resolve the NMAC is not generated by the TCAS-equipped aircraft. This requires that the error be approximately ALIM in size, or larger, where ALIM is a TCAS logic parameter defining the altitude separation TCAS attempts to achieve.

The reason for this is illustrated in Figure 3-3. TCAS, if within ALIM ft of the intruder's apparent altitude, will instruct the pilot to maneuver until it is ALIM + 75 ft away from that altitude. In order for there to be insufficient displacement in a critical NMAC situation, the intruder must appear to be separated in altitude by ALIM ft; TCAS would thus perceive satisfactory separation and not call for a maneuver to increase separation. This requires an error in reported altitude equal to ALIM less the critical NMAC separation criterion (100 ft).

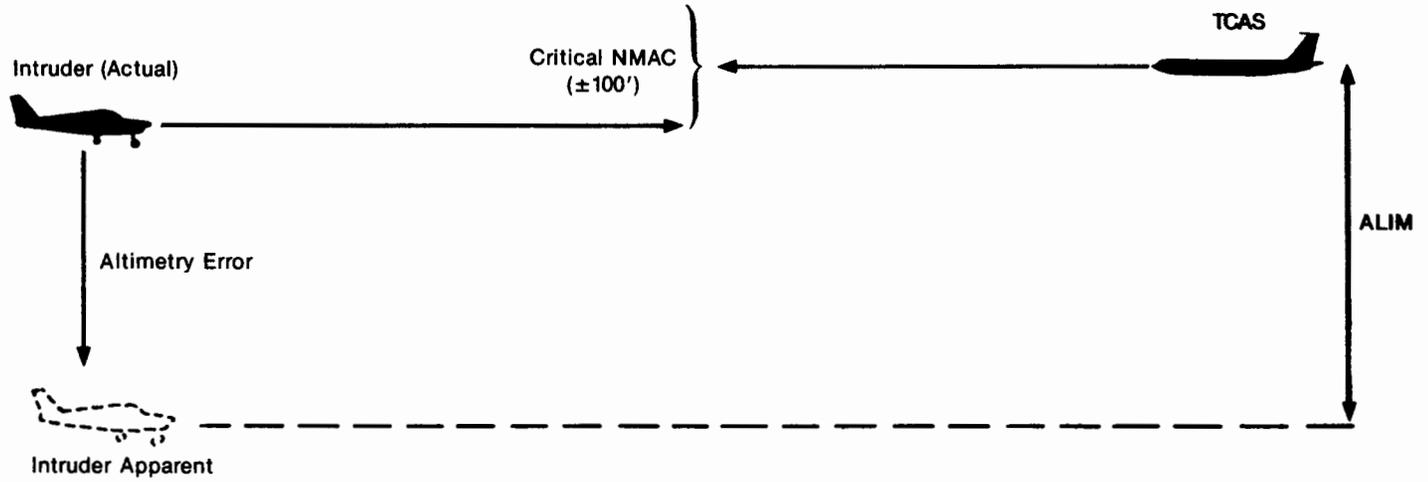


FIGURE 3-3
MINIMUM ERROR IN REPORTED ALTITUDE REQUIRED
TO PRODUCE UNRESOLVED NMAC

The probability of an error of this magnitude is affected by the quality of altimetry equipment in aircraft encountered by TCAS in IMC. As was the case in overall conditions, it is assumed that TCAS encounters aircraft with two different levels of altimetry equipment: high-quality altimetry, which includes corrections such as those provided by air data computers and is typically found on commercial air carriers; and lower-quality altimetry without such corrections, as would be found on most lower cost GA aircraft. While there is a requirement for checks of altimetry equipment for aircraft flying IFR (Appendix C), it is not possible to assess the impact of these checks on altimetry errors; consequently, each class of system is assumed to have the same error distributions and magnitudes as in overall conditions (no changes from the overall System Safety Study).

Three factors which determine TCAS exposure to these errors change in IMC:

- the mix of high-quality to lower-quality altimetry
- the altitudes at which encounters occur
- the probability that the intruder has Mode C

As shown in Section 3.1, the fraction of aircraft encountered in critical NMACs in IMC that are GA, and are assumed to have uncorrected systems, is .64 (compared to .80 for overall conditions). As encounters with air carrier (corrected) altimetry systems do not produce a significant level of risk relative to uncorrected systems, this fraction directly reduces unresolved risk due to altimetry error.

The altitudes at which critical NMACs occur affect the risk, because the collision avoidance parameters (e.g., ALIM) vary with altitude. The distribution of altitudes at which critical NMACs occur is similar for both IMC and overall conditions, except that NMACs were not observed above 15,000 ft in IMC. The result is a slight increase in Risk Ratio from these differences, but a smaller change than the decrease caused by less exposure to uncorrected altimetry.

As shown in Table 3-6, the fraction of aircraft in IMC with Mode C is estimated to be .84. This is an increase from overall conditions, which is .61, and increases the unresolved Risk Ratio.

The calculation of Risk Ratio due to altimetry error is described in Appendix A. It shows that the Risk Ratio for unresolved NMACs due to altimetry errors in IMC is .010. This number means that TCAS will not resolve 1 percent of those NMACs occurring today because of an error in the intruder's report of altitude. This represents an increase compared with overall conditions, for which the comparable risk is .003. The improvement in Risk Ratio due to the greater numbers of corrected altimetry systems in IMC does not compensate for the greater exposure to uncorrected systems (higher Mode C equipage) and lack of visual acquisition, resulting in an increase in the unresolved Risk Ratio due to altimetry errors.

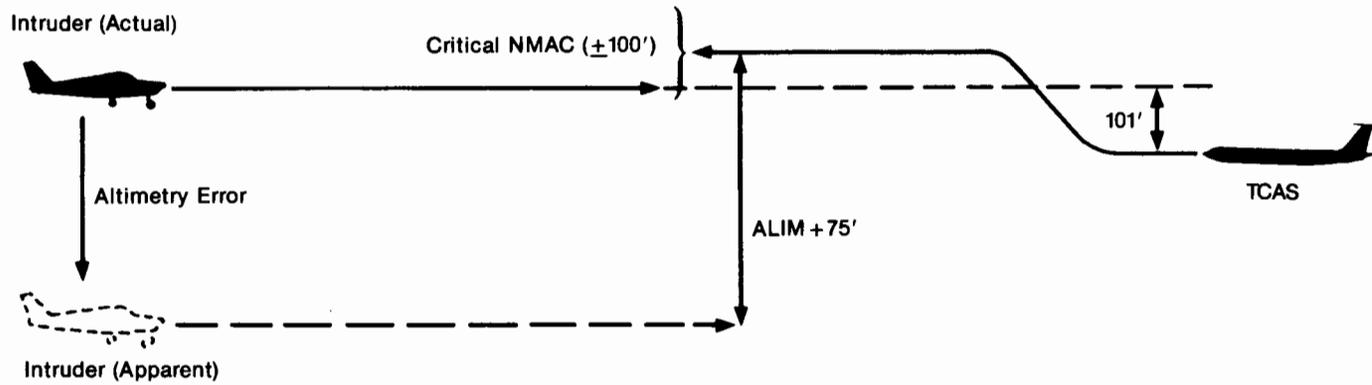
3.2.2 Induced NMACs

An induced critical NMAC occurs when a TCAS-equipped aircraft encounters an intruder greater than 100 ft altitude separation, and a RA is issued that--because of an error in the intruder's report of altitude--decreases the separation to 100 ft or less. The Risk Ratio for induced NMACs is the probability of the occurrence of those combinations of altitude separations and altimetry errors that would induce a critical NMAC relative to the rate at which NMACs occur today.

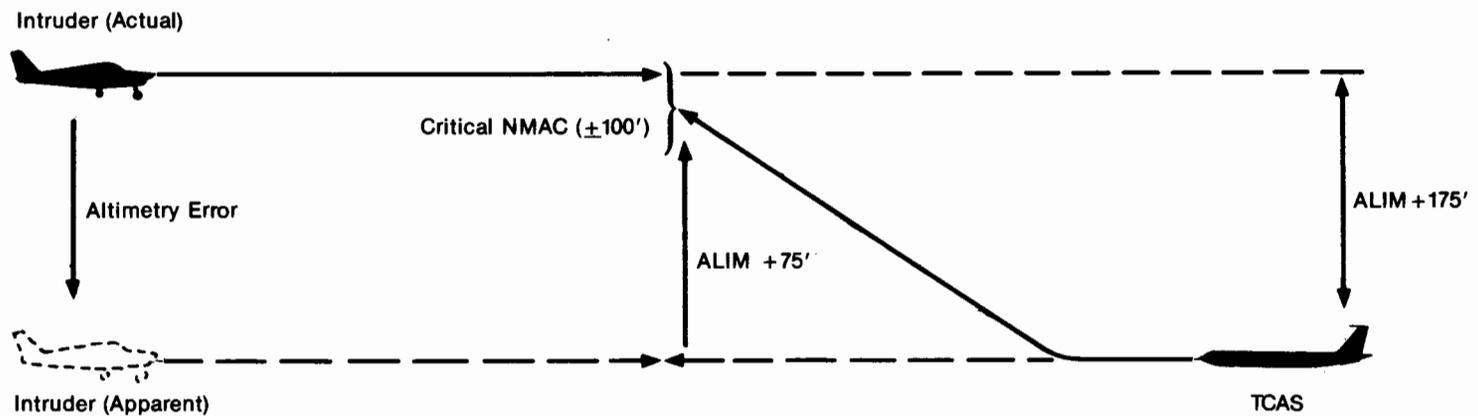
As was the case with unresolved NMACs, changes in the altitudes at which NMACs occur and the larger fraction of corrected altimetry in IMC do not substantially change TCAS susceptibility to induced NMACs; and once greater transponder equipage and lack of visual acquisition is taken into account, there is an increase in TCAS susceptibility based on these factors. What lowers TCAS susceptibility is less exposure to aircraft with altitude separations such that induced NMACs can occur.

Only aircraft passing a TCAS aircraft with altitude separation from 100 ft (just larger than critical NMAC separation) to ALIM + 175 ft (a maximum of 675 ft, since the largest ALIM for a critical NMAC observed in IMC is 500 ft) are susceptible to induced NMACs, as illustrated in Figure 3-4. The larger limit is depicted in Figure 3-4(b); it occurs when a TCAS encounters an intruder with a large altimeter error equal to ALIM + 175 ft. The altitude error of the intruder makes the intruder appear coaltitude; the TCAS aircraft climbs the maximum displacement of ALIM + 75 ft, ending up just within 100 ft of the intruder.

These conditions define a region of relative altitude for which TCAS is susceptible to induced NMAC both in overall conditions and in IMC. In overall conditions, the distribution of



a) Separation Must be More than 100' from the Intruder's Actual Location for Induced NMAC



b) Separation Cannot be More Than ALIM + 175' from the Intruder's Actual Location for Induced NMAC

3-18

FIGURE 3-4
ACTUAL SEPARATION LIMITATIONS ON INDUCED NMAC

relative altitude was observed to be substantially uniform out to at least 700 ft. This distribution has changed for IMC. Figure 3-5 shows the relevant portion of the distribution, taken from Figure 3-2. The probability of encounters in IMC with altitude separation from 100 to 700 ft, relative to the number with critical NMAC separation, shows a decrease of approximately 50 percent, with a corresponding reduction of the induced Risk Ratio. The calculation can be seen in Appendix A; it shows that the Risk Ratio for induced critical NMACs caused by altimetry errors is .0044, which is about the same as for overall (.0047). The greater numbers of corrected altimetry systems and the larger IFR separations in use in IMC effectively compensate for the higher exposure to uncorrected altimetry systems (higher Mode C equipage) and lack of visual acquisition in IMC.

3.3 Intruder Maneuvers

An intruder aircraft can cause an induced critical NMAC with a TCAS-equipped aircraft by making a sudden vertical maneuver after the time TCAS selects an RA. An example of how this can occur is illustrated in Figure 3-6. At Tau seconds prior to closest point of approach (the time at which TCAS selects an RA), the intruder has vertical rate ZDINT and altitude ZINT. The TCAS-equipped aircraft is flying level at altitude ZTCAS. The intruder is projected to continue its vertical rate and be at altitude ZPROJ at closest point of approach. TCAS compares its own altitude with ZPROJ, finds it to be less than ALIM ft, and issues a "Climb" advisory. After the advisory is issued, the intruder may change its rate; at closest point of approach its altitude is ZACT, which may be different from ZPROJ. If ZACT is within 100 ft of the altitude to which TCAS climbs, a critical NMAC results.

This section briefly discusses the methodology used to estimate the Risk Ratio due to intruder maneuvers and presents the result. Details of the computation and an analysis of the result can be found in Appendix B.

3.3.1 Methodology

The method by which the probability is estimated that an intruder maneuver would lead to a critical NMAC is substantially different from the method used in the overall Safety Study and merits discussion.

The overall Safety Study concentrated on the probability that an intruder projected to cross a TCAS-equipped aircraft,

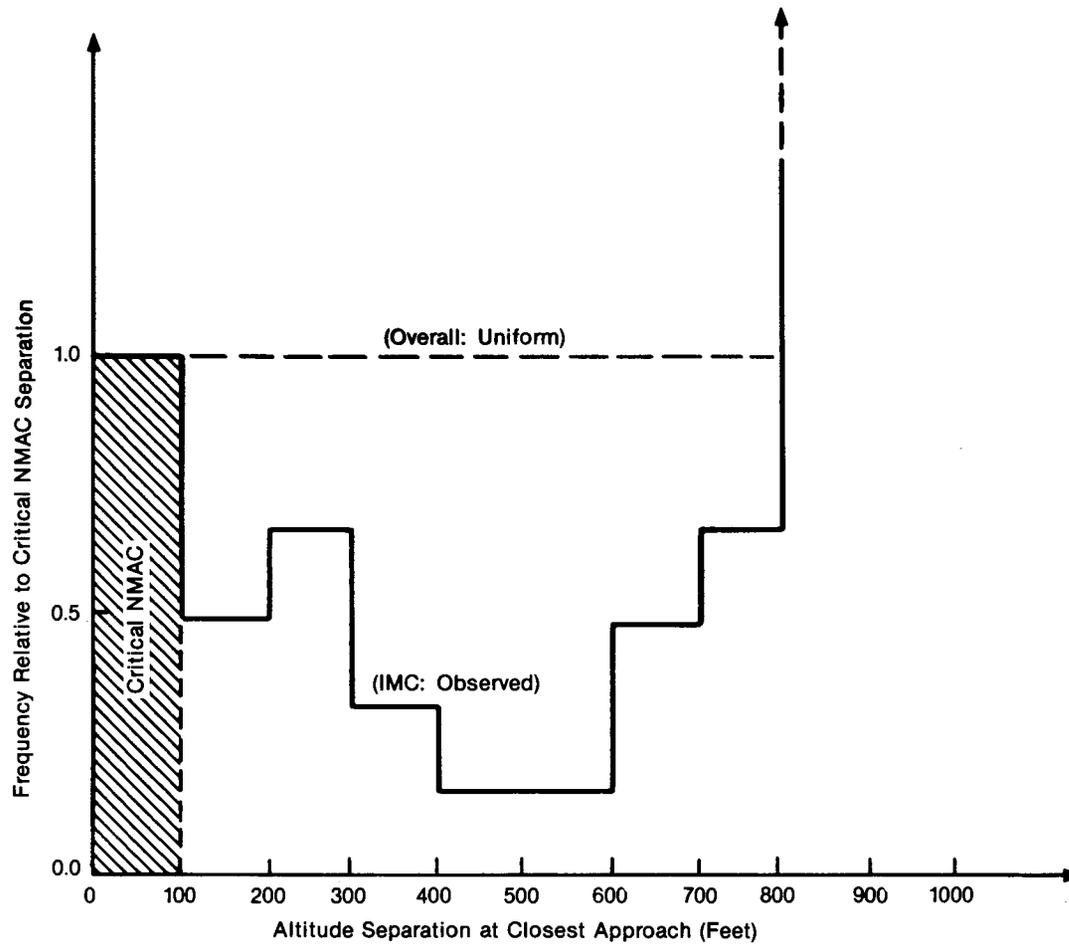


FIGURE 3-5
COMPARISON OF DISTRIBUTION OF ALTITUDE SEPARATION
IN OVERALL CONDITIONS AND IMC

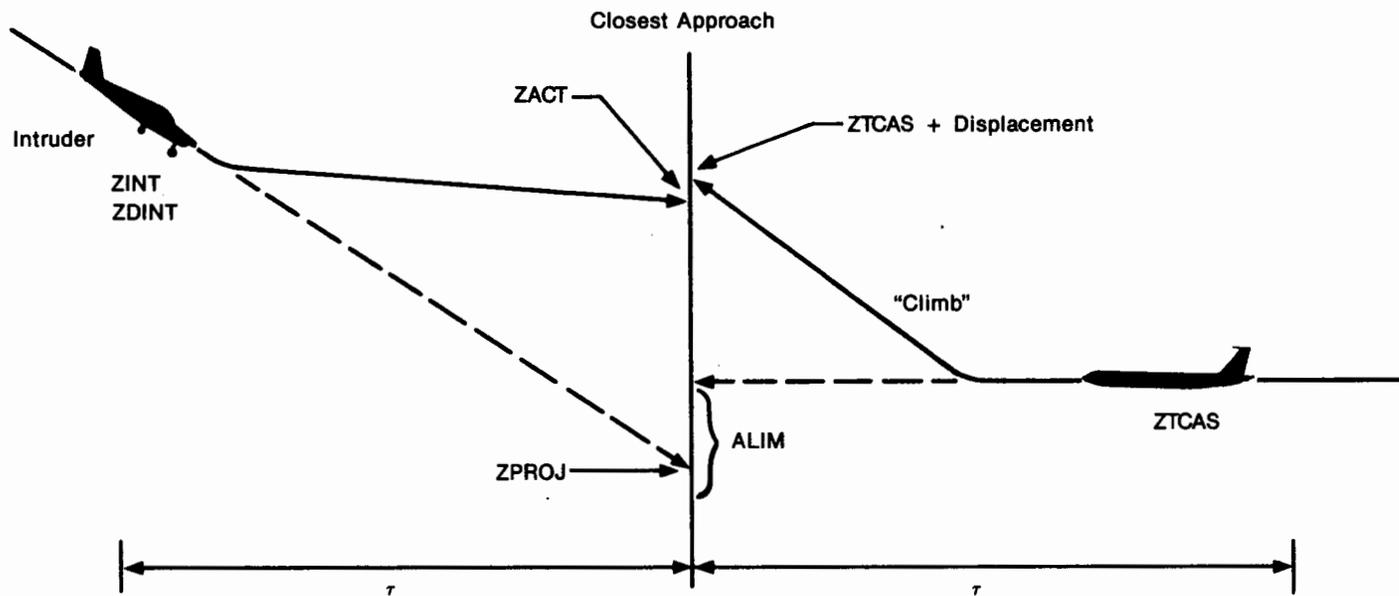


FIGURE 3-6
EXAMPLE SCENARIO OF INTRUDER MANEUVER
LEADING TO CRITICAL NMAC

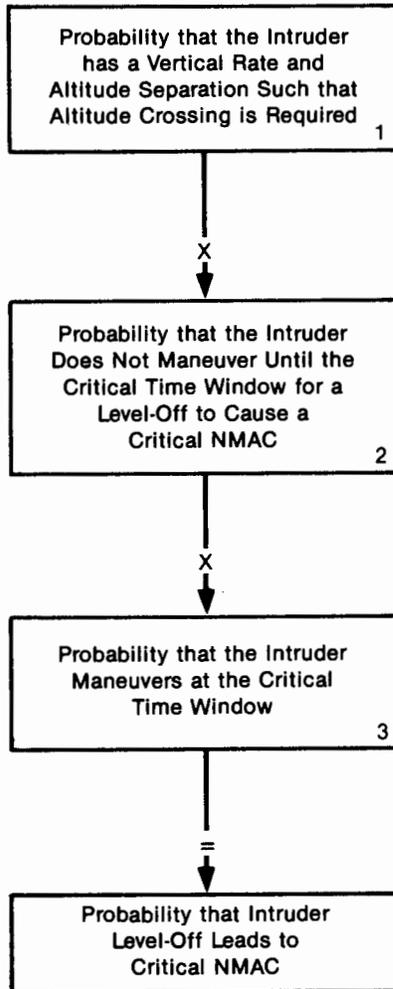
causing TCAS to choose an altitude-crossing RA, suddenly levels off, invalidating the advisory and resulting in a critical NMAC. Subsequent analysis treats other cases; however, this is the predominant case expected. The model used in the overall Safety Study has three key steps which are illustrated in Figure 3-7. Step one computes the probability that the intruder arrives with a relative altitude and vertical rate such that an altitude-crossing RA is issued. This probability was obtained from distributions of altitude and vertical rate data taken from Piedmont Phase I flights and FAA flights in a Boeing 727. The second and third steps compute the probability that the intruder maneuvers (levels off) at the right relative altitude (the "critical window"), using a Poisson model of the event "vertical acceleration" calibrated from vertical rates of intruder tracks from Piedmont Phase I and FAA flights. Step two calculates the probability that the intruder does not maneuver until the "critical window," and step three calculates the probability that the intruder maneuvers in the critical window. The last step is an approximation; it assumes that the maneuver is a level-off when actually the change in rate could be a slackening or even an increase in vertical rate.

In the process of assessing ATC impacts of TCAS, ARTS extractor tapes were collected and the TCAS logic simulated for pairs of aircraft. This results in a data file of tracks of aircraft that would receive TCAS TAs and RAs; this data is used to estimate the probability of an intruder maneuver leading to a critical NMAC.

The method involves direct examination of aircraft tracks to locate those with potential to induce a critical NMAC. It uses the difference between the altitude the intruder is projected to be τ seconds later and the actual altitude of the intruder τ seconds later to determine relative altitudes and vertical rates at which a TCAS could encounter this track and maneuver into a critical NMAC. Distributions of vertical rates and relative altitudes taken from Chicago ARTS tracks are then used to compute the probability that a TCAS-equipped aircraft would encounter this track at these relative altitudes and vertical rates.

This method thus differs from the overall Safety Study method in several key aspects:

- it directly examines aircraft tracks



**FIGURE 3-7
SYSTEM SAFETY STUDY CALCULATION OF PROBABILITY THAT
INTRUDER MANEUVER LEADS TO A CRITICAL NMAC**

- it takes into account the direction of a maneuver (the original method assumed the maneuver to be in the worst direction)
- it takes into account the magnitude of a maneuver (the original method assumed it to be of the size necessary to result in the NMAC--a level-off)

3.3.2 Results of Maneuvering Intruder Calculation

The risk of critical NMAC due to intruder maneuvers was calculated separately for those cases in which the TCAS aircraft is level and those cases where the TCAS aircraft has a vertical rate. The Risk Ratio for level TCAS is .0020, and for TCAS with a vertical rate, .00017--an order of magnitude below the level case. The reason that the non-level case is an order of magnitude lower is that the likelihood of choosing the advisory sense that is subject to the adverse maneuver is lower (larger differences between projected and actual altitudes are required).

The results for the level and non-level cases are weighed according to the proportions of level and non-level tracks in the Chicago ARTS data base. Eighty percent of tracks were observed to be level, while only twenty percent were non-level; multiplying the Risk Ratio results for level and non-level TCAS by these percentages and summing the results yields the final Risk Ratio for maneuvering intruders in IMC: .0016.

This Risk Ratio in IMC is substantially lower than that for overall conditions, which was .007. Several factors contribute to the lower Risk Ratio for IMC. The first is the probability of an aircraft being level. This fraction is estimated from the number of tracks which were observed to be level from both sets of tracks in the encounter pairs. (In the Chicago analysis no assumptions were made regarding TCAS equipage, so either aircraft in the pair could be the "intruder.") Twenty percent of tracks were classified non-level in IMC, whereas in overall conditions forty percent of tracks were so classified, reducing risk by approximately a factor of two.

Another factor which reduces susceptibility significantly is the vertical separation distribution. In overall conditions,

the distribution of altitude separation was seen to be uniform from 0 to 1000 ft, which means that an encounter with vertical separation of 500 ft is as likely as an encounter with NMAC separation. The vertical separation distribution in IMC (Figure 3-5, p. 3-20) shows that separation of 500 ft is less than half as likely as an NMAC encounter. Since susceptibility to inducing a critical NMAC as a result of an intruder maneuver is greatest for aircraft passing with about 500 ft separation, there is a corresponding reduction of induced risk in IMC.

To summarize, the low vertical rates and IFR separations that are characteristic of the IMC environment more than compensate for the lack of visual acquisition in IMC.

3.4 Other Factors

There are three other failure modes judged to have significance in the fault tree analysis: altitude encoding (C-bit and B-bit) errors, non-acquisition by TCAS surveillance, and avionics critical failures. Differences (if any) of their impacts are noted and evaluated here.

3.4.1 Altitude Encoding Errors

The nature of altitude encoding errors is discussed in detail in the overall Safety Study and a subsequent analysis (Reference 19). There are four types of failures:

- B-bit errors causing errors in altitude reports that are ALIM or greater, which lead to missed or inadequate RAs (unresolved NMACs)
- C-bit errors causing coasted reports, which lead to missed RAs (unresolved NMACs)
- B-bit errors that cause errors in altitude reports of approximately ALIM, which may lead to incorrect RAs (induced NMACs)
- C-bit errors causing TCAS to track vertical rates incorrectly, which may lead to incorrect RAs (induced NMACs)

Unresolved NMACs. Three events must occur for either a B-bit or a C-bit error to cause an unresolved NMAC: there must be an intruder in level flight with which the TCAS aircraft is in a

critical NMAC, there must be a B-bit or a C-bit error, and the error must (for C-bits) cause surveillance to coast the altitude reports, or (for B-bits) must cause an error in reported altitude of ALIM or greater. The two latter conditions relate to the equipment, and do not change in IMC. The factor that changes in the IMC environment is the probability of an intruder being in level flight, which has been observed to increase from .60 in overall conditions to .80 in IMC. While the risk of an unresolved NMAC due to B-bit or C-bit error increases correspondingly, it remains at least an order of magnitude below the other factors that can cause an unresolved NMAC and are thus not significant.

Induced NMACs. Change is seen, however, in the case of induced NMACs due to B-bit and C-bit errors. In the case of C-bit errors, which contribute more significantly to the induced Risk Ratio, three events must occur for the errors to cause an induced NMAC:

- a proximate, non-NMAC encounter (altitude separation of more than 100 ft but less than 1000 ft)
- an intruder with a vertical rate
- a C-bit error that causes at least a 300 ft error in projected position and is in a direction detrimental to resolution of the encounter

The first two factors change in IMC. The likelihood of a proximate encounter relative to critical NMAC separation, which is the area between 0 and 1000 ft under the distribution shown in Figure 3-2, increases from 10 in overall conditions to 13 in IMC (i.e., there are 13 times as many encounters between 0 and 1000 ft as between 0 and 100 ft). The likelihood of an intruder with a vertical rate, which was .40 in overall conditions, drops by half in IMC to .20. When the higher level of Mode C equipage is taken into account, the Risk Ratio due to C-bit error shows an increase from about .0006 in overall conditions to .0011 in IMC. This is the only component of induced risk which shows an increase from overall conditions to IMC.

The Risk Ratio for a B-bit error causing an induced NMAC was computed to be an order of magnitude lower than that for C-bit errors leading to induced NMACs in overall conditions. That result is dependent on two factors which change in IMC:

- The probability of encountering an intruder aircraft in level flight
- The probability that the B-bit error results in a critical NMAC, which is dependent on the relative altitude of the proximate aircraft

The fraction of intruders in level flight has been shown to increase from .60 to .80, which increases the Risk Ratio proportionally. However, the change in the distribution of relative altitude in IMC (Figure 3-2) means that the likelihood that the B-bit error results in a critical NMAC decreases by half, because the critical region for B-bit errors is altitude separation of 100 to approximately 700 ft. Thus, B-bit errors do not contribute significantly to the induced Risk Ratio in IMC.

This analysis is conservative in two respects:

- It is assumed that TCAS is as likely to encounter a bit error in IMC as in VMC; however, the greater proportion of air carriers and the near-total use of IFR (with the requirement for altimetry checks) should make it less likely. As was the case with altimetry errors, this factor is not assessed in the computation of the result.
- B-bit errors can result in displayed altitudes that are in error by as much as 3900 ft; also, during most altitude transitions there will be large altitude discontinuities. It is likely that these errors would be detected quickly and the transponder turned off. This factor is also not assessed in the computation of the Risk Ratio.

3.4.2 Surveillance Failure

In the overall Safety Study, all forms of surveillance imperfections were described and the available data was analyzed to determine their frequencies of occurrence. The form of surveillance failure which has the most impact is multipath, and it is most responsible for missed RAs. The occurrence of multipath leading to unresolved NMACs will not significantly change in IMC, and so the same failure rates for not having the intruder in track at the time of the TA (.06) and the RA (.03) are used in the fault tree analysis.

3.4.3 Equipment Failure

The equipment failure that is of principal concern is an undetected critical avionics failure which causes an incorrect RA to be generated in the presence of a proximate aircraft, leading to a critical NMAC. In order for equipment failure not to contribute significantly to the rate of induced NMACs, it must occur at a rate that is at least one order of magnitude lower than any other factor judged significant in the induced Risk Ratio. All three significant factors are on the order of 10^{-3} or greater; thus, to remain insignificant in this analysis, avionics critical failures must occur at a rate of 10^{-4} or less per current critical NMAC. This is the same level estimated for the overall Safety Study.

4. RE-EVALUATION OF FAULT TREE FOR INSTRUMENT CONDITIONS

The fault tree used in the System Safety Study of Minimum TCAS II provides the means by which the failure modes described in Section 3 will be quantitatively assessed. The fault tree identifies all means by which a critical near-midair collision can occur, organizes them into a logical structure, and systematically identifies all root causes and necessary conditions. The fault tree thus combines a comprehensive analysis of TCAS failure mechanisms with non-TCAS events; the interactions between them are fundamental to the effect of TCAS on the NMAC hazard.

It is not necessary to construct a new fault tree to analyze the IMC environment. The fault tree constructed for the overall Safety Study covers all fault mechanisms, including those that occur in IMC. From a qualitative standpoint, when analyzing the fault tree for IMC those branches which do not apply are simply not considered. These branches are treated quantitatively by applying failure rates of 1.0 for events that always happen, such as visual conditions inadequate for visual acquisition, or 0.0 for events that cannot happen. The computation process then operates in the same fashion as before. Appendix D provides a more detailed explanation of the effects on the fault tree of limiting the analysis to IMC.

4.1 Quantitative Analysis for the Nominal Case

The failure probabilities used in quantifying the fault tree for IMC are summarized in Table 4-1. The table also provides, for comparison, the probabilities for overall conditions. All these Risk Ratios take into account the fraction of aircraft that have Mode C transponders and the likelihood that surveillance acquires the track. The hourly risk conversion factors, which are the risk of a critical NMAC in today's system without TCAS, are provided also. The factors for IMC and overall conditions are the same, since the risk of a critical NMAC per flight hour was observed to be the same in both IMC and overall conditions.

As in the overall Safety Study, a set of nominal conditions is assumed when calculating the Risk Ratio. With the exception of those applying to visual acquisition, these are the same conditions assumed for the overall Safety Study. The assumed nominal conditions applying to the IMC environment are as follows:

TABLE 4-1
SUMMARY OF FAILURE PROBABILITIES USED IN
FAULT TREE EVALUATION

DESCRIPTION OF EVENT	PROBABILITY	
	IMC	OVERALL
UNRESOLVED		
1. No RA is displayed	.185	.41
1.a Encounter is with non-Mode C aircraft	.16	.39
1.b Surveillance fails to acquire aircraft	.025	.018
2. Inadequate RA is displayed	.010	.003
INDUCED		
3. TCAS displays RA which will lead to NMAC		
3.a Intruder maneuvers	.0016	.016
3.b Altimetry error	.0044	.0081
3.c C-bit errors	.0014	.001
HOURLY RISK CONVERSION FACTOR		
4. Risk of critical NMAC (Section 3.1.1, p. 3-1)	$1 \times 10^{-5}/\text{hr}$	$1 \times 10^{-5}/\text{hr}$

- Visual acquisition is assumed to be ineffective for the purpose of "see-and avoid."
- As there is no visual acquisition, the pilot follows the RA.
- Airborne traffic encountered by TCAS has the level of Mode C transponder equipage of today's IMC environment.
- The intruder is not TCAS-equipped.
- The pilot follows the nominal procedures involved in the use of TCAS; there are no "false moves" by prematurely moving based on TA information only.

These conditions allow the computation of the probabilities of unresolved and induced NMACs, as follows.

4.1.1 Unresolved NMACs

In overall conditions, a critical NMAC is resolved if either a correct RA is issued or the TA enables the pilot to visually acquire the threat (in those conditions where visibility supports such acquisition). In IMC, the only means by which an NMAC can be resolved is by a correct and timely RA. The Risk Ratio for an unresolved NMAC--the fraction of pre-existing NMACs that would be resolved with TCAS--is thus the probability that an RA is not issued in a timely fashion or is inadequate to resolve the NMAC.

From Table 4-1, the probability that no RA is displayed is .185 and the probability that an inadequate RA is displayed is .010. The Risk Ratio for an unresolved NMAC in IMC is the sum of these two, or .195. Thus, TCAS is expected to resolve more than 80 percent of critical NMACs in IMC. Most of the residue (.16 of the .195) is due to the intruder not having a Mode C transponder.

4.1.2 Induced NMACs

In overall conditions, an induced NMAC occurs if an incorrect Resolution Advisory is issued and the pilot does not visually acquire the threat, which would enable him to see that the RA is incorrect. Since in IMC visual acquisition is assumed to be ineffective for this purpose, the Risk Ratio for an induced

NMAC--the probability of an induced NMAC expressed as a fraction of the probability of a pre-existing NMAC--is just the probability that TCAS displays an RA which leads to an NMAC. This is the joint probability of an incorrect RA due to intruder maneuvers, to altimetry errors, and to C-bit errors, or .007 as shown in Table 4-1 (items 3.(a.), (b.), and (c.)). This is less than in overall conditions, in spite of the lack of visual acquisition.

4.2 Sensitivity Analysis

As the risk ratio for both unresolved and induced NMACs is based on the issuance (or lack) of a Resolution Advisory, we test the sensitivity of the factors used to estimate the correctness and effectiveness of RAs.

4.2.1 Parameters Tested

Sensitivity tests were performed for the following six parameters:

1. Mode C equipage. Estimated at .84, it is tested at 1.0 (100 percent equipage).
2. Surveillance failure. TCAS was estimated to have an intruder in track at the time of the RA with a probability of .97 (3 percent failure due mainly to multipath); it is tested improved to .99 and degraded to .94.
3. Altimetry Error. This study uses the same error magnitudes for GA altimetry as in the System Safety Study. Two sensitivity tests are performed:
 - a. Error magnitude. The standard deviation values for GA altimetry, taken from the System Safety Study, are alternately increased and decreased 20 percent.
 - b. Error distribution. Using the same standard deviations for GA altimetry, an exponential distribution (which has higher probabilities in the tails of the distribution) is used instead of the assumed Gaussian distribution.

These parameters are inputs to the computation of the Risk Ratio for GA altimetry. The means by which these factors are used in the calculation of the Risk Ratio is described in Section 3-2 and Appendix A of this report.

4. Maneuvering Intruder Hazard. This estimate is tested by increasing it 50 percent and decreasing it 50 percent.
5. Human Factors. As in the overall Safety Study, the nominal case in IMC assumes no pilot failures; it is tested with a failure rate of .05 (1 in 20).
6. Visual Acquisition Aided by the Traffic Advisory. A comparison is made between IMC and VMC, assuming for the VMC case that there is no visual acquisition of the intruder. This requires no computation for IMC, since it is the nominal condition.

4.2.2 Results of Sensitivity Tests

The changes in failure probabilities are provided in Table 4-2. Column 1 lists the sensitivity test. Column 2 lists the events affected by the changed parameter; in some cases, more than one event probability changes. Column 3 lists the probability for the nominal case; Column 4 shows what it changes to for that sensitivity test. In all but the altimetry error sensitivity tests, the sensitivity values are obtained directly. In the altimetry error sensitivity tests, the calculations of Section 3.2 and Appendix A are performed to obtain the probabilities shown.

The results of these sensitivity tests are listed in Table 4-3 and plotted in Figure 4-1. Both IMC and overall conditions are included in Figure 4-1 for comparison. As was the case in overall conditions, the Risk Ratio for unresolved NMACs (the upper set of lines) is highly sensitive to one factor: Mode C equipage. If there were 100 percent Mode C equipage in the air carrier environment, TCAS would resolve more than 95 percent of the pre-existing NMACs.

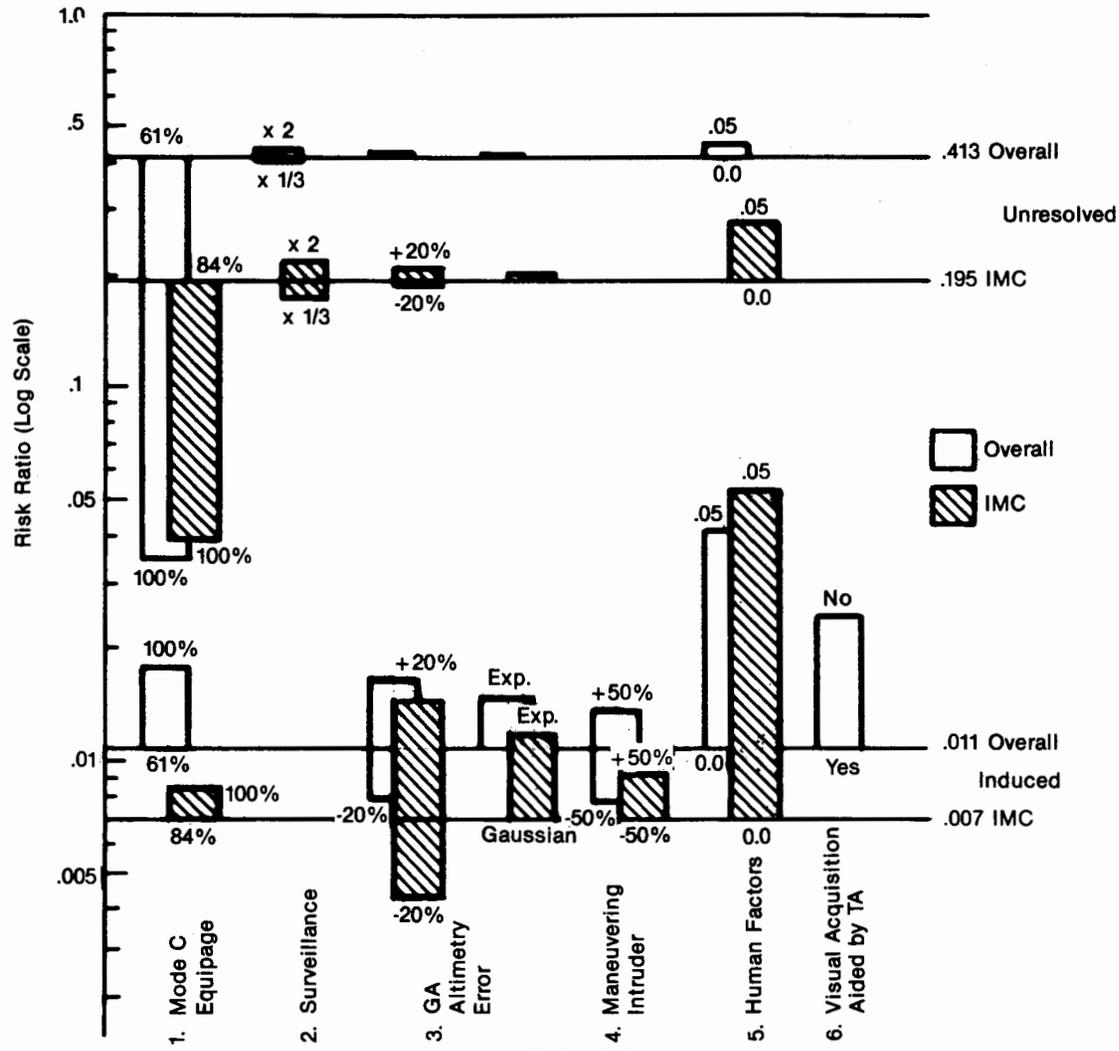
Induced risk shows slightly more sensitivity to most of the factors in IMC than in overall conditions. This is primarily due to the lack of visual acquisition, which in overall conditions enables the pilot to resolve the conflict by visual

TABLE 4-2
CHANGES IN FAILURE PROBABILITIES USED IN FAULT TREE EVALUATION FOR IMC

SENSITIVITY TEST	EVENT (Table 4-1)	NOMINAL PROBABILITY (Table 4-1)	SENSITIVITY VALUES
1. Mode C Equipage	3.a.) Encounter is with non-Mode C equipped aircraft	.16	0.0
2. Surveillance Failures	3.b. Surveillance does not require threat in time for RA	.03	.06, .01
3. Altimetry Error a. Magnitude	4.) Inadequate RA is displayed	.010	.022, .00144
	5.b.) RA is displayed which will lead to NMAC due to altimetry error	.0044	.013, .00062
b. Distribution	4.) Inadequate RA is displayed	.010	.016
	5.b.) RA is displayed which will lead to NMAC due to altimetry error	.0044	.0094
4. Maneuvering Intruder	5.a.) RA is displayed which will lead to NMAC due to intruder maneuver	.0016	.0032, .0008
5. Human Factors Failures	Inappropriate pilot reaction (per decision/encounter)	0.0	.05
6. Visual Acquisition by the Traffic Advisory	(No calculation involved for IMC.)	--	--

TABLE 4-3
CHANGES IN NMAC PROBABILITIES FOR SENSITIVITY TESTS FOR IMC

	PROBABILITY OF		
	NMAC	UNRESOLVED NMAC	INDUCED NMAC
Nominal Case	.202	.195	.007
1. If 100% Mode C	.048	.040	.008
2. If surveillance failure is 1/3	.185	.178	.007
2x	.227	.220	.007
3.a. If GA altimetry is 20% improved	.190	.186	.004
worse	.223	.207	.016
3.b. If GA altimetry error distribution exponential	.213	.201	.012
4. If the maneuvering intruder hazard is 50% less likely	.202	.195	.007
more likely	.204	.195	.009
5. If human factors failures are .05	.336	.276	.060
6. If no visual acquisition aided by the Traffic Advisory	.202	.195	.007



**FIGURE 4-1
SENSITIVITY ANALYSIS RESULTS**

means. Even so, the sensitivity is only slightly greater; and in the case of maneuvering intruder, the Risk Ratio is less sensitive to a 50 percent increase.

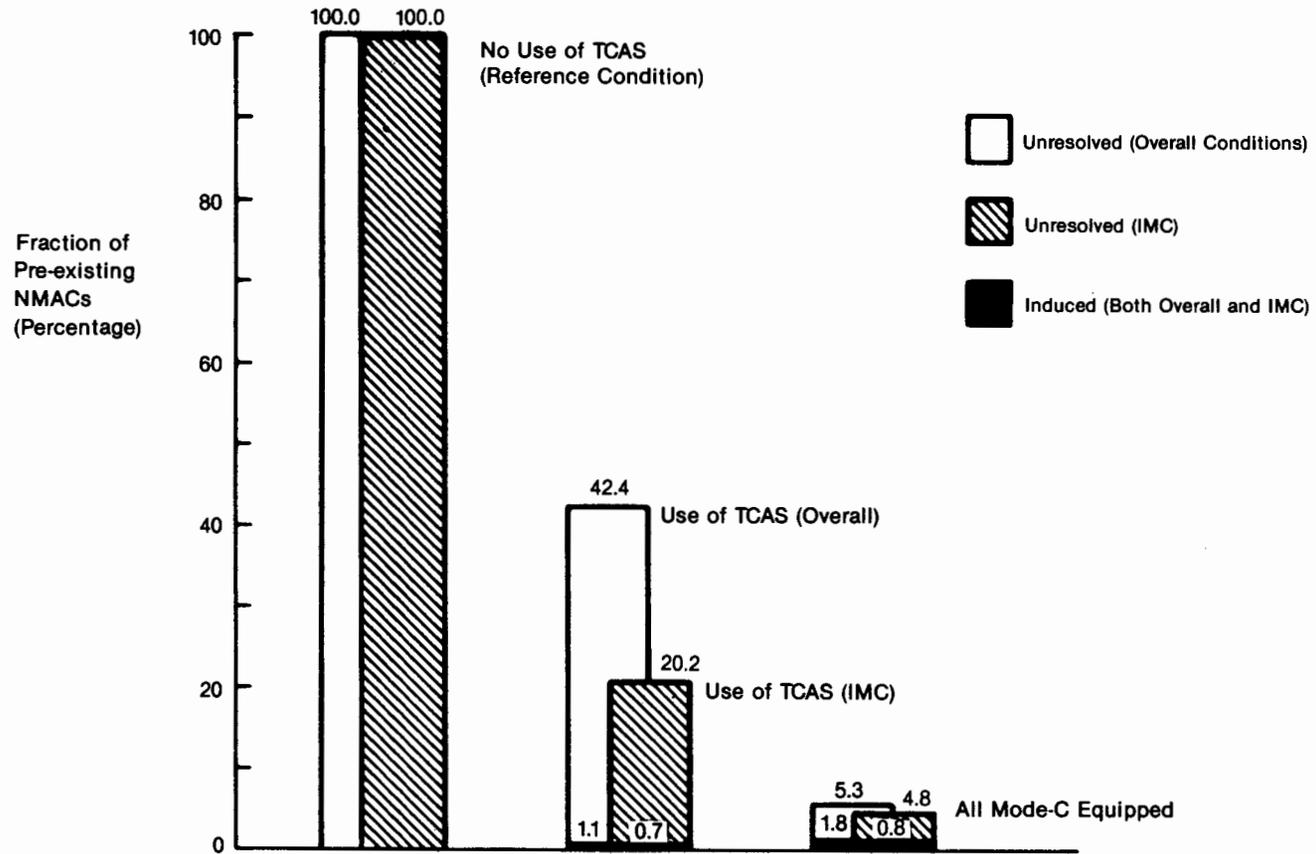
The effect of the use of visual acquisition to reduce the risk of induced NMACs in overall conditions can be seen from the last bar in Figure 4-1. This bar shows the effect of not using TA-aided visual acquisition to resolve critical NMACs. In IMC this is the nominal case. Visual acquisition provides great benefit for induced NMACs in VMC, reducing the risk in overall conditions by about half; however, this reduced level is still higher than in IMC. The unresolved component is insensitive to the use of visual acquisition in overall conditions. This is because in those cases where the pilot receives a TA and visually acquires the threat, he would also receive a timely and adequate RA which would resolve the conflict in 99 percent of the cases.

4.2.3 Relative TCAS Effects

The effects of using TCAS are illustrated in Figure 4-2 both for overall conditions and IMC. The first pair of bars indicates today's condition--no use of TCAS in VMC or IMC, with 100 percent of the pre-existing NMACs. These two bars represent approximately the same level of risk on a per-flight hour basis, as estimated in Section 3.1; however, since IMC represents a small portion of total flight (less than 15 percent), the total number of critical NMAC events in the two cases is different (the number of events per year in IMC is less).

With the use of TCAS, the number of NMACs is reduced to the level shown by the second pair of bars. TCAS shows a substantially greater effectiveness in resolving NMACs in the IMC environment than in overall conditions, with a smaller residue of induced risk than in overall conditions.

As the environment approaches full Mode C equipage (the third pair of bars), TCAS benefits increase to approximately 95 percent effectiveness in resolving NMACs in both the IMC and overall environments. Accompanying this will be slight increases in induced risk over today's level. However, regardless of levels of Mode C equipage, the IMC environment shows less induced risk than the overall environment.



**FIGURE 4-2
RELATIVE TCAS EFFECTS**

5. TCAS INTERACTIONS WITH THE ATC SYSTEM

In this study the analysis of the level of safety provided by the use of TCAS is extended to include factors external to those which determine whether TCAS will resolve an individual encounter. It includes an examination of an IMC environment to determine if there are interactions between the operation of TCAS and ATC operation of Instrument Flight Rules (IFR) airspace. For example, an investigation is made to determine whether following a TCAS Resolution Advisory (RA) could result in a new conflict or have some other undesirable effect. This section also considers other issues of interaction between TCAS and the ATC system that become of concern when there is implementation of TCAS on a large scale.

The approach used in this part of the analysis, first, to define the issues. Previous studies are then examined for any pertinent results regarding TCAS-ATC interactions. Finally, a new data source, the Chicago ARTS data base, is analyzed to provide definitive information on TCAS-ATC interactions.

5.1 Issues

The area of TCAS-ATC interactions covers a broad range of topics. For the purposes of this study, we divide them into three categories: those that deal with safety, those that deal with controller workload, and those that deal with capacity.

5.1.1 Safety

In a controlled IFR airspace, great weight is placed on rules and procedures to safely separate aircraft. For example, the Chicago radar approach control facility uses letters of agreement to establish traffic flow paths and altitudes in and out of their airspace. These patterns separate arrival and departure flows both laterally, by using different routes, and vertically by using different altitudes for each flow. A vertical maneuver resulting from following an RA issued in normal operations may have an undesired effect.

The approach taken to look for these effects is to examine ARTS data to find all aircraft that would receive RAs if they were TCAS-equipped. Results address the following issues:

Is the RA needed or is it a nuisance advisory? There is not a sharp dividing line between RAs that are nuisance alerts and those that are not. If an RA resolves an NMAC, it is

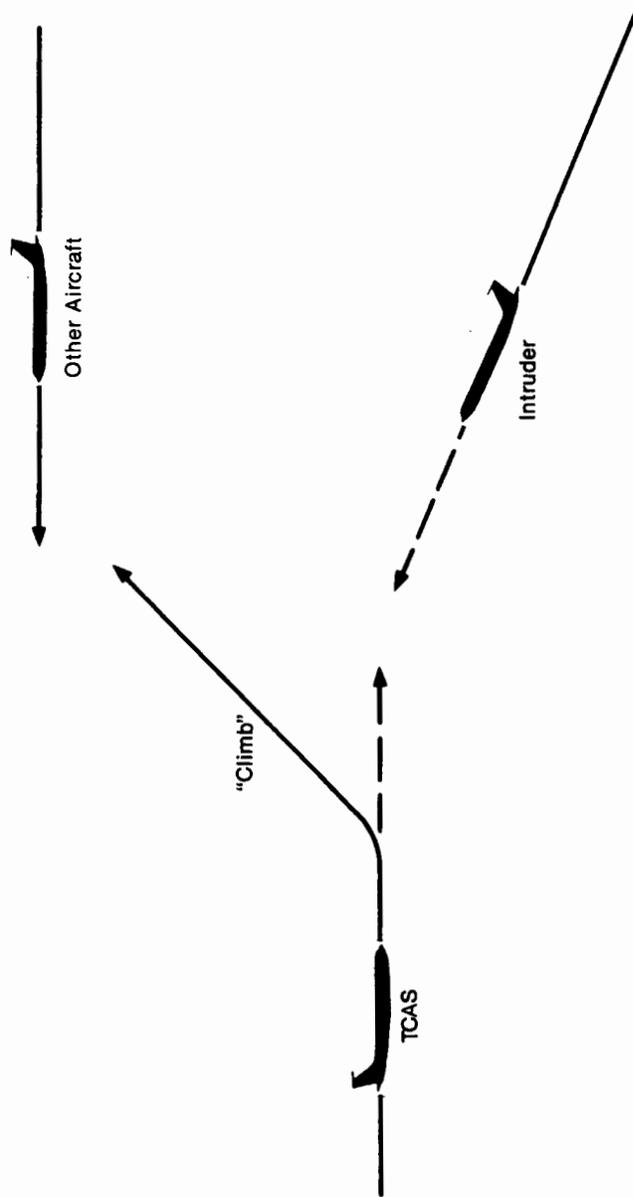
clearly needed. However, given the low rate at which critical NMAC encounters occur, it is extremely unlikely that a short sample of ARTS data (11 hours) will contain a situation in which an RA resolves an encounter of this type. A more appropriate standard of need for the advisories is the TCAS altitude parameters for issuing an advisory. A needed advisory should fall within or close to the parameter thresholds. On the other hand, an RA provided for an aircraft not in violation of IFR separation standards is clearly a nuisance advisory. We evaluate the degree to which an advisory fits either of these categories by comparing separation without the advisory both to the IFR standards and to the TCAS thresholds.

Is the maneuver compatible with pilot and controller intent?

In order to exactly determine this intent, radio transmissions between pilot and controller need to be known. Although these transmissions are not available, intent can be inferred from the actual flight path. Compatibility is evaluated by comparing an aircraft's actual flight path, taking into account maneuvers during the time an RA would have been displayed if the aircraft were TCAS-equipped, with the flight path the aircraft would have followed in response to that RA.

Is there a domino effect? A domino effect occurs when a TCAS-equipped aircraft following an RA against one aircraft comes into conflict with a second aircraft, as illustrated in Figure 5-1. A key part of this definition is that the conflict with the second aircraft occurs as a consequence of movement due to the RA, and would not have occurred otherwise. The potential for domino effects is investigated by noting the change in separation between aircraft that would receive corrective (displacement-producing) RAs and other aircraft in the vicinity.

In looking for potential domino effects, particular attention is paid to aircraft in holding patterns, as concerns have been expressed that because of the close proximity of aircraft in holding patterns, the intrusion of an aircraft may lead to multiple TCAS units issuing advisories that propagate among the aircraft in the pattern. This is illustrated in Figure 5-2. In this hypothetical example, an intruder blunders into the pattern, leading to a "Climb" advisory for the lowest aircraft in the pattern. That aircraft executes its advisory, leading to a conflict with the next aircraft in the pattern, which in turn could receive a "Climb" advisory, and so forth.



**FIGURE 5-1
DOMINO EFFECT**

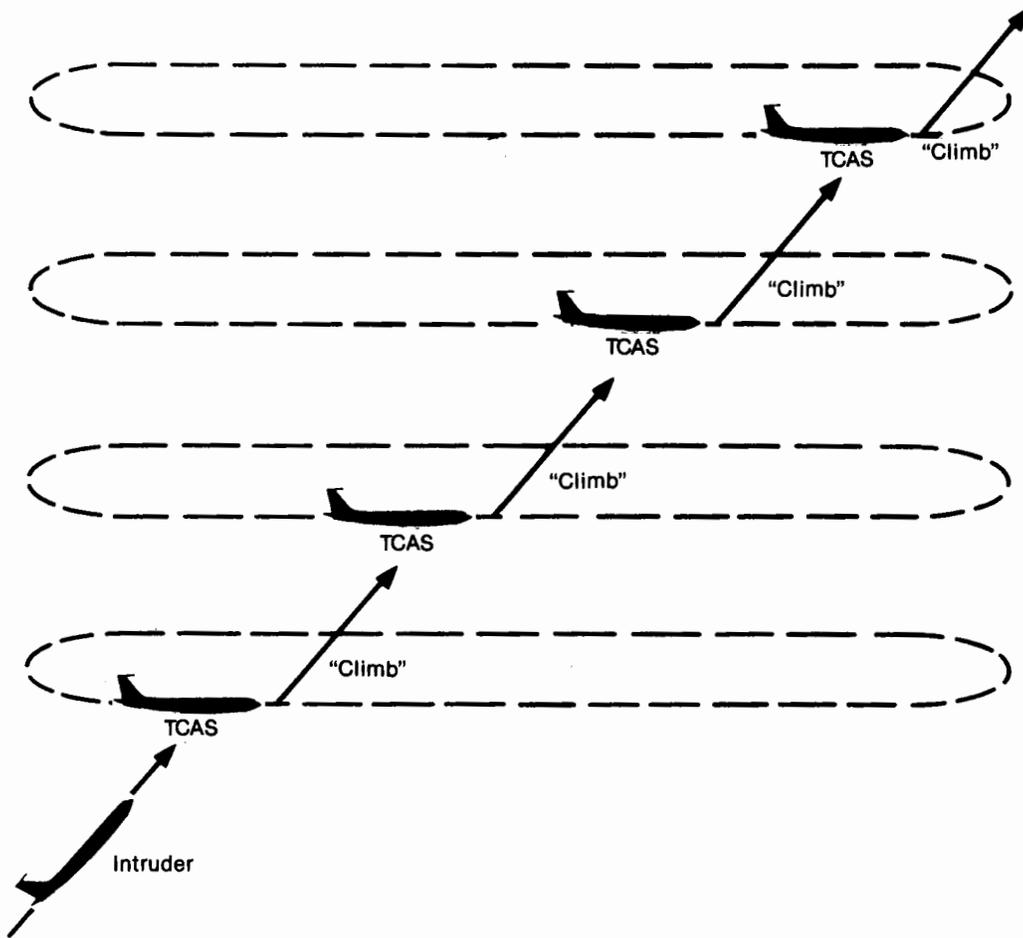


FIGURE 5-2
HYPOTHETICAL DOMINO EFFECT IN A HOLDING PATTERN

5.1.2 Controller Workload

The purpose of this portion of the analysis is not to do a formal study of controller workload, but rather to identify any characteristics of TCAS operations that may generate additional work for the controller. These characteristics are identified by an analysis of TCAS RAs that addresses the following issues:

Frequency of displacement. Many TCAS RAs do not cause any displacement (for example, "Don't Descend" issued to a level aircraft). In other cases, the displacement may be small. If an RA does not cause an altitude displacement, the controller might not know that a pilot received the RA (unless the pilot communicates that fact). A measure of TCAS activity seen by the controller, then, is the rate at which altitude displacements occur. Rates are computed for the entire airspace and by control position.

Disruption and restoration of normal ATC operations. A maneuver made in response to an RA may not necessarily cause disruption to ATC operations. The magnitudes of advisory displacements are examined to note the altitude deviations called for by TCAS and the nature and severity of any recovery that may be required.

5.1.3 Capacity

TCAS could have an impact on capacity if following a TCAS RA causes resequencing to be required, resulting in a gap in the flow of traffic. The magnitudes of displacements and the locations of advisories within the Chicago terminal airspace determine the degree to which this might occur. A small displacement in a critical phase of flight, such as approach and landing, may affect the ability of the pilot to complete the approach, resulting in a missed approach and an unused landing slot. However, a larger displacement while traveling from a holding fix to final approach may have no impact on capacity. The locations of all RAs and the displacements involved are evaluated to estimate the impact that TCAS might have on capacity.

5.2 Previous Studies

An examination of previous studies of TCAS (or any of its predecessor systems) provides some background on TCAS-ATC interactions. The TCAS program has accumulated more than 3000 aircraft hours of pertinent data. This data consists of ATC

controller-in-the-loop simulations, plots extracted from ground radar automation equipment, and aircraft flight tests using TCAS equipment onboard test and in-service aircraft. These tests and simulations were used to assess the interactions of TCAS with the ATC system. Alert rates were studied and statistics gathered noting the number of nearby aircraft whenever a Resolution Advisory was generated. Locations of alerts in high-density areas were plotted and characteristics of alerts that might be unnecessary were noted. These previous studies aided the development of logic features to control TCAS-ATC interactions. These studies are reviewed and results addressing TCAS-ATC interactions are described.

5.2.1 The Studies

There are five studies of TCAS (or its predecessor, BCAS) which deal with the interactions of TCAS and ATC: two full controller simulations; an analysis of ARTS tracks similar to the Chicago analysis which follows; flight tests; and an in-service evaluation of TCAS. Each is briefly described here.

Air Traffic Control Simulation of Chicago. This simulation of the Full Beacon Collision Avoidance System (BCAS) [Reference 12] used the ATC simulation facility at the FAA Technical Center (Figure 5-3) to model the operation of the Chicago O'Hare terminal area. The purpose of the simulation was to investigate the interaction between air traffic control and Full BCAS in a high-density environment featuring parallel ILS approaches. Twelve hours of simulation were performed using traffic patterns and navigational fixes typical of those in use in 1979. Traffic densities and types of aircraft were representative of 1970 traffic levels. All aircraft were Mode C equipped (as is typical of Chicago, which is classified as a Terminal Control Area where Mode C equipage is required).

Air Traffic Control Simulation of Knoxville. This simulation of Full BCAS [Reference 13] also used the ATC simulation facility at the FAA Technical Center. The purpose of the simulation was to assess the impacts of BCAS on controllers and control procedures in a moderate-density terminal environment with significant overflight traffic. The Knoxville terminal area was simulated; overflight traffic, in addition to arrivals and departures, was included. Sixteen hours of simulation were performed using traffic patterns and navigational fixes representative of those in use at Knoxville in 1979. Traffic densities were those projected for the mid 1980s. Two traffic conditions were modeled, all IFR operations and mixed IFR/VFR traffic.



**FIGURE 5-3
CONTROLLER POSITIONS FOR CHICAGO O'HARE ATC SIMULATION**

Active BCAS Simulation Using Houston Radar Data. The purpose of this study [Reference 14] was to develop an optimal set of collision avoidance parameters to reduce unneeded alerts yet maintain satisfactory separation protection. Two data bases were analyzed: 1) A collection of ARTS III radar data consisting of 65 high activity hours over ten days at Houston Intercontinental Airport; 2) National Transportation Safety Board (NTSB) reports for 15 midair collisions that occurred since 1965. Alert rates were evaluated with the Houston ARTS data to determine the effects of varying the parameters in each sensitivity level; the collisions reported in the NTSB reports were then modeled to determine the ability of BCAS to resolve them.

Flight Tests. Lincoln Laboratory conducted several sets of flight tests using experimental TCAS units, BCAS units, or units of the ground-based Intermittent Positive Control (IPC) collision avoidance system. In most cases the encounters involved only two subject aircraft; however, occasionally other aircraft were also encountered.

IPC encounters with targets of opportunity (encounters with non-test aircraft, or "unplanned" encounters) during flight testing were reviewed to obtain information on vertical maneuvers. A total of 35 such encounters were examined.

Flight tests were also performed by Lincoln Laboratory using experimental TCAS units. In particular, the most recent flight tests [Reference 15] were conducted using equipment and logic similar to the current TCAS design. Twenty-one test flights were flown using six subject pilots. There was a total of 121 encounters of which 15 were with non-test (unplanned) intruders. The test pilots commented on the acceptability of the RAs given.

Between July and September 1980, the FAA conducted operational flight tests of an Active BCAS Experimental Unit (BEU). The flight tests were composed of 129 approaches to 28 airports with a total of 60 flight hours of data recorded. The purpose of the tests was to determine how many unplanned alerts would occur during normal flight operations and whether each alert was desirable or not wanted.

Phase I Operational Evaluation. This evaluation of TCAS II [References 16 and 17] involved placing TCAS units onboard regularly scheduled Piedmont Airlines 727s. Data was collected over a period of 928 flight hours. Although TCAS displays were

not located in view of the pilots, data was recorded both on the alerts the system provided and on all aircraft tracks stored in the TCAS tracking system. Observers on the flights completed questionnaires to provide supplemental information. The advisories and tracked aircraft were analyzed to examine the circumstances surrounding individual alerts, and to assess the potential interaction of TCAS with the ATC system.

5.2.2 Study Results

These studies provide information on the safety, controller workload, and capacity issues discussed in Section 5.1. Particular results include the potential for domino effects, actions of TCAS on parallel approaches, and disruption of the ATC system.

Domino Effects. In the process of examining the data from these studies, no situations were observed such that a TCAS-equipped aircraft, by following an RA against one aircraft, would have come into a conflict with a second aircraft. To obtain additional information about the potential for domino effects, multi-aircraft situations were also analyzed. A multi-aircraft encounter is one in which TCAS displays an RA against two or more intruders simultaneously.

Multi-aircraft situations were observed in four of the studies: the Knoxville Simulation, the Houston Radar Data Study, the 1980 FAA flight tests of an Active BCAS Experimental Unit, and the Lincoln Laboratory TCAS flight tests. No multi-aircraft encounters were observed in the Chicago Simulation, Lincoln Laboratories IPC flight tests, or the Piedmont Phase I Operational Evaluation.

The Knoxville multi-aircraft encounter is illustrated in Figure 5-4. The Full BCAS system, using ground system automation information, generated a vertical speed limit alert for N4525B, flying VFR at 3500 ft, against UA703, flying IFR on an airway at 4000 ft. Shortly after generating this alert, BCAS observed N6665M flying on the same airway as UA703 but at 3000 ft. Limitations of the logic at that time did not allow for the display of an advisory against a second intruder while one was currently being displayed against the original intruder. Thus, N4525B could not receive an advisory against N6665M, who passed closer than UA703 in range, until the first conflict, with UA703, was resolved.

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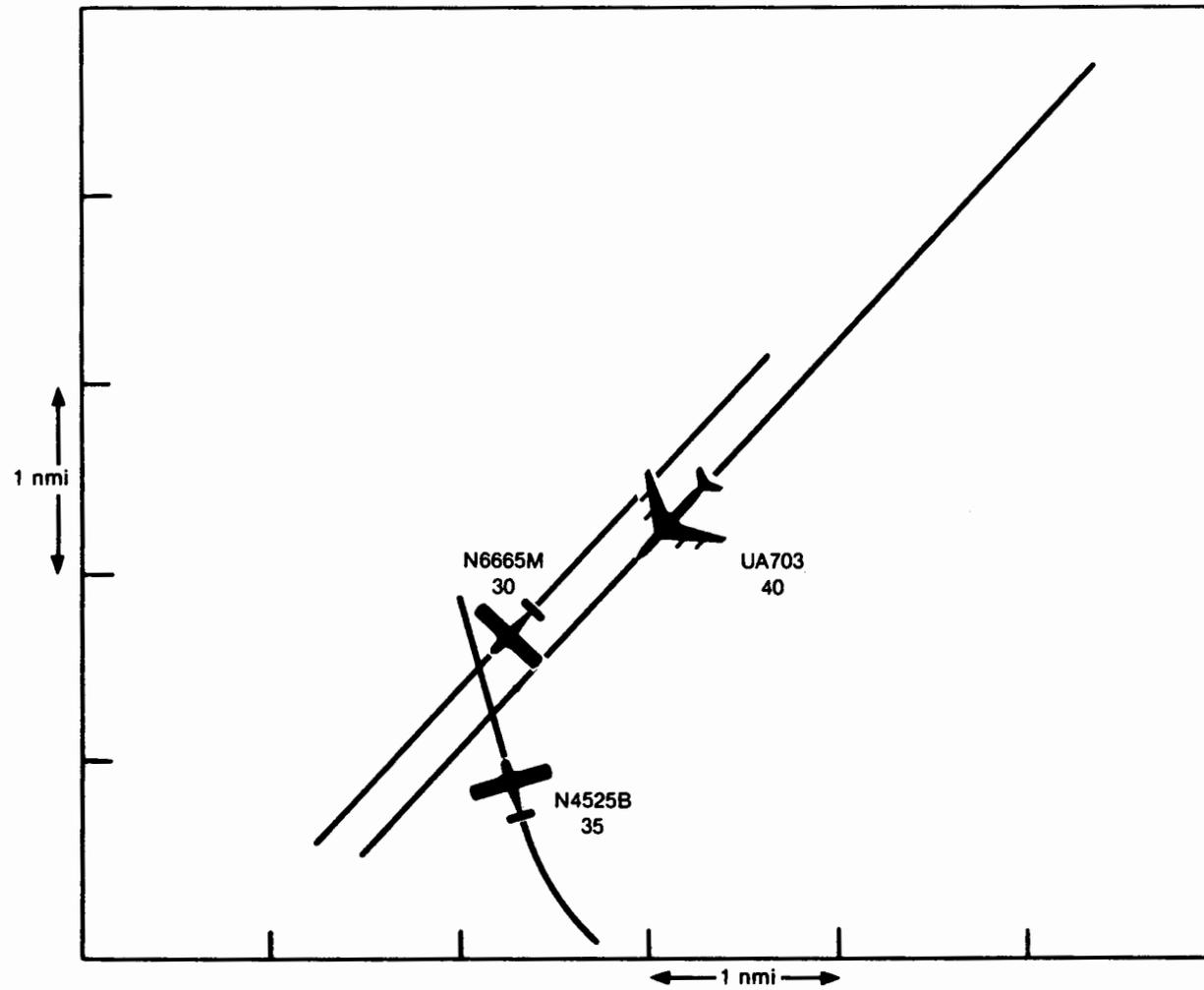


FIGURE 5-4
HORIZONTAL VIEW OF MULTIPLE ENCOUNTER IN KNOXVILLE SIMULATION

Even with the existing larger BCAS altitude separation parameters, this encounter is not a domino effect, as no aircraft was instructed to move from its altitude. Current TCAS logic would provide a "Don't Descend" for UA703, a "Don't Climb/Don't Descend" for N4525B, and a "Don't Climb" for N6665M, if each aircraft was TCAS-equipped.

In the Active BCAS Houston Simulation, two multi-aircraft encounters were observed with the old BCAS logic. The sensitivity level control, which became a part of the TCAS logic, eliminates both of these. One of these occurred at low altitude near the airport, for which TCAS would generate only a Traffic Advisory (TA). The other is reduced to a single-aircraft encounter as a result of TCAS' sensitivity level control.

As a result of the encounter in the Knoxville Simulation, it was concluded that a multi-aircraft logic should be developed. This logic was developed and is a part of the TCAS logic; however, no valid multi-aircraft encounter has been observed since the introduction of this logic, nor have encounters occurred which disclose any instance or potential for a domino effect.

Parallel Approaches. Parallel approaches were modeled in the Chicago O'Hare controller simulation. Most alerts (85 to 90 percent) in the simulation were vertical speed limits, which occurred at the outer marker. A large number of the alerts (42 percent) were extremely brief, because when aircraft converge on parallel approaches their projected positions overlap for a short period of time.

The sequence of events that causes these short alerts is illustrated in Figure 5-5, using parallel approaches to 27L and 27R as an example. At time t , Aircraft 2 is projected to continue its current path and pass behind Aircraft 1. As it begins to turn parallel to Aircraft 1, the projected position of Aircraft 2 converges with that of Aircraft 1, until time $t+4$ seconds, when their projected positions overlap. The aircraft are separated by 1000 ft; this altitude separation is within the old BCAS logic parameters, generating a vertical speed limit ("Limit Descent"). At time $t+6$ seconds, the aircraft have stopped closing in range and the advisory is removed. Current TCAS logic now issues for Resolution Advisories only if range τ is less than 25 seconds (at altitudes below 10,000 ft), or 20 seconds if within 2500 ft of ground level, and

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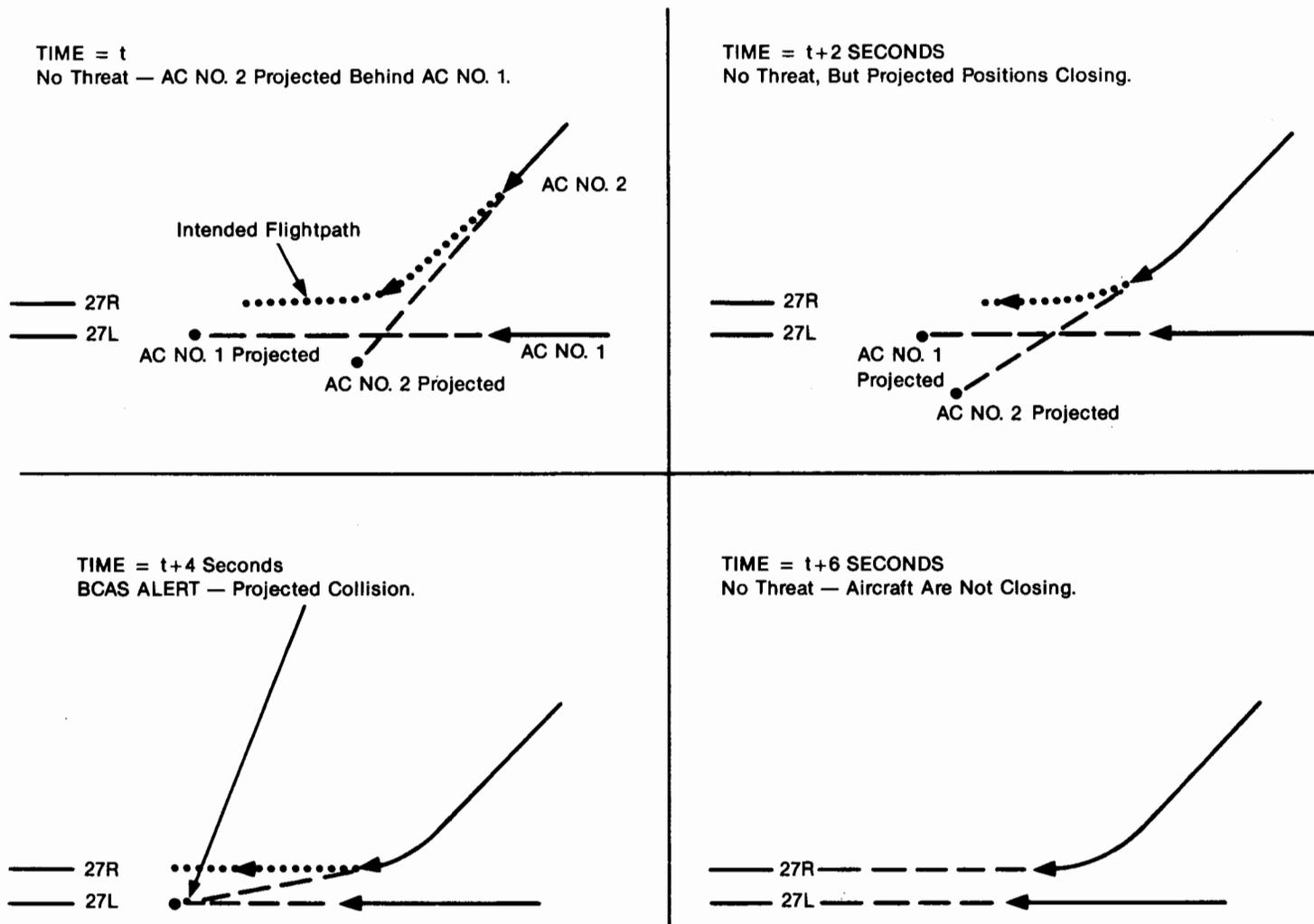


FIGURE 5-5
SEQUENCE OF EVENTS CAUSING A SHORT-DURATION
BCAS VERTICAL SPEED LIMIT ADVISORY

altitude separation is 750 ft or less; the improved effect on parallel approaches encounters in the Chicago ARTS data base introduced by these parameter values will be discussed in Section 5.3.2.3.

In the simulation, most of the alerts which altered flight paths did not affect completion of the approaches in VFR; however, six of the BCAS alerts did cause missed approaches. Four were caused by aircraft on the runway surface; TCAS now has logic that eliminates alerts for aircraft on the ground.

Disruption of the ATC System. The results of the questionnaires given to controllers after both the Chicago and the Knoxville simulations indicate that, even with the greater sensitivity in use at that time, BCAS did not excessively disrupt the system from their viewpoint, although controllers did indicate a concern that some alerts occurring between two aircraft with high closure rates at long distances may have been issued too soon.

The Chicago and Knoxville simulations provide some information regarding the disruption of the ATC system. In the Chicago simulation, only 10 percent of the alerts altered aircraft flight paths. The Knoxville simulation generated the important result that positive alert ("Climb" or "Descend") parameters at certain altitudes were larger than VFR separation standards. Current TCAS logic is more consistent with the ATC system in that it now attempts to generate no more than 500 ft separation below 18,000 ft.

The Houston BCAS alert rate analysis resulted in design changes that eliminated a substantial number of unwanted alerts. At the same time, the logic continued to provide adequate warning time in the simulated re-creation of actual midair collisions, with one exception: the midair collision near Carmel, NY, where an aircraft made a sudden violent maneuver into another aircraft. If the aircraft were equipped with TCAS, a Resolution Advisory would have been generated but not in time to correct the maneuver. However, a Traffic Advisory would have been displayed well before the sudden maneuver was made; it would have shown the relative altitude of the other aircraft, and might have prevented the maneuver.

With the sensitivity level control now used in TCAS, alert rates are low. The Piedmont Phase I flight tests show an overall alert rate per aircraft of one Resolution Advisory in 40 flight hours. Peak occurrence of advisories were in the terminal area, where alerts occurred at the rate of one RA

every 15 flight hours. It is also important to note that not all of these advisories cause deviations in the flight path of the aircraft. The fraction of RAs in the Chicago ARTS data base that are corrective (displacement-producing) will be determined in Section 5.3.2.2.

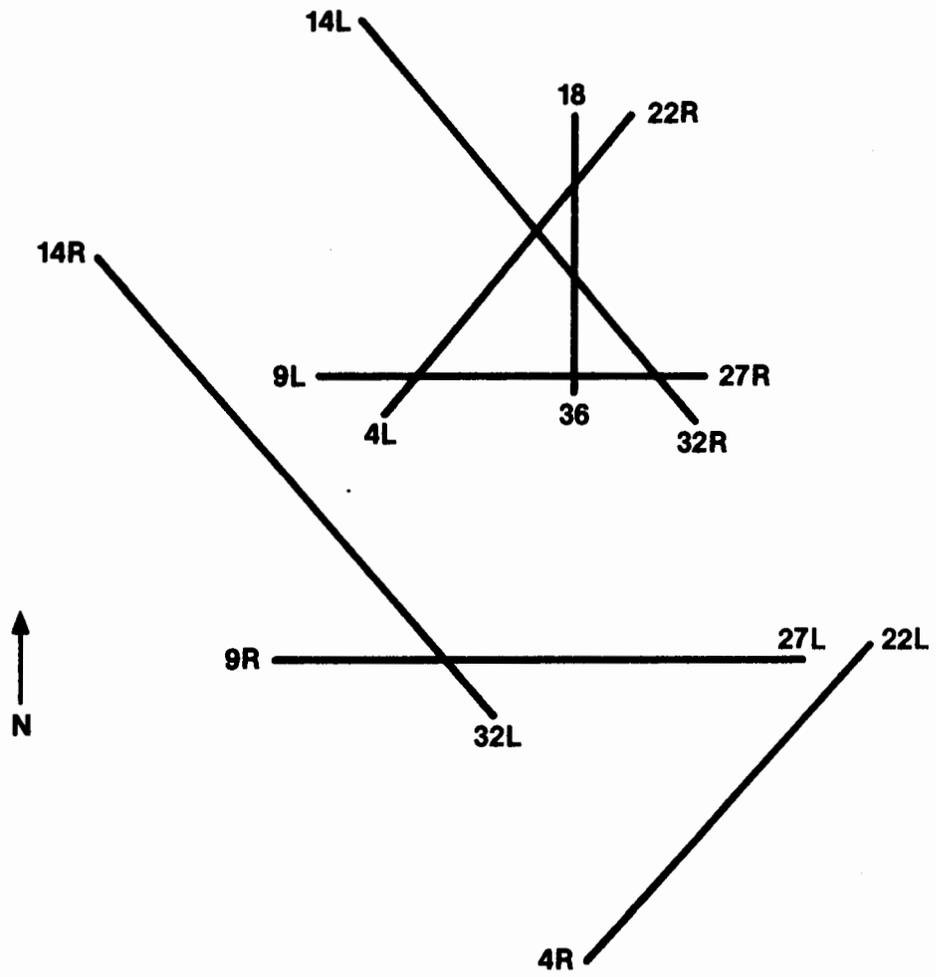
5.3 Chicago Terminal Airspace Analysis

While these previous studies provide useful information on ATC interaction, more detailed and definitive information is desired. The Chicago ARTS data provides this information; the principal results and conclusions of this study regarding TCAS-ATC interactions are drawn from it. This new computer simulation of the TCAS logic on aircraft pairs in the Chicago ARTS data base is described in Section 2.1. A better understanding of the results of this analysis is gained from knowledge of the procedures used by controllers in the Chicago terminal area. Section 5.3.1 provides a short description of these practices, including control positions and procedures for controlling flow of aircraft; Section 5.3.2 discusses the results of the TCAS encounter simulations.

5.3.1 Chicago Terminal Area ATC Practices

The intent of the pilot and controller cannot be determined without the use of recordings of pilot-ATC communications (which were not available); however, a reasonable inference can be made from the actual flight paths together with a knowledge of ATC practices. Information such as runway configurations in use and procedures required by letters of agreement provides a great deal of understanding about what an aircraft was doing and enables identification of the control position responsible for that aircraft. This information is used as a basis for making judgments about the compatibility of TCAS with ATC practices. While there can be some deviations from normal procedures, these will be relatively infrequent in the highly structured, high-volume Chicago Terminal Area.

Runway Operations. Figure 5-6 illustrates the runway configuration at Chicago O'Hare airport. There are three pairs of parallel runways plus a short runway used primarily by GA aircraft. Centerline separation for each set of parallel runways (4-22, 9-27, and 14-32) supports the operation of independent parallel approaches in IMC, although parallel approaches were not in operation during all the data collection periods.



**FIGURE 5-6
RUNWAY CONFIGURATION AT CHICAGO O'HARE**

Table 5-1 lists the runway configuration in use during each data collection period. Parallel approaches were operating during two of the four data collection periods; during the remaining times converging approaches were in use. The number of departures and arrivals at O'Hare is also provided; these

values were obtained from the extractor tape data by counting the number of aircraft entering and leaving a cylindrical volume centered on the airport with a radius of 4 miles and height of 3000 ft. For the purpose of counting the total number of parallel approaches made, it is assumed that all arrivals made approaches to the parallel runways in use.

As shown in Table 5-1, the Chicago terminal area handles a large volume of traffic, even in IMC and marginal VMC. During the 11.24 hour data collection period, there were a total of 883 arrivals and 794 departures at O'Hare Airport alone; this corresponds to an average rate of 78.6 arrivals and 70.6 departures per hour. A further illustration of the density of traffic in this area is shown in Figure 5-7, which represents a "snapshot" of the Chicago airspace at 5:05 p.m. on Friday, April 11, 1980. The "+" symbols represent the positions of aircraft; the numbers beside these symbols indicate each aircraft's altitude in hundreds of ft. The outer edge of the TCA is shown for reference; Chicago O'Hare Airport is in the center.

Traffic Patterns. Control of traffic arriving or departing Chicago area airports (those under the jurisdiction of the Chicago approach control) is based on a "four corner post" operation. This is illustrated in Figure 5-8. By letter of agreement, aircraft are passed from the center to the terminal at 10,000 ft over the fixes at the four corners (the intersections labeled KUBBS, FARMM, PLANO, PLANT, and the Chicago Heights VORTAC). If there is holding, the center retains control of the aircraft in the patterns, which are located at the fixes. Aircraft proceed from these fixes along the indicated arrival routes, descending to 7000 ft until they pass over the departure routes. They are then cleared to 4000 ft to make approaches to the runways. If independent parallel approaches are in use, aircraft making an approach to one of the runways will be cleared to 5000 ft, and the other to 4000 ft, so as to provide 1000 ft altitude separation until they intercept the localizer. They then make normal instrument approaches.

Departures are given clearances to climb to 5000 ft after takeoff; they maintain 5000 ft until they have crossed

TABLE 5-1
 RUNWAY CONFIGURATIONS AND ARRIVAL/DEPARTURE RATES
 AT CHICAGO O'HARE DURING DATA COLLECTION PERIODS

DATE	DAY	Local Time	RUNWAY CONFIGURATIONS IN USE		NUMBER OF	
			Arrivals	Departures	Arrivals	Departures
4/09/80	Wednesday	0919-1100	14R,L	(unknown)	149	109
4/09/80	Wednesday	1210-1654	22R,27L	22L,32L	257	216
4/11/80	Friday	1401-1605	4R,9L	4L,9R	154	160
4/11/80	Friday	1605-2005	9R,L	4R,L	<u>323</u>	<u>309</u>
					883 (78.6/hr)	794 (70.6/hr)

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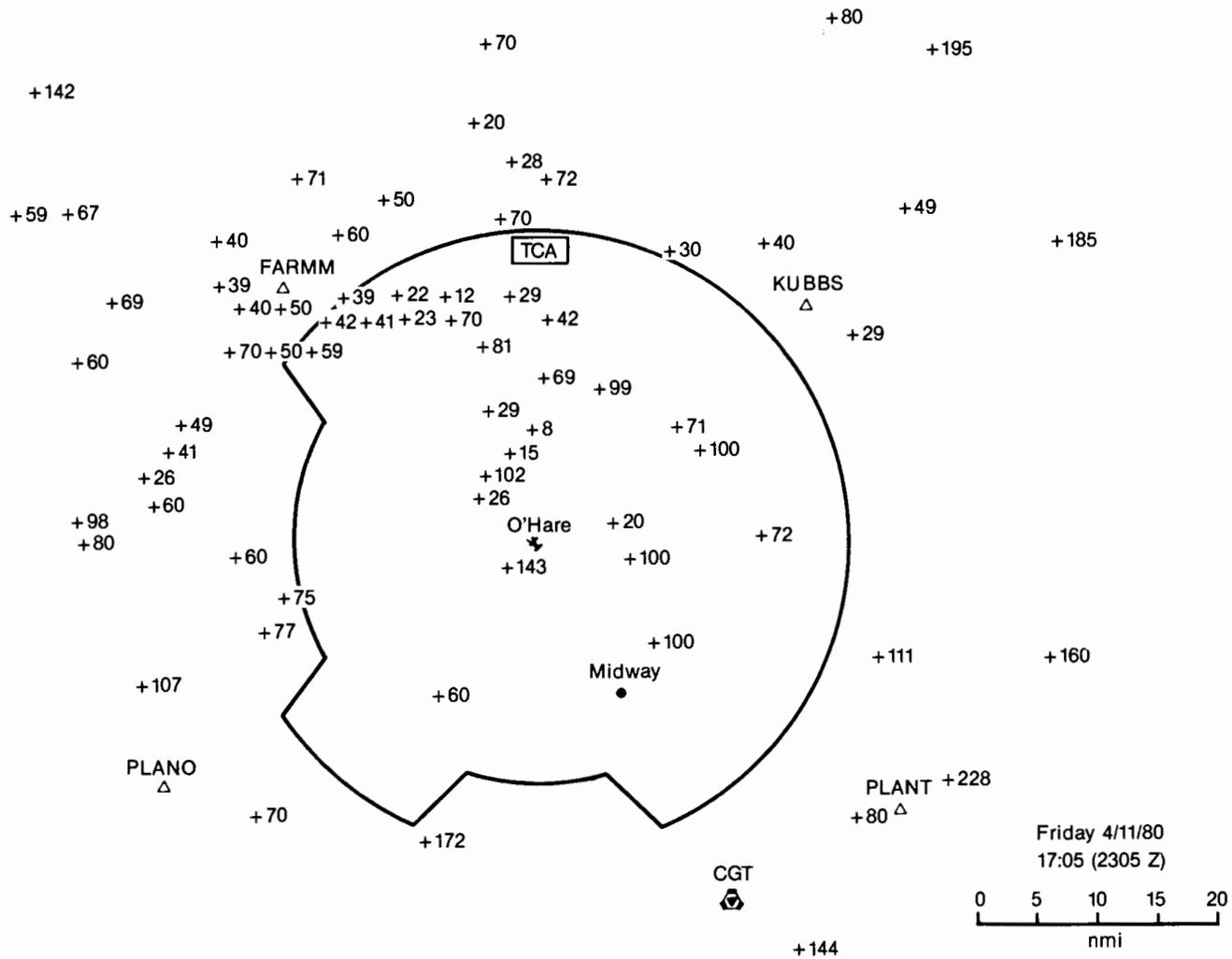


FIGURE 5-7
SAMPLE OF TRAFFIC — CHICAGO TERMINAL AIRSPACE

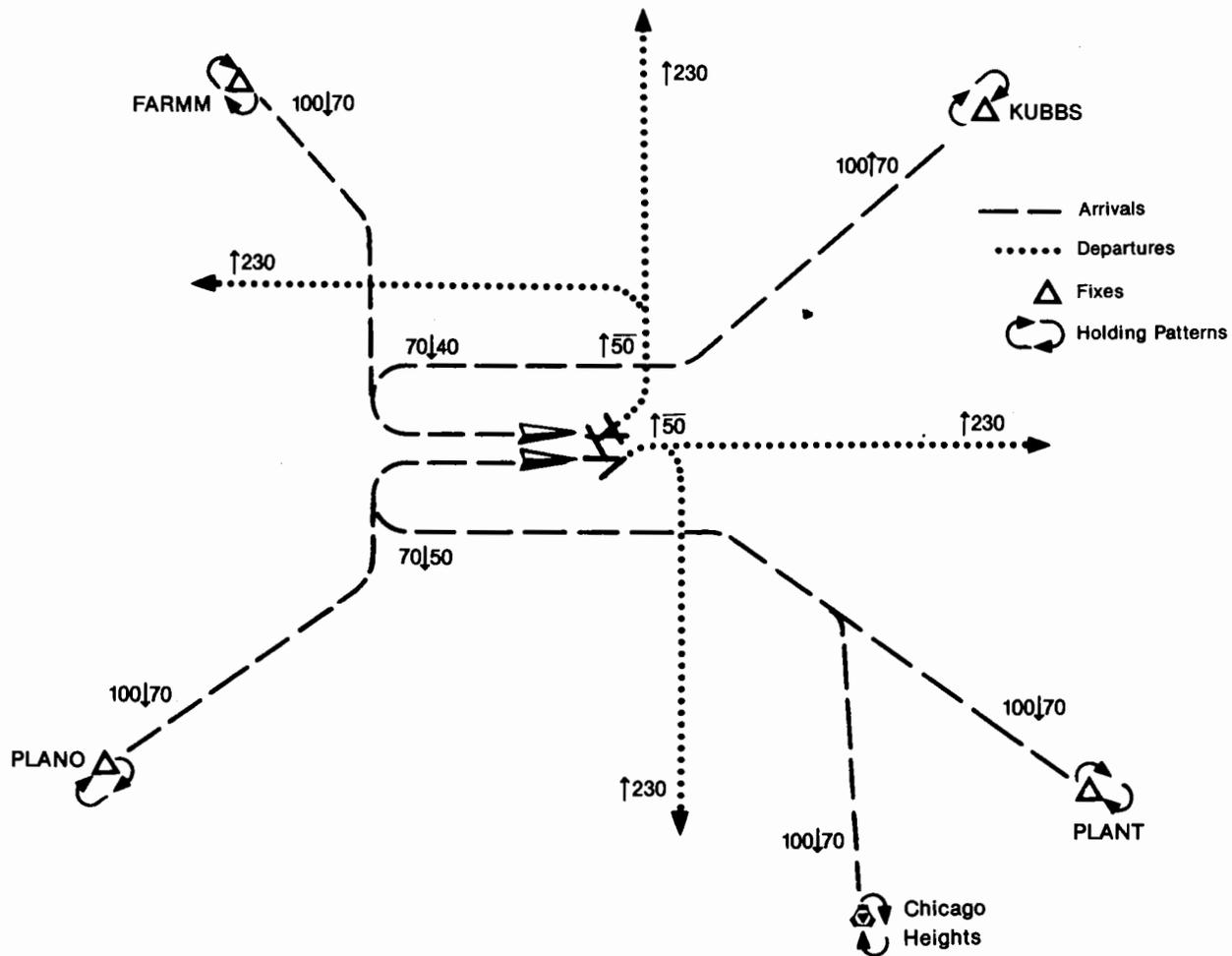


FIGURE 5-8
EXAMPLE OF PATTERN USED FOR CHICAGO O'HARE TRAFFIC

underneath the arrival routes. They are then cleared to 23,000 ft and handed off to the center. Arriving aircraft for satellite airports cross the Chicago terminal area at 6000 ft and descend to 3000 ft (under the departures) to make an approach to their destination airport. The 6000 ft altitude level is also used for overflights (aircraft transiting the Chicago terminal area) and for maneuvering aircraft for approach to the other primary runway in order to balance arrival streams.

While Figure 5-8 depicts one runway configuration (arrivals to 9R and 9L, departures on 4L and 4R), the pattern is rotated as necessary to fit other runway configurations.

Sectorization. Sectors in the Chicago terminal area are created by dividing the airspace between arrival runways (for approach controllers) and between departure runways (for departure controllers) as illustrated in Figure 5-9. Two controllers are assigned to each of the arrival streams. One controller talks to the center and controls the rate of aircraft handed to approach control; the other talks to the aircraft and merges the traffic streams. If independent parallel approaches are in use, a radar controller monitors the non-transgression zone between the localizers. Should either aircraft violate this zone, this controller issues instructions for the other aircraft to make a missed approach. One controller is assigned to each of the departure streams. There are generally one or two additional controllers to handle overflights and satellite airports.

This level of controller staffing will be assumed when measuring workload.

Effects of These Practices on the Use of TCAS. As can be seen, the Chicago terminal area is a highly structured environment. It demonstrates two characteristics that have implications for the use of TCAS:

1. ATC provides large vertical separations for aircraft that are climbing or descending. Chicago approach control uses 7000 ft for O'Hare arrivals, 5000 ft for O'Hare departures, and 3000 ft for arrivals to satellite airports, thus providing 2000 ft of altitude separation for aircraft with vertical rates.
2. Aircraft climb and descend with relatively slow vertical rates. Aircraft have available to them long distances over which to make relatively low-rate descents.

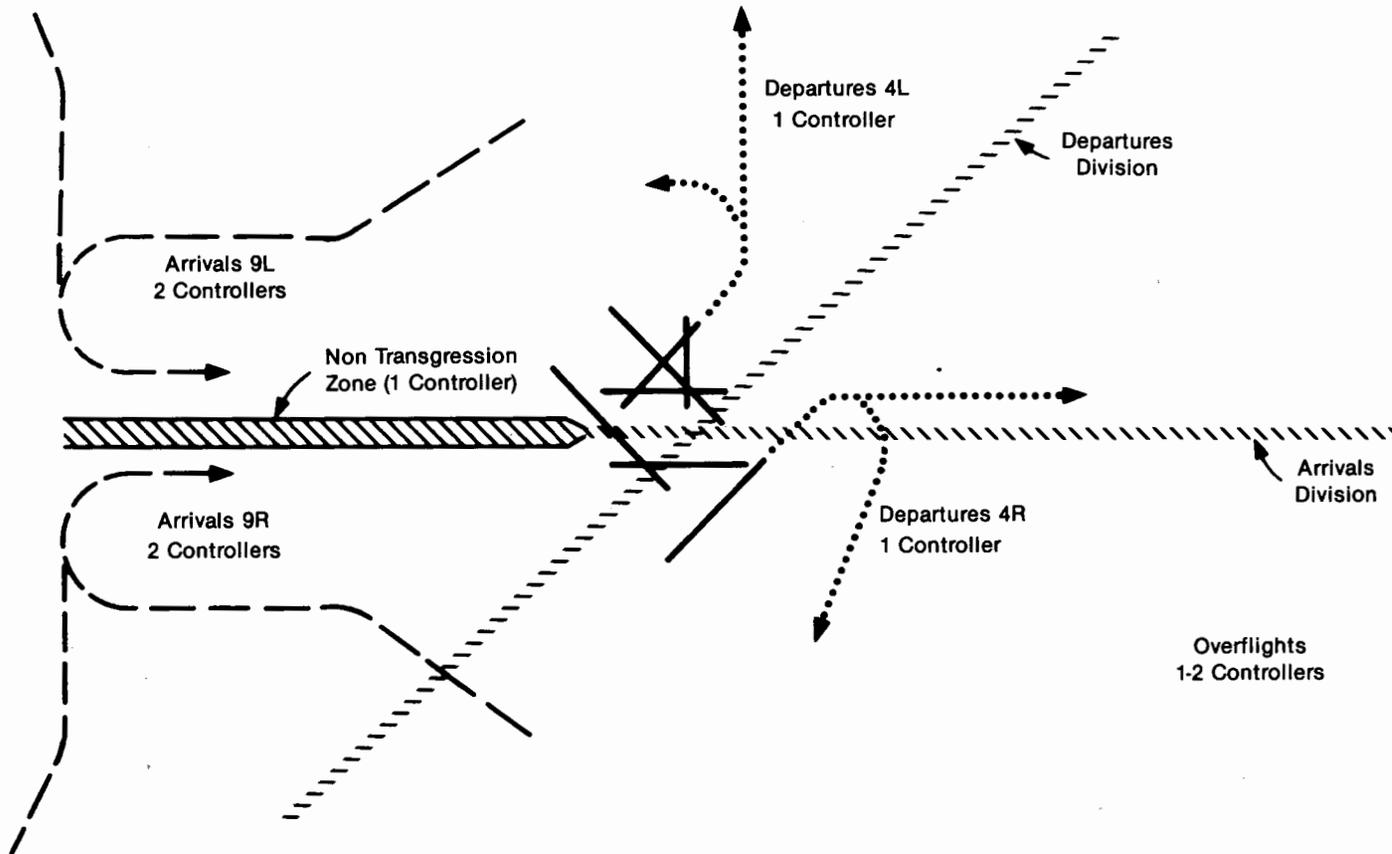


FIGURE 5-9
CHICAGO APPROACH CONTROL POSITIONS

These characteristics have two effects. The large altitude separations and low vertical rates result in low rates of RAs compared with an environment in which VFR is being used, even in a terminal area as busy as Chicago. Since at these altitudes TCAS will issue RAs 25 seconds before coaltitude, a closing vertical rate of 4800 fpm (combined) is necessary for this threshold to be passed. Also, the use of IFR separations (1000 ft vertical) or larger, combined with slow vertical rates means that conditions at Chicago demonstrate low susceptibility to induced NMACs due to intruder maneuvers in IMC compared with a more general VFR environment, which uses 500 ft separations between IFR and VFR aircraft.

5.3.2 Results from TCAS Encounter Processing

Filtering the Chicago ARTS data through the TCAS Traffic Advisory logic, as described in Section 2.1, produced 275 aircraft encounters likely to generate TAs. After smoothing the aircraft tracks, every aircraft was then individually simulated as TCAS-equipped with a non-TCAS threat to obtain independent advisories for each aircraft. Each encounter was simulated twice: (1) Aircraft 1 as TCAS-equipped, Aircraft 2 as the intruder; (2) Aircraft 1 as the intruder, Aircraft 2 as TCAS-equipped. Of these 275 encounters, 228 generated TAs and 14 generated RAs. This section presents the results of an analysis of these 14 RA-producing encounters.

Of the 28 aircraft involved, 24 received RAs when simulated as TCAS-equipped. Since TCAS continually tracks its own vertical rate, whereas the intruder may only be tracked for a short time before an advisory is issued, there can be slight differences in TCAS' tracking of the two aircraft. In four of the encounters, these differences are enough to generate RAs when one aircraft is taken as TCAS-equipped, while the encounter just misses the RA thresholds when the other aircraft is taken as TCAS-equipped.

To measure the maximum individual displacement that would be caused by the RAs, the aircraft were modeled one at a time as responding to the advisories. If in an actual encounter both aircraft are TCAS-equipped, less displacement would be required of each aircraft since the separation to be achieved would be divided between the two. In addition, TCAS coordination would insure that neither aircraft chooses an adverse maneuver once the other has an advisory.

The results obtained from these TCAS encounter simulations address the safety, workload, and capacity issues discussed in Section 5.1. Special emphasis is placed on an analysis of the potential for domino effects, the compatibility of advisories with ATC, and the effects of TCAS on parallel approaches.

5.3.2.1 Safety

Interactions between TCAS and the ATC environment that impact safety are evaluated by an examination of the encounters that result in RAs. Separation between the aircraft in the encounter is examined, both without the advisories being followed (as actually happened in Chicago) and with any displacements that would result from following the advisories. The TCAS displacement is compared with the intent of the pilot, as inferred from the actual flight path, to determine the compatibility of the advisory with the overall operation of the ATC system.

The analysis is then extended to the surrounding airspace. The location of the next nearest aircraft is examined to see how separation from that aircraft is changed by following the advisory. Checks are made to determine if IFR separation standards are violated, or if new RAs are generated, which provides an indication of whether a domino effect exists or not. Finally, since concerns have been expressed that holding patterns show potential for domino effects, a detailed examination is made of RAs which occur for aircraft in holding patterns.

Separation from Threat. In the Chicago ARTS data base, aircraft maneuvered in accordance with ATC instructions only, since no aircraft were actually TCAS-equipped. The tracks of these aircraft provide a baseline for evaluation of the need for and correctness of the RAs generated by the simulations. The need for an advisory is evaluated by comparing the actual separation at closest point of approach (CPA) with the TCAS advisory thresholds and with the IFR separation standards. The correctness of the advisory is evaluated by noting whether the advisory would maintain or increase separation.

Figure 5-10 is a plot of the vertical and horizontal separations at closest point of approach for 11 of the encounters which produced RAs. Three cases involving aircraft making parallel approaches are excluded, because the critical point to evaluate TCAS on parallel approaches is not at

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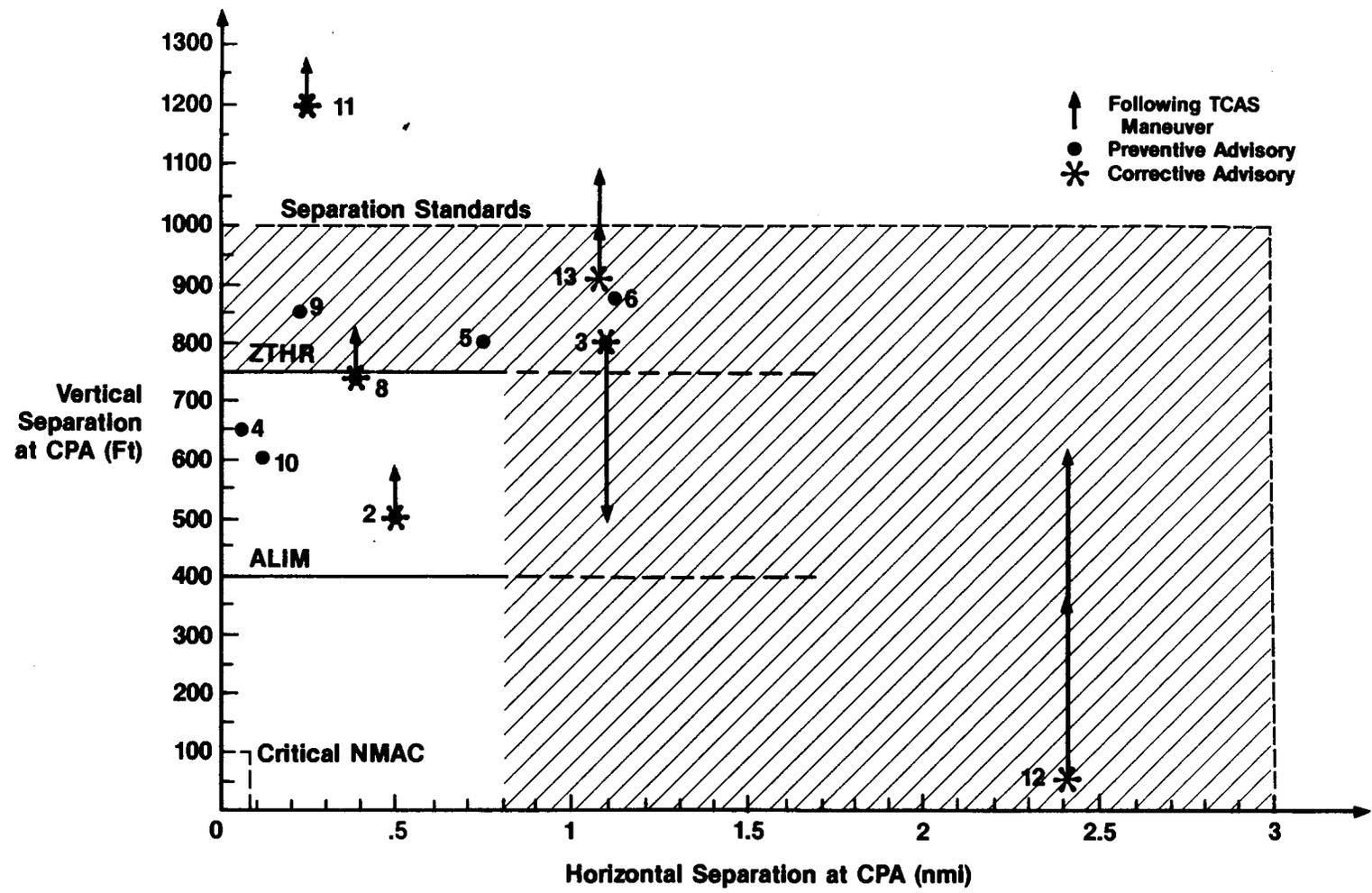


FIGURE 5-10
VERTICAL AND HORIZONTAL SEPARATION AT CLOSEST APPROACH
(EXCLUDING PARALLEL APPROACHES)

closest approach, when the aircraft are coalitude but not closing in range; rather, it is as they turn onto final approach. Analysis of parallel approaches are therefore treated separately (in Section 5.3.2.3).

Each point in the figure represents the actual separation at CPA between the two aircraft in each encounter. Each encounter is given a number for reference in the text and for reference to the horizontal and vertical plots in Appendix E. The dots are for aircraft that would receive preventive advisories, requiring no change in flight path; the stars represent corrective advisories requiring some vertical displacement from the current flight path. A point which has both a dot and a star indicates that one of the aircraft would receive a preventive advisory if it were TCAS-equipped and the other would receive a corrective RA if it were TCAS-equipped. The arrows show the vertical displacement and the resulting separations that would have occurred if the aircraft were to follow the RAs. The same reasons that cause TCAS to generate only one corrective RA in a pair (encounter geometries, aircraft maneuvers, tracked rate changes, etc.), cause advisory strengths to differ, resulting in different amounts of displacement for each aircraft in the encounter. These are shown as stars with two arrows.

The large dashed box shows the IFR minimum separation standards of 3 miles horizontally and 1000 ft vertically. All of the aircraft that would receive RAs pass within the IFR separation standards, even though it cannot be concluded that all these encounters are necessarily system errors. Although the vertical separation of the aircraft in Encounter 11 is greater than 1000 ft at minimum range (the point shown), it is only 500 ft when they are still converging and the range is just over a mile (not shown).

The figure also shows the RA vertical separation thresholds ALIM (400 ft) and ZTHR (750 ft) for the altitudes at which most of the encounters occur (under 10,000 ft). ALIM is the threshold for issuing positive RAs ("Climb" or "Descend") and ZTHR is the threshold for issuing negative RAs (limit rates).

In most cases, TCAS would maintain vertical separation at approximately ZTHR. However, in two cases (Encounters 11 and 13) it appears that TCAS would issue corrective RAs for safely separated aircraft. TCAS issues RAs 25 to 30 seconds prior to CPA and bases the strength of an advisory on the projected vertical miss distance at that time. In both of these

encounters, the aircraft were projected to have vertical miss distances of less than ALIM, with one aircraft descending toward the other. After the time the RA would have been issued, the descending aircraft leveled off and maintained or increased vertical separation to that well above these thresholds.

Encounter 12 is an encounter in which horizontal miss distance filtering may eliminate an alert for aircraft that pass with over two miles of horizontal separation. The aircraft were initially closing head-on, but both executed right turns prior to CPA, thus resulting in the large horizontal miss distance. TCAS provides correct advisories for each aircraft in the vertical dimension, however, increasing separation from less than 100 ft to ALIM or greater.

As expected, there were no critical NMACs (500 ft horizontal and 100 ft vertical separation). Except for Encounter 12, all of the encounters had more than 500 ft vertical separation. These encounters demonstrate a low susceptibility to induced NMACs caused by altimetry error, since a large error in these reported altitudes would be required to reduce the vertical separations to less than 100 ft.

In all the encounters except for Encounter 3, the RAs maintain or increase vertical separations. Encounter 3 is a relatively slow-closing encounter where the threat made a sudden vertical maneuver and was tracked with a sufficient vertical rate to project an altitude crossing. The threat then actually leveled off and began to diverge in range, at which point the advisory was removed. By following the altitude crossing advisory, the TCAS aircraft would move closer to the threat approximately 300 ft vertically before reaching minimum range with a vertical separation of 500 ft. Although the RA is a nuisance, it would not create an unsafe situation since the horizontal miss distance is over a mile.

To summarize, while a few nuisance RAs were observed, all aircraft that would have received Resolution Advisories passed within the IFR separation standards of 3 miles horizontally and 1000 ft vertically. One advisory was observed, which would have decreased separation; however, it is not a threat to safety as the aircraft are separated by more than a mile horizontally. All other advisories maintain or increase vertical separation. TCAS-to-TCAS coordination, not taken into account in the analysis, would insure that no adverse sense selection takes place for those encounters in which both aircraft are TCAS-equipped.

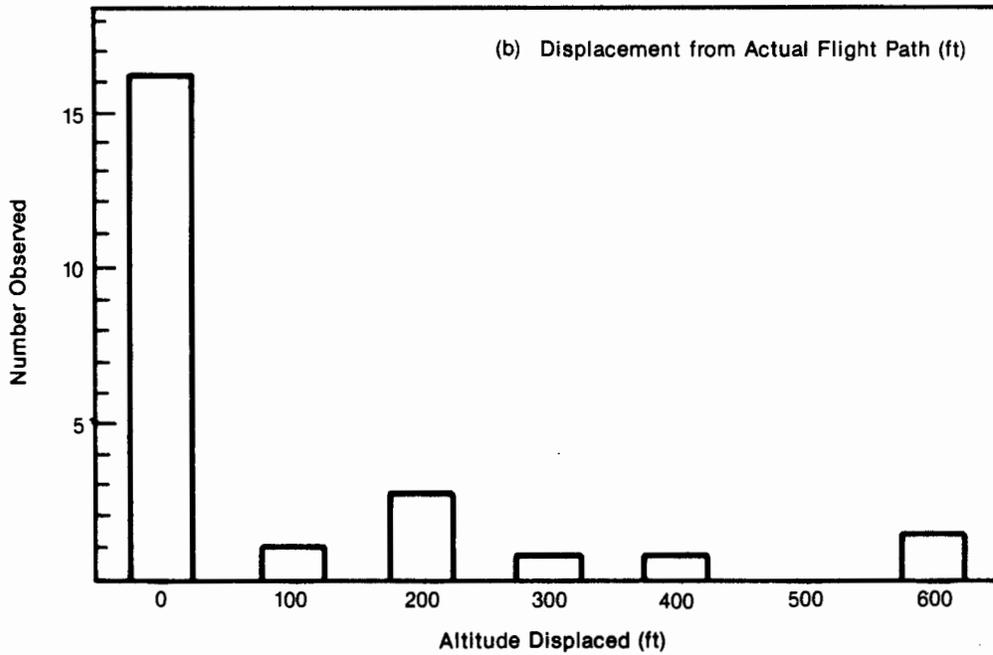
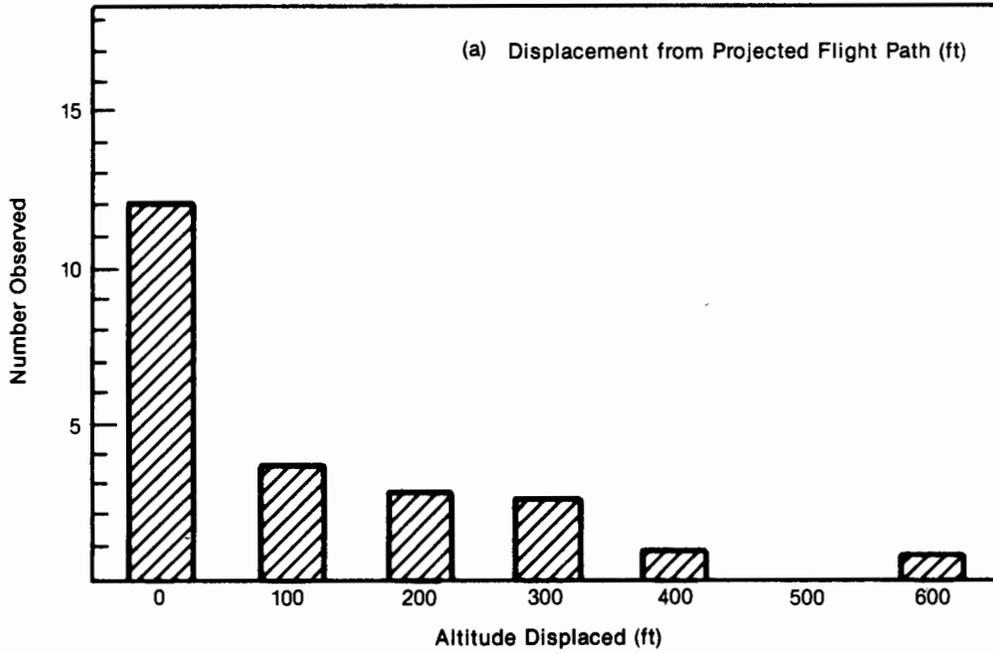
Compatibility of Advisories. The compatibility of a TCAS RA with pilot intent is evaluated by comparing the flight path the aircraft actually followed with the flight path TCAS would have called for. The direction of the TCAS maneuver relative to any maneuvers actually made, as well as the displacement generated, provide an indication of how compatible the RA is.

At the time an RA is chosen, TCAS assumes each aircraft will continue at its current tracked vertical rate. The RA is chosen so as to provide safe separation from the threat with the least amount of deviation from this projected flight path. A distribution of these displacements from the projected flight path is shown in Figure 5-11(a) for the 24 aircraft receiving RAs in the Chicago ARTS data base. This distribution indicates that the displacements expected by TCAS are generally small; 79 percent of the aircraft require less than 300 ft of displacement from their projected flight paths. Twelve (half) of the aircraft require no displacement (they receive preventive RAs).

However, since some of the aircraft actually made maneuvers subsequent to the time an RA would be issued, some of the actual flight paths differ from the projected flight paths. A distribution of the displacements from the actual flight paths for the same 24 aircraft is shown in Figure 5-11(b). The similarity between this distribution and the distribution above indicates that there is actually little maneuvering; aircraft generally follow their projected flight paths.

Of the 24 aircraft which would have received RAs, 83 percent would have been displaced from their actual (intended) flight paths by less than 300 ft. Sixteen (67 percent) of the aircraft would not be required to deviate from their flight paths at all. These include the 12 aircraft that would receive preventive RAs and four aircraft that executed maneuvers. In these four cases the maneuvers TCAS would have called for closely followed their actual maneuvers; consequently, there would be no resulting displacement from their flight paths.

While the small amounts of displacements indicate there would be little disruption, it is useful to observe the actual maneuvers of each aircraft individually to determine whether the maneuver is in the same direction as the maneuver that TCAS would call for. Only one aircraft actually maneuvered in the opposite direction from the advisory issued in the simulation (Encounter 12). Several of the RAs would simply get the aircraft to its intended altitude a little sooner, or slow down



**FIGURE 5-11
DISPLACEMENTS FROM PROJECTED AND ACTUAL ALTITUDES**

or delay a vertical maneuver until the threat passes by. Although these RAs create displacement from the aircraft's actual flight paths, they still can be considered compatible.

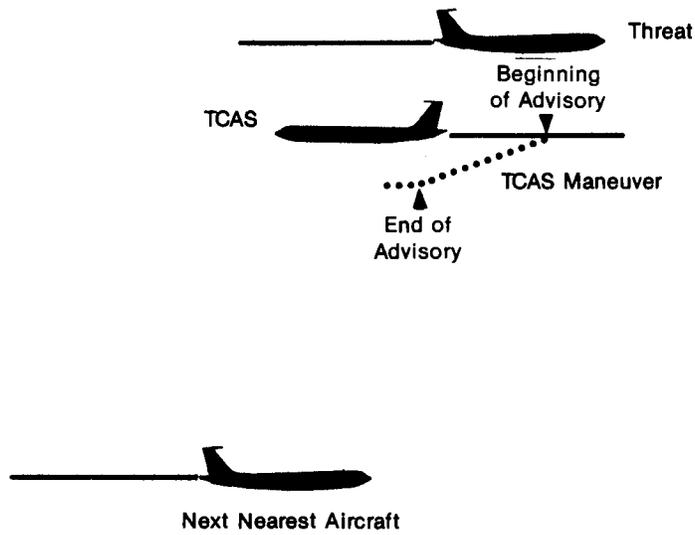
To summarize, most TCAS RAs produce little or no displacement, and the direction of most TCAS maneuvers are in the same direction as the actual maneuvers observed. This indicates that TCAS RAs are in general compatible with the intended flight paths of the aircraft.

Separation From Next Nearest Aircraft. The potential for a domino effect is investigated by measuring the change in separation from the next nearest aircraft for each aircraft in the Chicago ARTS data base that would receive a corrective RA. The next nearest aircraft is not the aircraft causing the TCAS advisory, but is simply the nearest traffic that could possibly come into a conflict with the TCAS aircraft as it follows its RA. Because none of these aircraft pose a threat at the time the RA is issued, TCAS does not take them into consideration when selecting the advisory for the actual threat.

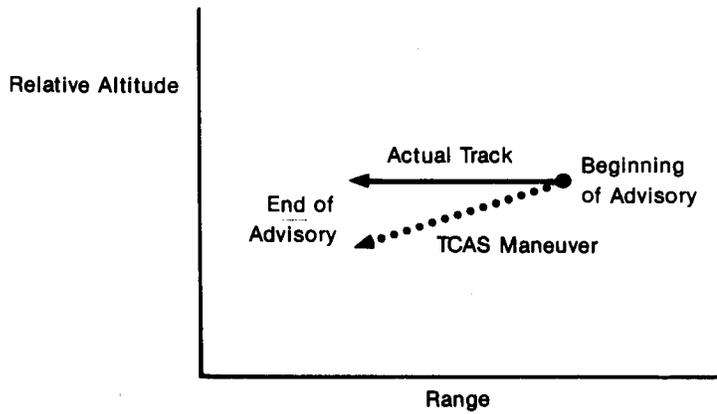
Out of the 12 corrective advisory cases, five next nearest aircraft diverge in either range or relative altitude, two hold position relative to the TCAS aircraft, and three are too far away to result in any conflicts (separated by more than 8 nmi or 3000 ft.) As a result of the displacement created by the advisories, the "TCAS-equipped" aircraft and its next nearest aircraft converge in both range and relative altitude in two cases. Only these two RAs show any potential to result in a new conflict.

Figure 5-12 illustrates a method for analyzing the relative movement between the TCAS-equipped aircraft and the next nearest aircraft. The example in Figure 5-12 (a) shows a TCAS aircraft responding to an RA which moves it toward the next nearest aircraft. Figure 5-12 (b) plots the change in separation between the TCAS aircraft and the next nearest aircraft during the RA. The endpoints of the tracks indicate the range and relative altitude separations before and after the advisory.

Using this graphical method, the changes in separation from the next nearest aircraft for all the aircraft receiving RAs in the Chicago ARTS data base are shown in Figure 5-13. Only the corrective RAs generate displacement from the actual flight path; this change is indicated by a dotted line. The points

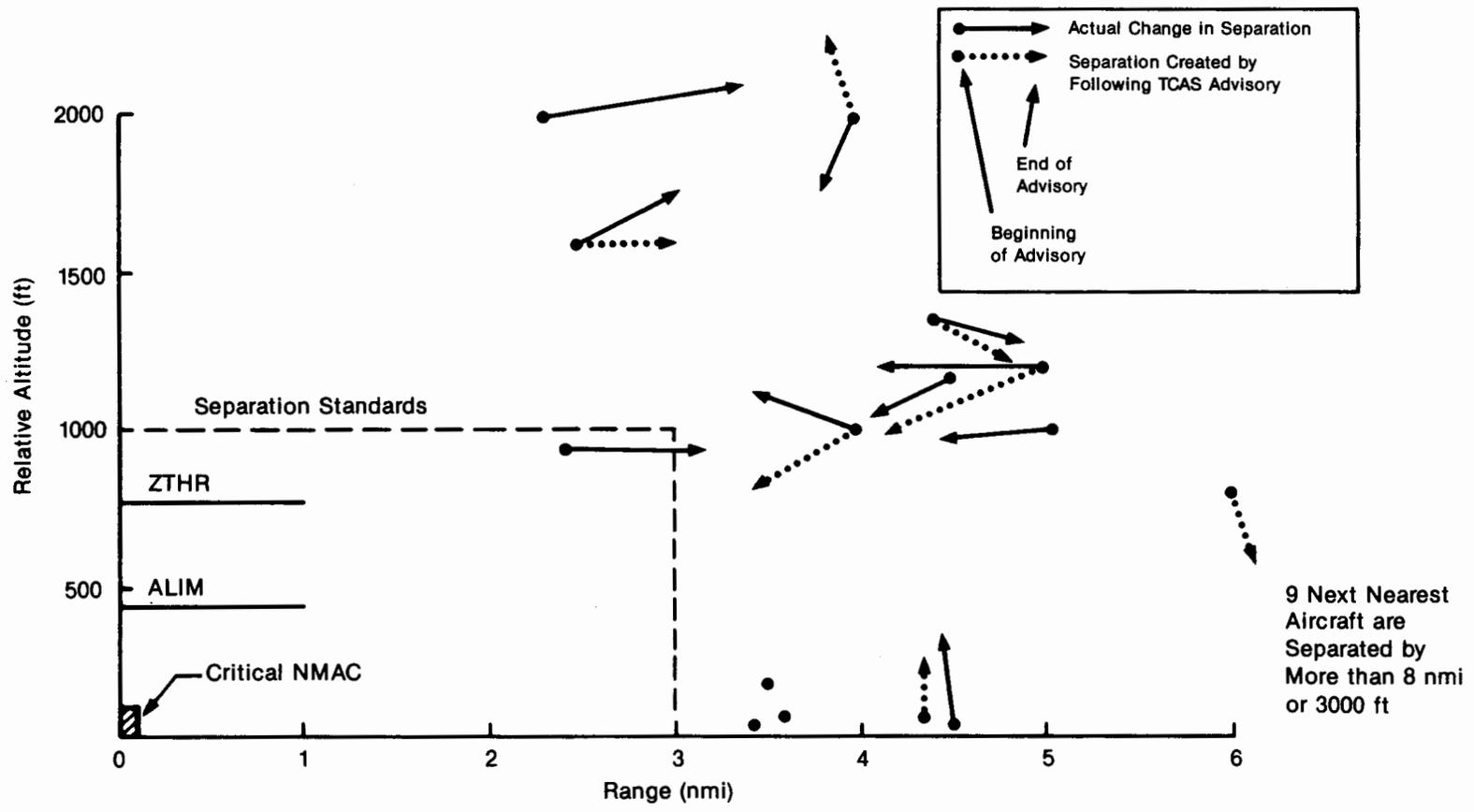


(a) Example of TCAS Movement Relative to Next Nearest Aircraft



(b) Plot of TCAS Movement Relative to Next Nearest Aircraft

FIGURE 5-12
METHOD OF PLOTTING TCAS MOVEMENT
RELATIVE TO NEXT NEAREST AIRCRAFT



**FIGURE 5-13
SEPARATION FROM NEXT NEAREST AIRCRAFT
DURING RESOLUTION ADVISORY**

that have no arrows represent aircraft maintaining the same range and relative altitude throughout the advisory, which are usually aircraft in trail. We can note that the nearest maneuvering traffic tends to cluster near the IFR separations of 1000 ft vertically and 3 to 5 miles horizontally; the in-trail traffic tends to follow at 3 to 4 miles.

The two cases in which the TCAS maneuver brings the aircraft closer in both range and relative altitude are shown with the dotted lines pointing toward the origin. This figure shows however, that the separations are all well beyond the TCAS advisory thresholds of ZTHR and ALIM, and all but one are greater than the IFR separation standards. The only aircraft within the separation standards diverges in range and is beyond 3 miles at the end of the advisory. The TCAS aircraft involved does not need to maneuver and therefore does not change this separation.

Upon simulating each maneuvering TCAS aircraft with its next nearest aircraft, no advisories (TAs nor RAs) were generated because of the large range and relative altitude separations. Since Chicago is a dense traffic environment, and the TCAS maneuvers are not found to create any new conflicts in the Chicago ARTS data base, this suggests that opportunities for observing domino effects may be extremely rare.

Holding Pattern Example. One of the previously noted RA encounters (Encounter 13) occurred while the aircraft were in a holding pattern. Upon examination of the surrounding airspace, a third aircraft was seen to be holding below. Because of concerns about the potential for domino effects specifically in holding patterns, a detailed analysis of this encounter is presented.

The encounter is illustrated in Figure 5-14. Aircraft A is descending rapidly to 9000 ft while Aircraft B holds below it at 8000 ft. If Aircraft A were TCAS-equipped, it would receive a "Limit Descend" RA to slow its descent. Aircraft B would receive a "Descend" RA if it were TCAS-equipped. This would cause Aircraft B to move toward Aircraft C holding at 7000 ft. However, no RA would be generated for Aircraft C because it is currently on the opposite leg of the holding pattern at a range of 3 miles, and is not threatened by Aircraft B descending from 8000 ft.

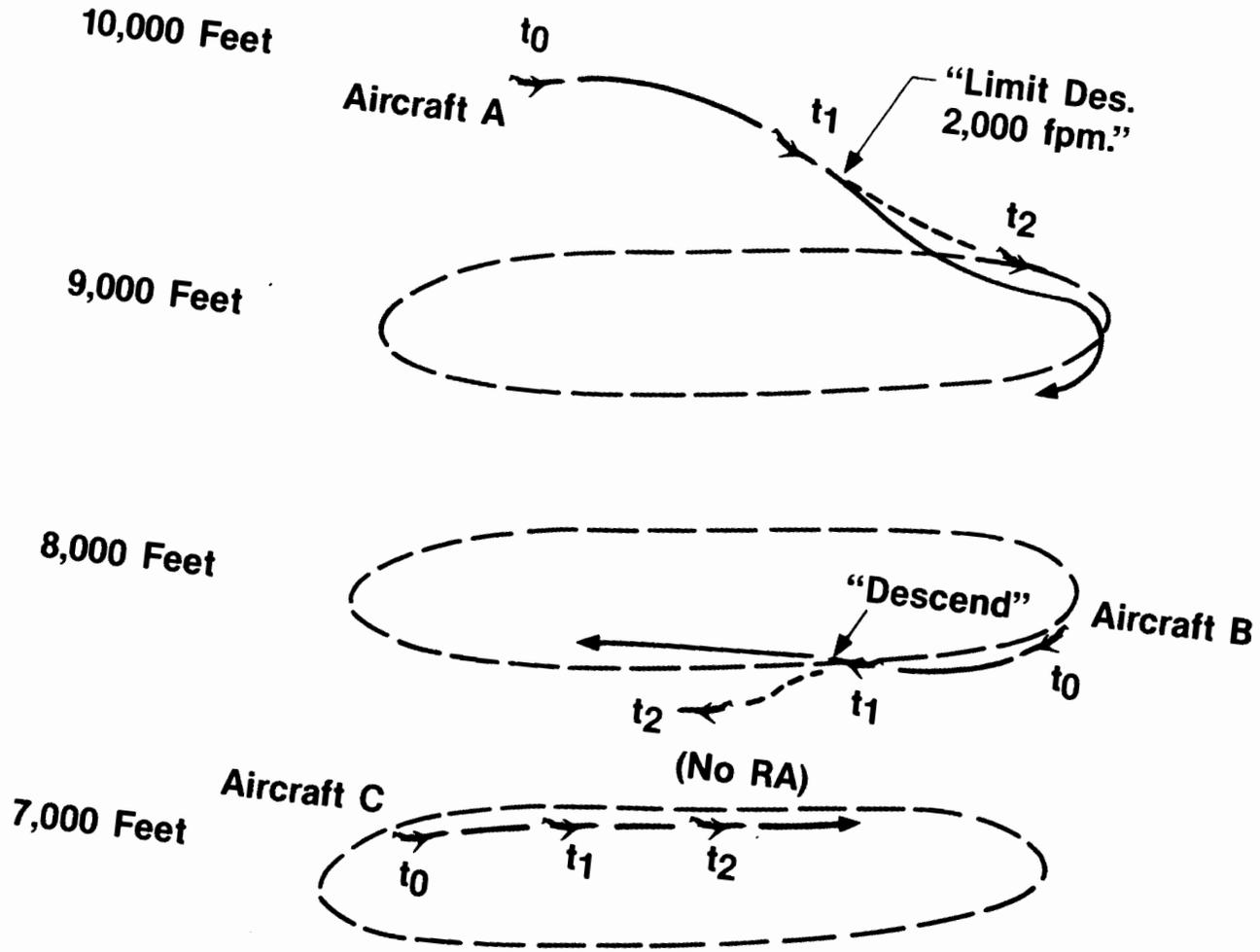


FIGURE 5-14
HOLDING PATTERN ADVISORY

Figure 5-15 shows the vertical profile of the encounter. At time t_1 , Aircraft A is projected to be 22 seconds from coalitude with Aircraft B, at which point an RA is issued. Aircraft B initially receives a preventive RA ("Don't Climb") that is quickly strengthened to "Descend". The RA is continued until the aircraft pass closest point of approach (CPA) and begin diverging. By following the RA, Aircraft B is displaced 300 ft to 7800 ft while Aircraft C remains 1000 ft below at 6800 ft when they pass each other at time t_2 .

In this encounter, no new RA is generated between Aircraft B and C because both the range and altitude tests fail by wide margins. If instead the aircraft were to be on the same leg of the holding pattern, then the range would be close enough to pass the range thresholds. If Aircraft C were directly below Aircraft B, the range would be at a minimum but a RA would be generated only if Aircraft B descends to within 750 ft of Aircraft C. Even if this happens, however, no movement would be necessary for Aircraft C. A preventive RA ("Don't Climb") would be generated for Aircraft C while a "Don't Descend" RA would stop Aircraft B from getting any closer. If the position of the aircraft were different, therefore, it would be possible for a new RA to be generated. However, even then Aircraft C would not be required to maneuver, and thus no domino effect would occur.

The hypothetical domino effect discussed in Section 5.1 (Figure 5-2), in which multiple TCAS aircraft are stacked directly above each other in a holding pattern and the TCAS maneuvers propagate throughout the pattern, is not possible. In simulations, the TCAS multi-aircraft logic prevented movement from propagating past the second aircraft in the pattern. As soon as the first TCAS detects the second aircraft, it immediately stops its climb (or descent). The second TCAS will detect the first aircraft and may issue an RA requiring a small amount of displacement, but not enough to cause the third aircraft to maneuver. Since in actual practice, adjacent aircraft in the pattern are typically held on opposite legs, the first aircraft may maneuver to avoid the intruder, but the rest of the stack would remain unaffected.

To summarize, the next nearest aircraft to those receiving RAs were observed to not be closing on the TCAS-equipped aircraft, and were safely separated in all cases. An aircraft pair was observed to receive RAs in a holding pattern, but no domino effect was observed; instead the logic design tends to minimize disruption of flight paths.

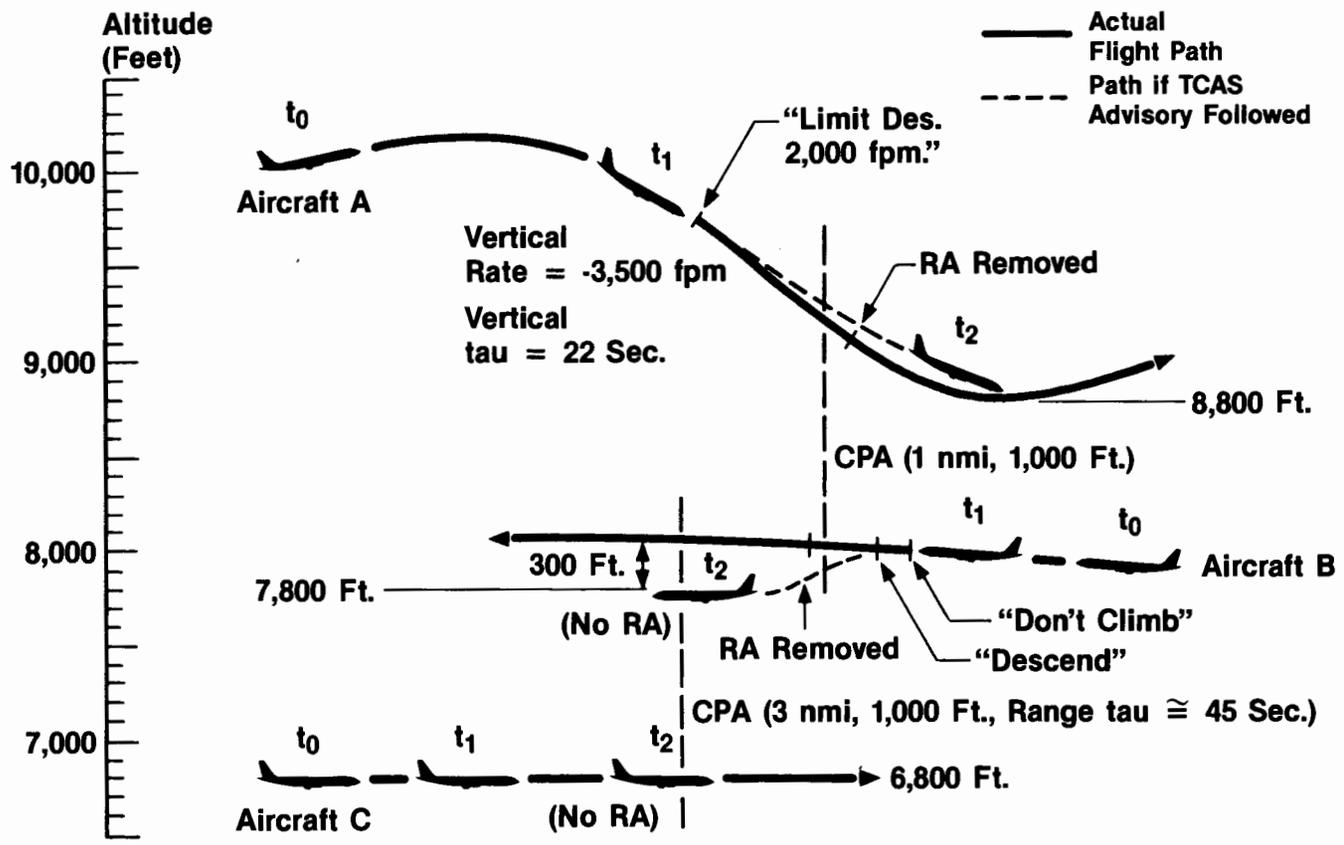


FIGURE 5-15
HOLDING PATTERN ADVISORY — VERTICAL PROFILE

5.3.2.2 Controller Workload

Measures of controller workload include how often RAs occur, where they occur, and how much displacement is created. The previous section discussed the amount of displacement created by the TCAS RAs. Over 80 percent of the RAs create less than 300 ft of displacement, and most of the TCAS maneuvers are in the same direction as the aircraft's actual flight path. Whether the controller will observe the displacements is dependent on the circumstances of the encounter; however, it was found that the maneuvers do not create new conflicts with other traffic.

Advisory Rates. By estimating the total number of track-hours for all the aircraft in the Chicago ARTS data base, it is possible to compute average rates for TAs and RAs on a per-aircraft flight hour basis. Estimating the total track-hours is done by multiplying the time span of the data by the average number of aircraft tracked per radar scan over that time span. These rates are one TA per 1.4 aircraft hours, and one RA per 27 aircraft hours.

We can compare these rates to the advisory rates taken from the Piedmont Phase I study for aircraft flying in terminal areas in all conditions. In the Piedmont Phase I study, operation below 10,000 ft was taken as terminal airspace. The rates for overall conditions are one TA per 3 aircraft hours, and one RA per 15 aircraft hours. Table 5-2 shows the TA and RA rates for both IMC and overall conditions.

It was found that TAs occur in the terminal area about twice as frequently in IMC as in overall conditions. This is primarily due to the fact that parallel approaches were in use during most of the periods in which the data was collected. TAs would be generated for most parallel approaches due to the planned close proximity while each aircraft turns onto the approach. This increases the TA rate over that found in the Piedmont study, where parallel approaches were the exception. On the other hand, RAs occur in the terminal area in IMC at about half the rate observed in overall conditions. This is a direct result of the larger vertical separations and slower vertical rates observed in the IMC Chicago data; these reduce the likelihood of RAs.

The distribution of vertical separations for the Chicago data shown in Figure 3-2 (Section 3.1) illustrates how most IFR aircraft maintain a separation of 1000 ft, unlike overall

TABLE 5-2
ADVISORY RATE COMPARISON

	Chicago (IMC)	Piedmont (Terminal, All Cond.)
TA Rate	1 per 1.4 a/c hrs	1 per 3 a/c hrs
RA Rate	1 per 27 a/c hrs	1 per 15 a/c hrs

conditons, which were seen to have separations uniformly distributed between zero and 1,000 ft. Therefore, in IMC fewer of the aircraft pass within the RA threshold (ZTHR) of 750 ft.

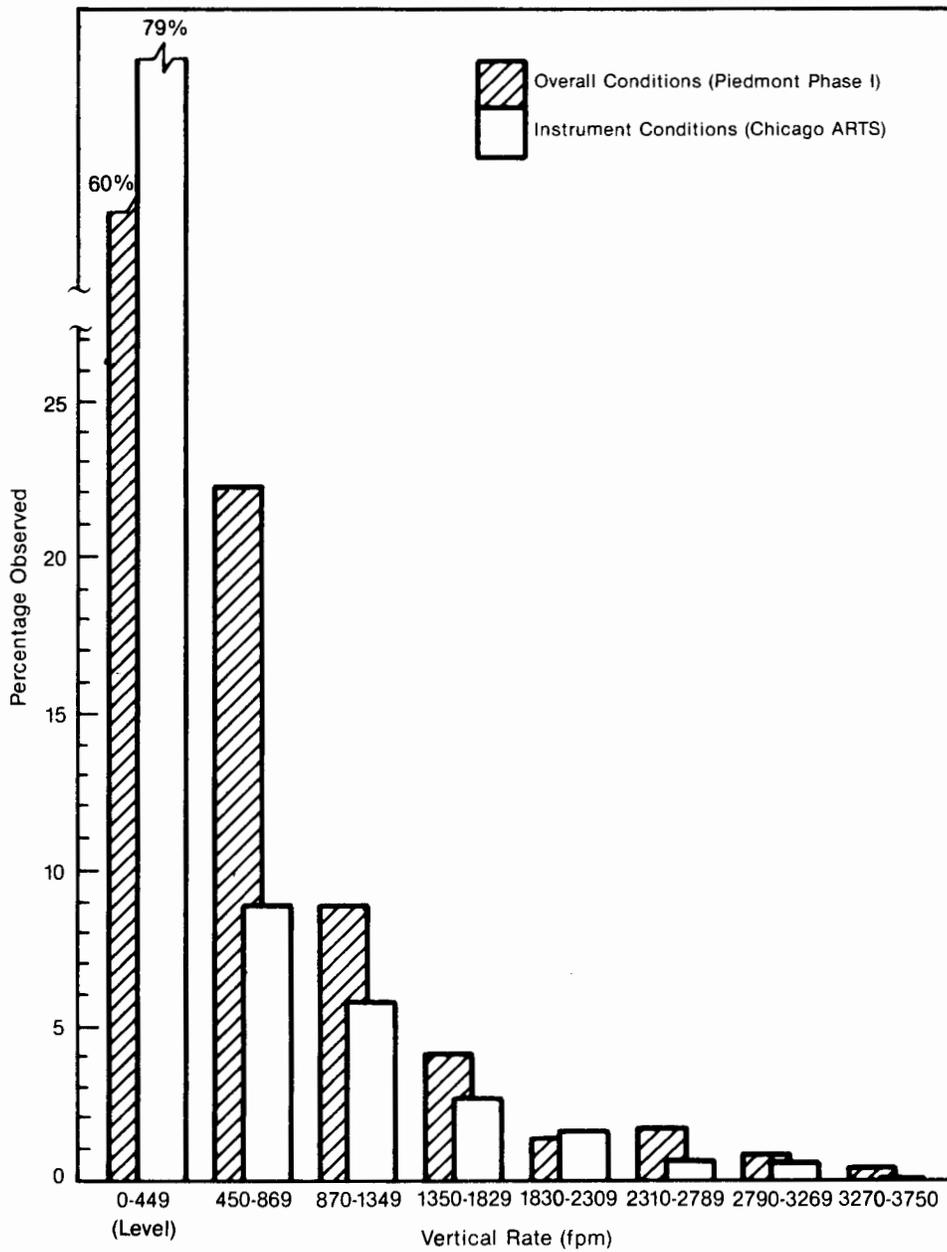
Figure 5-16 is a distribution of the vertical rates observed in both studies. The aircraft tracks on parallel approaches were excluded from the Chicago data base for the IMC distribution. Nevertheless, almost 80 percent of the aircraft flying in IMC were observed as level, compared to the 60 percent observed as level in overall conditions. Very high rates were rare for either study; however, moderate rates were much more predominant in overall conditions than in IMC. Therefore, since the majority of the aircraft in IMC are observed to fly level with 1000 ft of separation, the likelihood of having the vertical rates needed to generate a RA is significantly lower than that in overall conditions.

Table 5-3 is a comparison of the frequency of types of RAs between IMC and overall conditions. The table shows that in overall conditions, 82 percent of the RAs received are corrective, while in IMC only 50 percent are corrective. RAs are more likely to be corrective in VMC because of the use of the VFR separation standards of 500 ft and the higher vertical rates. Since most aircraft in IMC are level and pass outside the RA thresholds, little maneuvering is necessary to maintain this safe separation. Thus, RAs in IMC are more likely to be preventive.

The distribution of the strengths of the RAs is shown in Figure 5-17. The positive RAs ("Climb" or "Descend") are all corrective, while most of the negative and limit rate RAs are preventive. This is also because most of the aircraft are flying nearly level; a "Climb" or "Descend" requires some vertical movement while a "Don't Climb" or "Don't Descend" usually does not.

The structure of the airspace in IMC, therefore, not only reduces the rate that RAs occur to half that in overall conditions, but it also reduces the frequency of maneuvering needed to comply with the RAs.

Encounter Locations. An analysis was undertaken to see whether the terminal IMC environment created any concentration of RAs. The altitudes of the aircraft receiving RAs, shown in Figure 5-18, are distributed over a wide range, with a slight concentration at the 4000 and 5000 ft levels from the three RA



**FIGURE 5-16
COMPARISON OF VERTICAL RATES IN IMC AND OVERALL CONDITIONS**

TABLE 5-3
RESOLUTION ADVISORY TYPE COMPARISON

	CHICAGO	PIEDMONT
	IMC	All Conditions
Preventive	12 50%	3 18%
Corrective	12 50%	14 82%

5-41

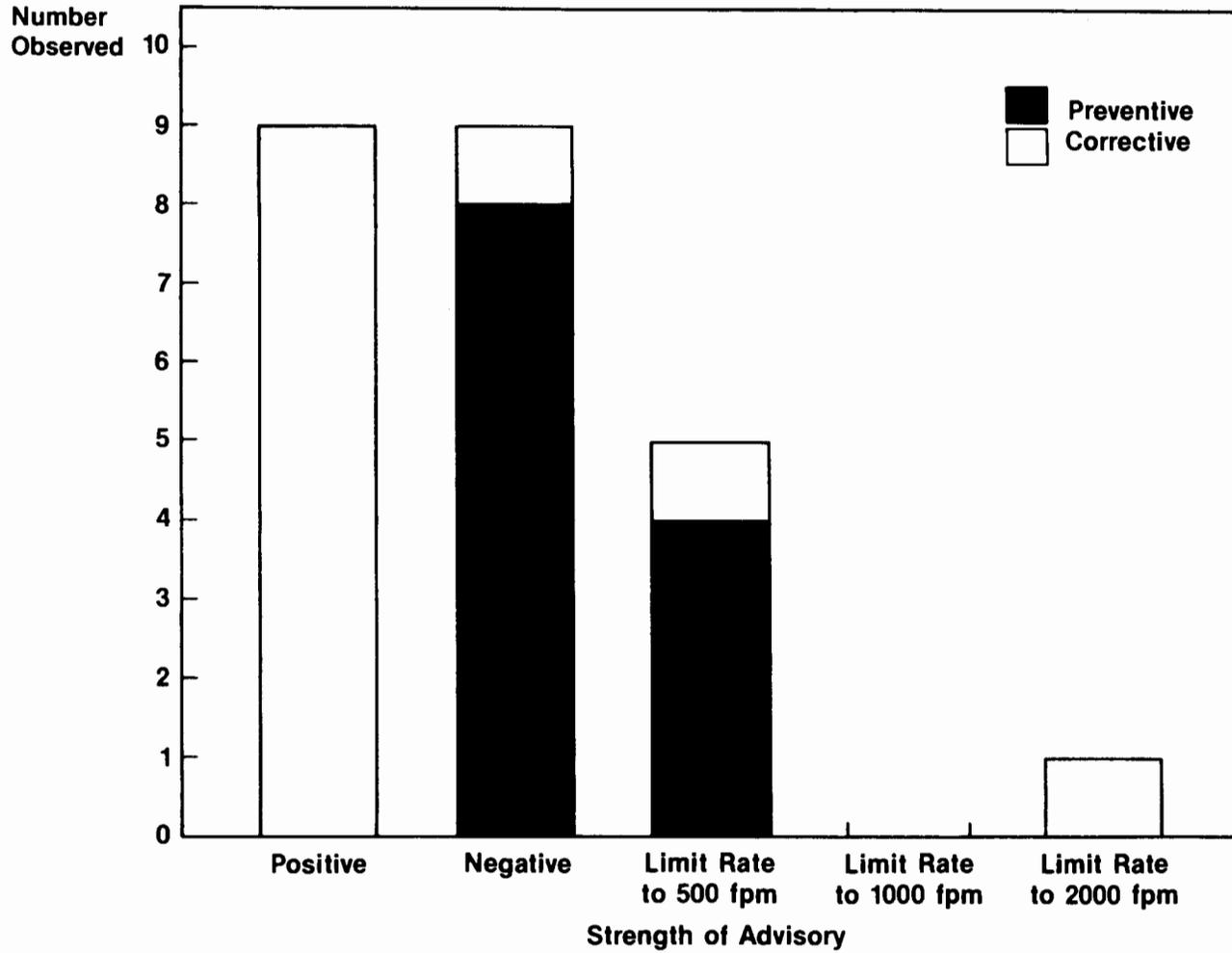


FIGURE 5-17
STRENGTHS OF RESOLUTION ADVISORIES

5-42

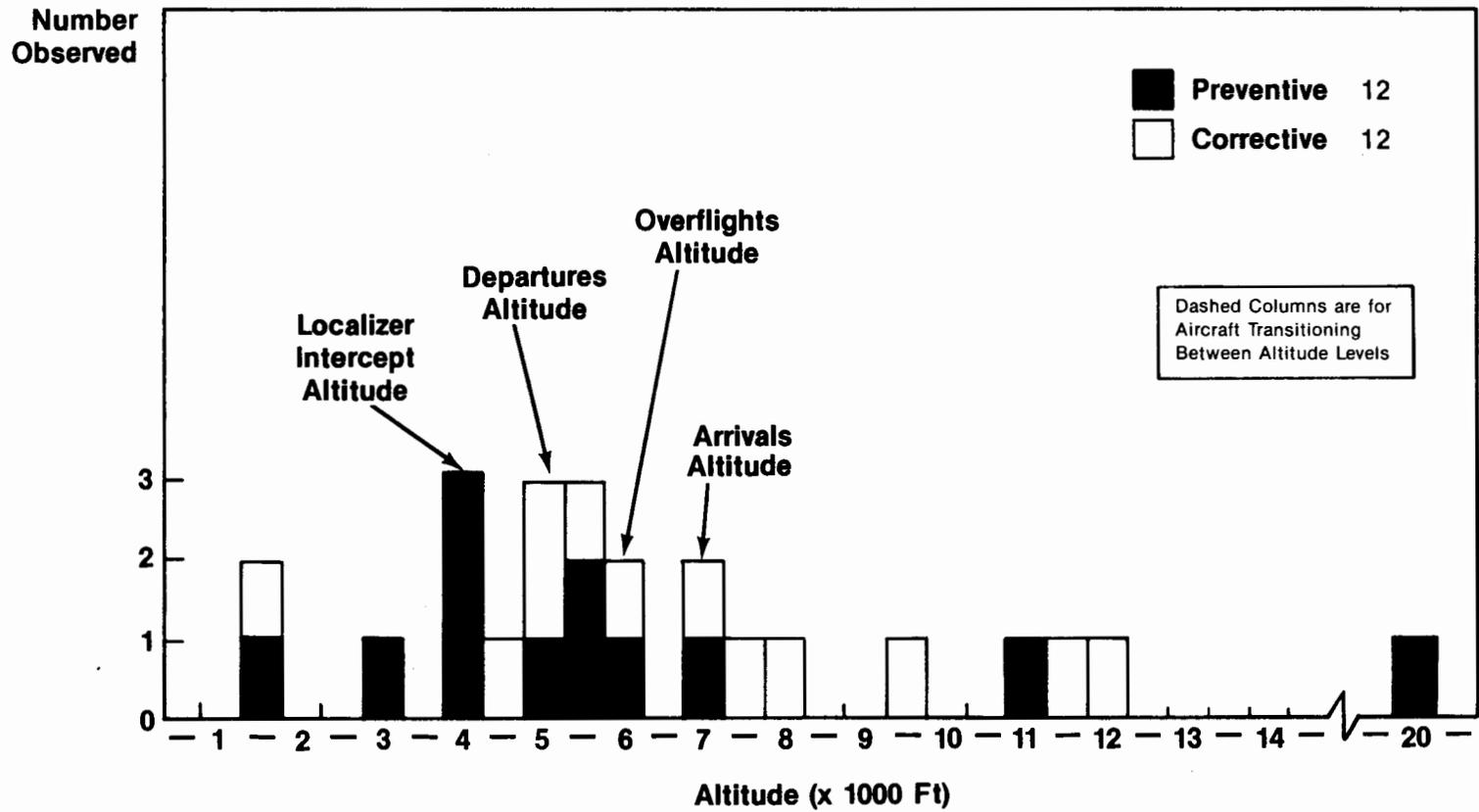


FIGURE 5-18
DISTRIBUTION OF ALTITUDES OF AIRCRAFT
RECEIVING RESOLUTION ADVISORIES

encounters on parallel approaches. However, there is no heavy concentration of advisories at any particular altitude. This is an encouraging result considering that there were an estimated 472 aircraft making parallel approaches in the Chicago data base, and that specific altitudes are used for arrival and departure traffic flows.

A detailed look at the locations of the RA encounters reveals much about the encounter geometries and the reasons for the advisories. Table 5-4 summarizes the encounters producing RAs in the Chicago data base. The three figures that follow show the locations of each of the encounters in the Chicago airspace. Additional details of each encounter, including individual vertical and plan-view plots, are found in Appendix E.

Figure 5-19 shows the traffic patterns used during the Wednesday morning 1.8 hr data collection period, together with the one RA encounter that would have occurred. Standard arrival routes are shown as dashed lines and departure routes are shown as dotted lines. The aircraft tracks are indicated with hash marks during the time of the advisory. If equipped with TCAS, these aircraft would have received RAs while making their turns onto parallel approach. Each aircraft is under the control of separate arrival controllers. One aircraft is at 4400 ft and descending while the other is at 5000 ft and level. The RA is generated because vertical separation is less than 750 ft while they are projected to be sufficiently closing in range. This particular encounter is described in further detail in the parallel approach discussion in Section 5.3.2.3.

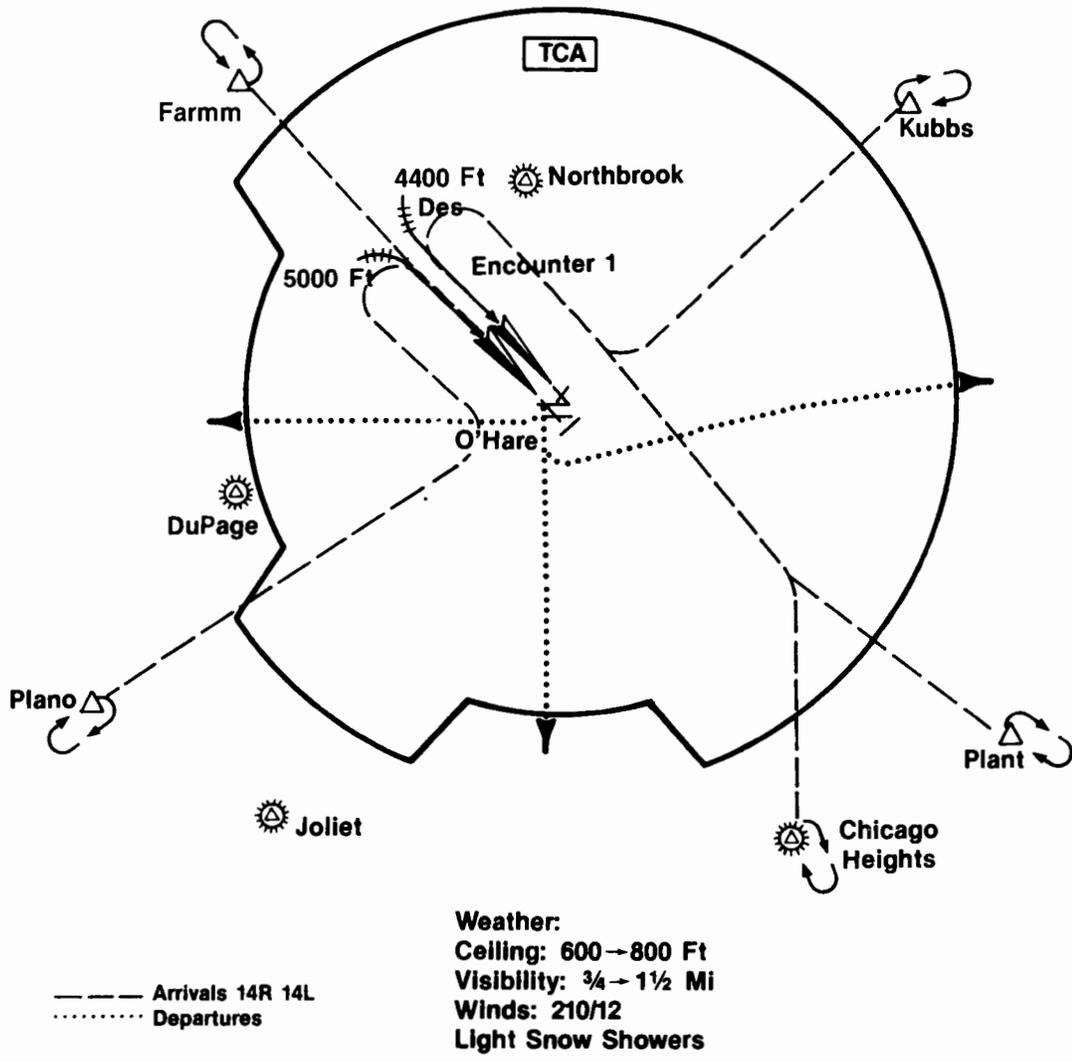
The Wednesday afternoon time period (Figure 5-20) shows five RA encounters that would have occurred over 3.46 hours. Encounter 2 involves aircraft arriving at Midway airport. Most of these aircraft would have received preventive advisories, requiring no vertical displacement.

The Friday afternoon time period (Figure 5-21) shows an additional eight RA encounters that would have occurred over 6 hours. Encounters 7 and 14 occur while turning onto parallel approaches, and Encounter 13 is the holding pattern example described in Section 5.3.2.1. Therefore, with the exception of the three parallel approach encounters, no concentration of RAs were found for any particular location in this airspace.

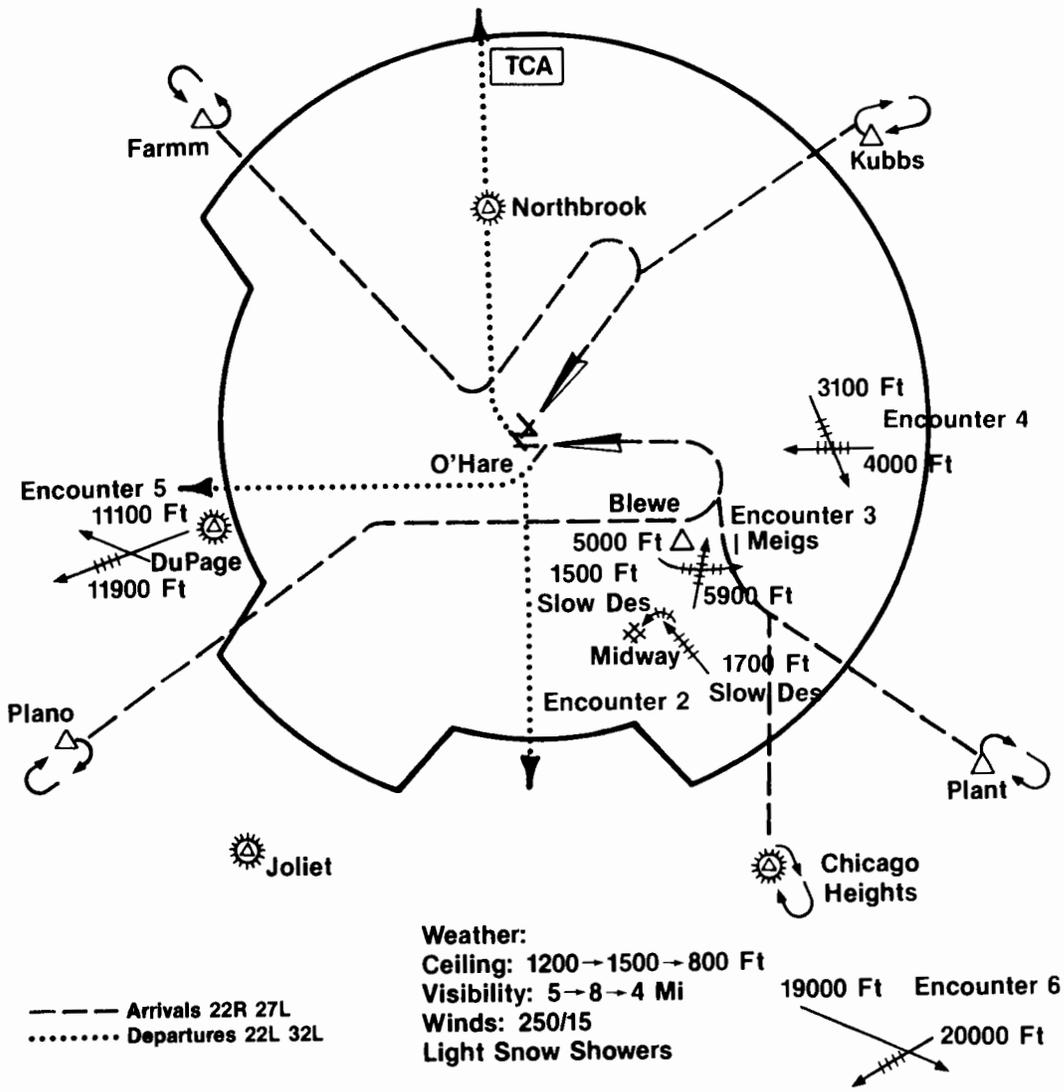
TABLE 5-4
SUMMARY OF ENCOUNTERS PRODUCING RESOLUTION ADVISORIES IN THE CHICAGO AREA

FIGURE	OBSERVATION PERIOD	ENCOUNTER NUMBER	ENCOUNTER SITUATION	AIRCRAFT ALTITUDES (100s of Ft)		RESOLUTION ADVISORY PRODUCED		
				Aircraft 1	Aircraft 2			
5-19	Wednesday 9:19 am - 11:00 am 1.8 hours (600-800' ceiling, 3/4 - 1 1/2 mi. visibility, light snow showers at ORD)	1 PA*	a/c 1: turning final, 14R a/c 2: turning final, 14L	50	44↓40	Don't Descend Descend		
		2	a/c 1: turning final to MDW a/c 2: descending to land MDW	15↓slow	17↓slow	Don't Climb Don't Descend		
5-20	Wednesday 12:10 pm - 4:54 pm 3.5 hours. Data not recorded during entire collection period (1200-1500-800' ceiling, 5-8-4 mi. visibility, light snow showers at ORD)	3	a/c 1: eastbound SW of Meigs a/c 2: northbound	50	59	Don't Climb Descend		
		4	a/c 1: westbound NE of Meigs a/c 2: southeast bound	40	31	Limit Descend 500 fpm Don't Climb		
		5	a/c 1: southwest bound W of DPA a/c 2: northwest bound	111	119	Don't Climb None		
		6	a/c 1: southwest bound S of CGT a/c 2: southeast bound	200	190	Don't Descend None		
5-21	Friday 2:01 pm - 8:05 pm 6 hours (500-700' ceiling, 2 1/2 - 3 mi. visibility, light rains at ORD)	7 PA*	a/c 1: turning final, 9R a/c 2: turning final, 9L	50	41	Climb Descend		
		8	a/c 1: both maneuvering a/c 2: to join downwind, 9L	80↓	70	Limit Descend 500 fpm Descend		
		9	a/c 1: northbound E of Meigs a/c 2: southeast bound	40	34↓slow	Don't Descend None		
		10	a/c 1: southeast bound NE of DPA a/c 2: southwest bound	68	62	Don't Descend Don't Climb		
		11	a/c 1: turning final, 9L a/c 2: southwest bound (?)	56↓slow	65↓	Descend Limit Descend 500 fpm		
		12	a/c 1: northbound near CGT a/c 2: southeast bound	120	115↑	Climb Descend		
		13 HP**	a/c 1: holding at PLANO a/c 2: holding at PLANO	100↓fast	80	Limit Descend 2000 fpm Descend		
		14 PA*	a/c 1: turning final, 14R a/c 2: turning final, 14L	50	42↓40	Limit Descend 500 fpm None		
		*PA = Parallel Approach **HP = Holding Pattern						

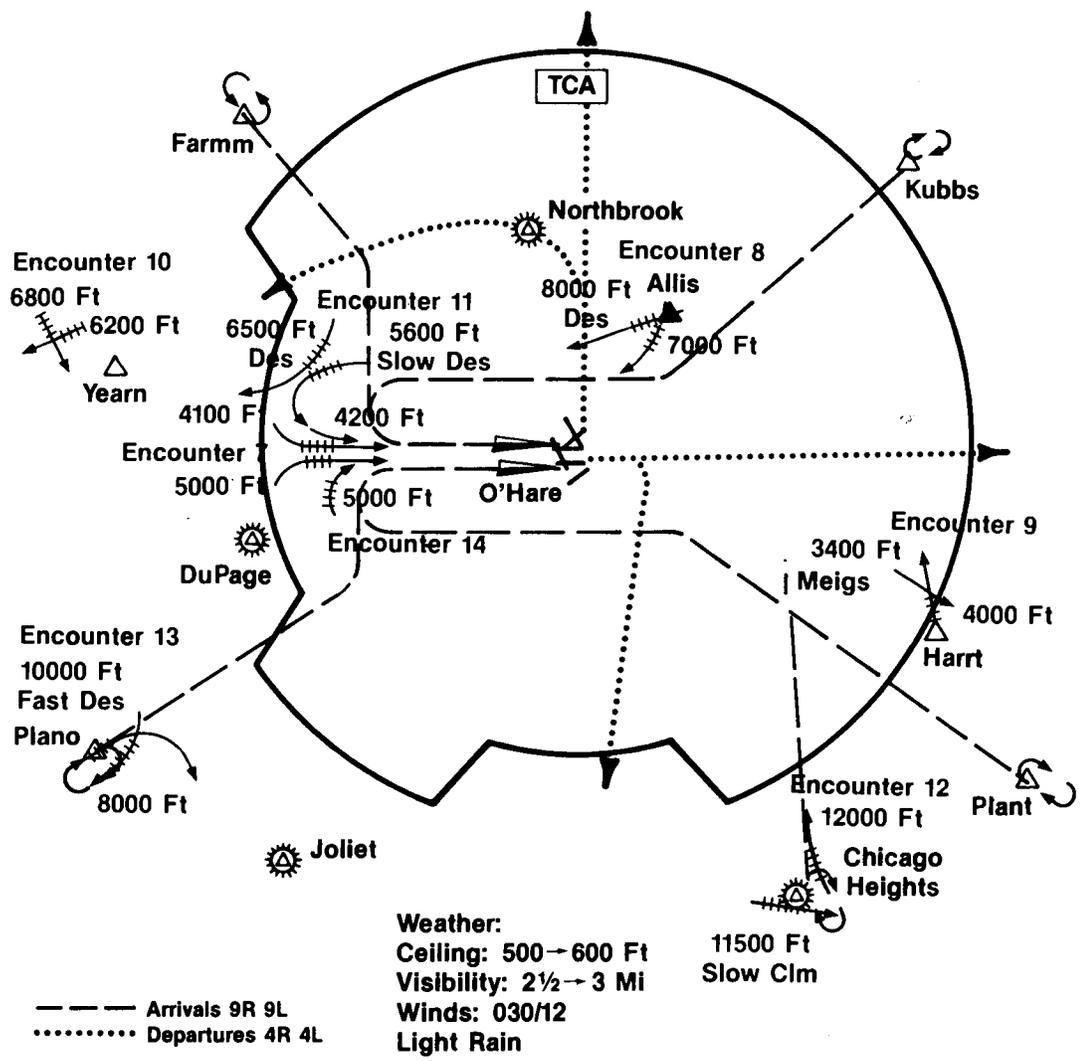
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**FIGURE 5-19
 LOCATION OF RESOLUTION ADVISORIES
 WEDNESDAY MORNING**



**FIGURE 5-20
 LOCATION OF RESOLUTION ADVISORIES
 WEDNESDAY AFTERNOON**



**FIGURE 5-21
 LOCATION OF RESOLUTION ADVISORIES
 FRIDAY AFTERNOON AND EVENING**

RA Rates In Terminal Area. Table 5-5 lists the number of RAs that would occur and their rates for each of the runway configurations in use at O'Hare assuming that all aircraft are TCAS-equipped. The first two columns list the arrival and departure runways in use; the next three columns list the time periods of the data collected. The next column lists the total number of RAs received and the corresponding rates at which they occur (number of RAs/number of hours) for the entire Chicago airspace. The last column lists the number of corrective RAs (those that require displacement) together with their corresponding rates. RAs occurred at an average rate of 1 every 28 minutes; corrective advisories occurred at a rate of one every 56 minutes. The peak period was Friday evening from 4 to 8 p.m., during which time advisories occurred at a rate of almost 4 per hour. However, the previous two hours were not as busy and no advisories were generated. All these rates are over the entire airspace; of interest is the rate at which an individual controller may observe Resolution Advisories.

RA Rates for Controllers. An upper bound on RA rates for controllers is computed by counting the number of RAs for aircraft in each sector. The sectorization is assumed as described in Section 5.3.1. Aircraft assumed to be under the control of the Chicago ARTCC or local towers were not included in the calculation of these rates. The number is an upper bound because all aircraft are assumed TCAS-equipped. Furthermore, a controller would only become aware of an advisory if an aircraft made a significant maneuver, if the pilot called him by radio telephone, or if Mode S equipment downlinked a Resolution Advisory report for display.

With these assumptions, the average rate at which an aircraft controlled by a Chicago Terminal controller would receive an RA is once every 2.96 hours. Corrective RAs would occur once every 6.24 hours. In discussions with FAA Air Traffic Service personnel, it was determined that only altitude deviations of 300 ft or more would be of concern to a controller. Deviations this large would only occur for a controller at an average rate of once every 18.72 hours.

The most aircraft observed to receive RAs in a single sector occurred during the Friday evening data collection period for arrivals to runway 9L. It involved the four aircraft in Encounters 8 and 11 (as shown in Figure 5-21) as well as one of the aircraft in Encounter 7. This corresponds to a rate of one RA every 47 minutes for that controller. Three of these five

TABLE 5-5
RESOLUTION ADVISORY RATES IN CHICAGO TERMINAL AREA IN IMC

RUNWAY ARR.	CONFIG. DEP.	DAY	TIME	HOURS	ALL RAS		CORRECTIVE RAS	
					No.	Rate (1/x min.)	No.	Rate (1/x min.)
14R,L	(unknown)	W	9:19- 11:00	1.82	2	55 min.	1	109 min.
22R,27L	22L,32L	W	12:10- 16:54	3.46	8	26 min.	3	70 min.
4R,9L	4L,9R	F	14:01- 16:05	2.06	0	N/A	0	N/A
9R,L	4R,L	F	16:05- 20:05	3.90	14	17 min.	8	29 min.

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aircraft receive corrective RAs (a rate of one per 1.3 hours) but they all require displacements of 200 ft or less. Therefore, although this controller may have the most aircraft receiving RAs, all of the aircraft would make small displacements which may not be of major concern to the controller. Furthermore, noting that the TCAS maneuvers generated by all the corrective RAs are generally compatible with the intended flight path, the displacements often support control procedures rather than disrupt them.

To summarize, the large separations and slow vertical rates observed in IMC reduce the RA rate to half that found in overall conditions. The RAs that do occur generally require little maneuvering; over 80 percent of the advisories require less than 300 ft of displacement. Unless otherwise notified of the advisories, a controller may observe an aircraft maneuvering 300 ft or more as a result of an RA approximately once every 19 hours. Furthermore, with the exception of three parallel approach encounters, no concentration of RAs were found in the Chicago airspace. The significance of these three parallel approach encounters, as well as the capacity impacts of advisories on parallel approaches, is addressed in the next section.

5.3.2.3 Capacity

In the analysis presented in the previous section, the locations of all the encounters producing RAs were plotted and the amounts of displacement noted. It was observed that RAs received for most encounters do not appear to create severe impacts on the ATC system. This is due to the infrequent occurrence of RAs, small displacements, and compatibility with observed maneuvers. In most cases, sequencing has not yet been established at the time of the RA and there is time available for recovery from any displacement from the flight path. In these cases, there is little potential for the RAs to affect capacity. Locations where RAs were observed to have potential to affect capacity are the parallel approaches.

Parallel approach operations represent a unique case for TCAS in three ways:

- It is a critical phase of flight; a pilot executing a parallel approach is occupied with procedures involved in approach and landing.

- Sequencing and spacing have already occurred; interruption of the process may cause a reduction in runway utilization.
- The geometries of parallel approaches involve the placing of aircraft in much closer proximity than is usual in IFR, without visual contact.

For these reasons, special attention is paid to parallel approaches.

Nature of Parallel Approach Advisories. Three parallel approach encounters were observed to generate RAs. Five of the six aircraft involved in these encounters received RAs; three of these were corrective. The reasons RAs were generated for only these three particular parallel approach encounters out of an estimated 472 in the data can best be explained with an example.

Figure 5-22(a) shows the plan view of one of the parallel approach encounters that generated RAs (Encounter 1). On a typical parallel approach into O'Hare the aircraft turn onto approach at 4000 and 5000 ft and fly parallel paths with horizontal separation of 1 mile. The vertical separation of 1000 ft is maintained until the aircraft are established on their respective localizers. During the turn, the aircraft are closing quickly in range, and the altitude separation is usually less than the TA threshold of 1200 ft. Therefore a TA should be anticipated on every parallel approach in which there is an aircraft on the other approach. However, a RA is generated only if the altitude separation is reduced to less than the RA threshold of 750 ft.

Figure 5-22(b) shows the vertical profile of this encounter. The altitude separation was only 600 ft when the aircraft began their turns. If the aircraft were TCAS-equipped, RAs would have been issued when they were projected to be within 25 seconds from closest approach. The lower aircraft should have been at 4000 ft before starting its turn. Instead it was at 4400 ft at the start of the turn and descended to 4000 ft near the end. The aircraft would receive a corrective "Descend" RA to cause it to descend a little sooner. Once a separation of 750 ft is achieved, the RA is removed, leaving the aircraft still above its intended altitude of 4000 ft. The top aircraft would receive a preventive "Don't Descend" RA at the same time to make sure it remains level at 5000 ft. The TAs would be maintained until the aircraft become parallel, at which point the aircraft are no longer closing in range.

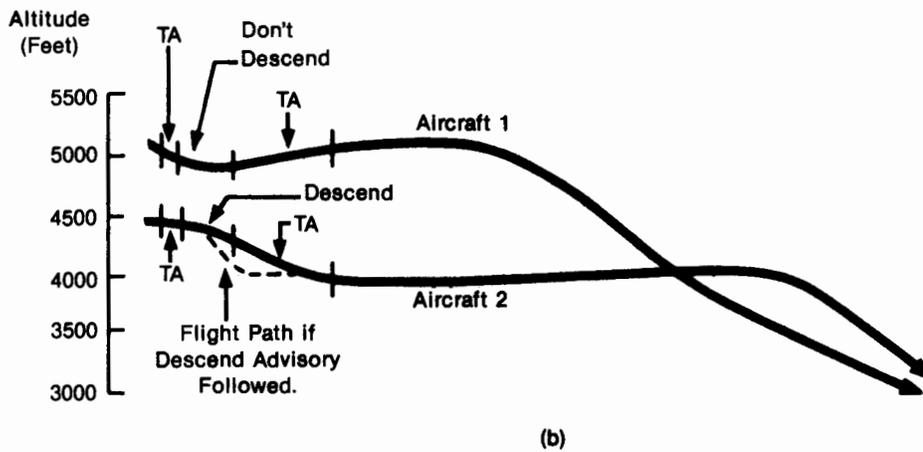
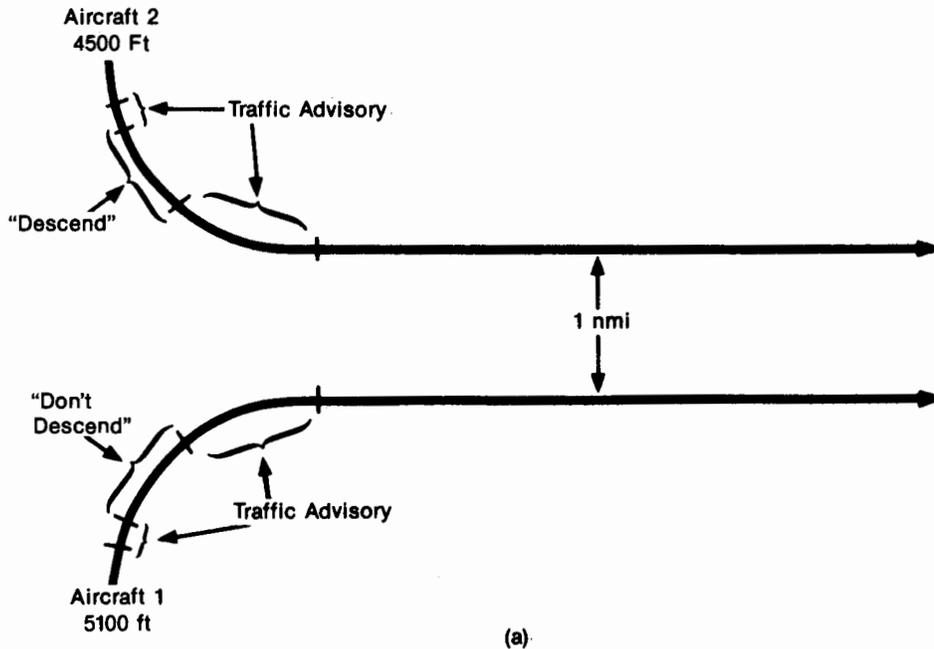


FIGURE 5-22
PLAN VIEW AND VERTICAL PROFILE OF PARALLEL APPROACH ADVISORY

The other two parallel approach encounters which generate RAs are similar to this one in that the RAs are caused by the pairs of aircraft having less than 750 ft vertical separation while the aircraft are closing in range. These RAs may not be disruptive since the displacements are small (all are 300 ft or less), the aircraft are not required to deviate from their clearances, and the RAs are removed well before the aircraft intercept the glideslope. Nevertheless, unnecessary RAs on parallel approaches may be distracting to the pilot during this critical phase of flight, especially since these aircraft are closely monitored and there is no threat of a near-midair collision. TAs, on the other hand, could become an aid to the pilot making a parallel approach in IMC, since they would regularly indicate the location and relative altitude of the aircraft on the other approach.

Rate of RAs on Parallel Approaches. During the 5.7 hours in which parallel approach operations were being conducted, there were an estimated 472 arrivals at O'Hare. Assuming all these aircraft were TCAS-equipped and made parallel approaches, this corresponds to a rate of one RA-producing encounter every 1.91 hours. One aircraft would receive a corrective RA for every 157 aircraft making parallel approaches. (It is assumed that all arrival aircraft at O'Hare make the parallel approaches, since the cloud ceilings reported during the data collection do not support the use of a third converging arrival runway.)

While the rate of advisories on parallel approaches is sufficiently low that it should not be disruptive, it is useful to see if there is a means to prevent unnecessary advisories. The parameters used in independent parallel approach operations (such as runway centerline separation, localizer intercept angle, and stagger between aircraft) were studied to find whether a simple means exists to control RAs on parallel approaches.

The nature of parallel approach operations is such that the range test will be satisfied on almost all parallel approaches unless there is a small intercept angle or the aircraft are staggered by at least 1 1/2 miles (not done in independent parallel approaches); however, the procedure of providing altitude separation of 1000 ft eliminates RAs on more than 99 percent of parallel approaches. Close monitoring of altitude separation appears to offer the best potential to prevent unneeded RAs on parallel approaches.

6. FINDINGS AND RECOMMENDATIONS

The principal findings address the two focal points of this study, System Safety and ATC Interactions. The System Safety results are derived from the analysis presented in Sections 3 and 4; the ATC Interactions results are derived from the analysis in Section 5. In both cases, real-world data is used to assess the effects that TCAS would have in an IMC environment.

6.1 System Safety

TCAS System Safety is assessed in the same fashion as in the previous Safety Study done for overall conditions. A Risk Ratio is defined as the risk of encountering a critical near-midair collision (critical NMAC) when equipped with TCAS, relative to the risk when not equipped. Risk is assessed on a per-flight hour basis for those aircraft expected to be equipped with Minimum TCAS II--air carriers (part 121 operators). This risk is assessed quantitatively and compared with the risk in overall conditions.

As was the case for the overall study, the philosophy is to make a conservative but realistic assessment of the impact of the change in environment in IMC. Visual acquisition is assumed to be ineffective and thus provides no benefit; at the same time, the benefits of the more structured IFR environment and the changed characteristics of aircraft in IMC are assessed.

6.1.1 Findings

The following findings are made with regard to TCAS System Safety in IMC:

1. While the original System Safety Study found that only 14 percent of critical NMAC incidents involving air carriers in today's system occur in IMC, given that an air carrier is in IMC the risk of a critical NMAC (measured on a per-flight hour basis) is approximately the same as in overall conditions. This is attributed to the fact that air carriers are more likely to experience IMC at low altitudes, where they will typically be in the terminal areas with the associated greater numbers of surrounding aircraft.
2. The characteristics of aircraft encountered have been observed to differ in IMC compared with overall

conditions in two key respects: the fraction that is Mode C equipped is higher by one-third, and the fraction that is air carrier (and carries high-quality altimetry) doubles. The higher Mode C equipage increases the proportion of critical NMAC encounters that TCAS will resolve; however, it will also increase exposure to those aircraft with altimetry errors and to those that may maneuver to defeat a TCAS Resolution Advisory. The larger number of air carriers reduces the effect of altimetry errors.

3. The characteristics of encounter geometries also change in IMC compared with overall conditions: the relative altitude of encounters in IMC are larger than in VMC due to the use of IFR separation standards, and the vertical rates observed in IMC are lower than those in overall conditions. These characteristics reduce the susceptibility of TCAS to the two predominant failure modes that can cause induced NMACs, altimetry errors and maneuvering intruders.
4. The quantitative assessment of the effects described in 2 and 3 shows that TCAS will have a greater effectiveness in resolving critical NMAC encounters in IMC than in overall conditions. The proportion of encounters it will resolve increases from 60 percent to 80 percent--a one-third improvement--due primarily to increased Mode C equipage. The proportion of encounters that will be unresolved due to altimetry errors increases by a small amount (less than 0.1 percent), but this effect is more than compensated for by the higher Mode C equipage.
5. A basic assumption in the original System Safety Study is that visual acquisition, aided by the display of a Traffic Advisory, enables the pilot to avoid an intruder even if an incorrect Resolution Advisory were issued due to altimetry error or other causes. The effect of this is that visual acquisition reduces the induced component of the Risk Ratio in overall conditions by more than 50 percent--a substantial benefit that is unavailable in IMC. In addition, the higher levels of Mode C equipage in IMC increases exposure to those failure modes which could cause an induced critical NMAC. However, the characteristics of encounter geometries in IMC (IFR separations and low vertical rates) compensates for these factors; thus, following Resolution Advisories in IMC is expected to be safer than following them in VMC after clearing the airspace.

6. Two factors which are favorable to the analysis were not quantitatively assessed, to be conservative. The first is TCAS-to-TCAS coordination. When both aircraft in an encounter are TCAS-equipped, maneuvers are coordinated; as long as each aircraft does not maneuver contrary to the displayed advisory, an induced NMAC will not occur. It has also been shown that the fraction of aircraft encountered in critical NMACs that are expected to be equipped with TCAS (the air carriers) has doubled.

The second factor is the biennial check of the altimetry of aircraft flying IFR, which is described in Appendix C. This is expected to reduce the likelihood of large altimetry errors which could cause an induced NMAC.

6.2 TCAS-ATC Interactions

The findings regarding the interactions of TCAS operations and the operation of the ATC system are based on an analysis of predicted TCAS operations in the Chicago terminal area on IMC days. Chicago was chosen as presenting the most severe environment for the analysis because of the following characteristics:

- The principal airport in the area, O'Hare, handles large volumes of aircraft in all weather conditions, frequently in parallel approach configurations.
- In addition to O'Hare, there are a number of high-volume reliever airports in the area.

A terminal area was chosen, because there is more maneuvering in terminal environments than en route, and because TCAS experience to date indicates advisory rates in terminal environments are higher.

More than 11 hours of high-activity data containing 641 aircraft flight hours was analyzed. The issues involving the use of TCAS in day-to-day operations that were assessed include: the potential for conflicts with aircraft other than the threat; the potential for increased controller workload; and the potential for a reduction in system capacity.

6.2.1 Findings

Principal findings regarding TCAS-ATC interactions are:

1. The possibility of a domino effect is extremely remote. The orderly nature of the IFR system ensures that aircraft are well-separated; the next-nearest aircraft to a TCAS-equipped aircraft (other than the threat) was seen to be as follows:
 - separated by 3 miles or more in range, and 1000-2000 ft in altitude
 - for 80 percent of Resolution Advisories, not closing on the TCAS aircraft. (Frequently, they were diverging.)

A displacement resulting from a TCAS Resolution Advisory cannot result in a Resolution Advisory against the next nearest aircraft under these conditions.

Examination of locations in which aircraft are placed in close proximity also demonstrates reasons why domino effects are not expected to occur. In a holding pattern, no set of conditions has been uncovered that would cause more than two aircraft in the pattern to displace from its altitude. The more usual occurrence in those cases where a TCAS-equipped aircraft is required to maneuver in a holding pattern is a 300 foot deviation, followed by recognition of the next aircraft in the pattern. This leads to a preventive sequence of Resolution Advisories, which stops maneuvers rather than propagates them. Thus, domino effects are not normally expected to occur.

2. It is unlikely that TCAS will be considered disruptive to ATC. In IMC, the rate at which Resolution Advisories occur is low. On a per-aircraft flight hour basis, the rate is half that in overall conditions; the average rate per sector in the Chicago environment is 1 per hour. While some advisories do occur which can be classified as nuisance alerts because of large horizontal miss distances (1 mile or more), all aircraft pairs receiving advisories were observed to pass within 3 miles and 1000 ft (IFR separation standards).

3. Resolution Advisories, when they occur, are compatible with ATC intent; no recovery action is seen to be needed. Altitude displacements are small; 80 percent were observed to be less than 300 ft. When aircraft that would receive RAs were observed to maneuver, all but one maneuvered in the same direction as that called for by TCAS.
4. No major increase in pilot-controller communications workload is likely because of the low rates of advisories, the small displacements, and the compatibility of TCAS advisories with ATC intent.
5. No severe capacity impacts are foreseen. The only place where advisories occur after aircraft have been sequenced for approach is on parallel approaches; TCAS would impact less than 1 percent of them. This is because TCAS alarm thresholds are highly compatible with ATC procedures, which call for providing 1000 ft of vertical separation when establishing aircraft on final approach; Resolution Advisories were only seen when 750 ft or less vertical separation was provided. Traffic Advisories, however, will be provided on most parallel approaches; the effect of this additional traffic information is expected to be beneficial.

6.3 Recommendations

1. No changes in the TCAS logic or parameters were found to be necessary to introduce Minimum TCAS II to the IMC environment for the following reasons:
 - TCAS shows a greater effectiveness in resolving critical NMACs in IMC than in overall conditions, with a decrease in the risk of an induced NMAC.
 - TCAS alert rates are low and resulting displacements small; no lowering of sensitivity is warranted.
 - Special situations, such as holding patterns and parallel approaches, were analyzed. It was found that it would not be useful to invoke a special logic (by means of a pilot switch, for example) in any of these situations.

2. Several factors which should be addressed in a pilot training program were discussed in the System Safety Study for overall conditions. Based on the analysis of the IMC environment, two of these require re-emphasis:
 - Traffic Advisories are intended to aid visual acquisition (in VMC) and to prepare the pilot to act should a Resolution Advisory follow. Premature maneuvering based on the Traffic Advisory alone could be self-defeating. There is a greater susceptibility to this in IMC, since visual acquisition is not likely to occur.
 - The overall System Safety Study showed that the pilot is better off trusting the displayed advisory than ignoring it, with a ratio of resolved NMACs to induced NMACs of 23:1 (58:1 if visual acquisition aided by the TA is taken into account). In IMC, this is even more the case; the ratio of resolved to induced NMACs is 115:1.
3. Critical avionics failures, namely those which could cause a critical NMAC and for which the performance monitor does not shut off the system, must occur at the rate of 10^{-4} or less per critical NMAC to be negligible relative to other factors that could induce a critical NMAC. This is the same level as for overall conditions.

APPENDIX A

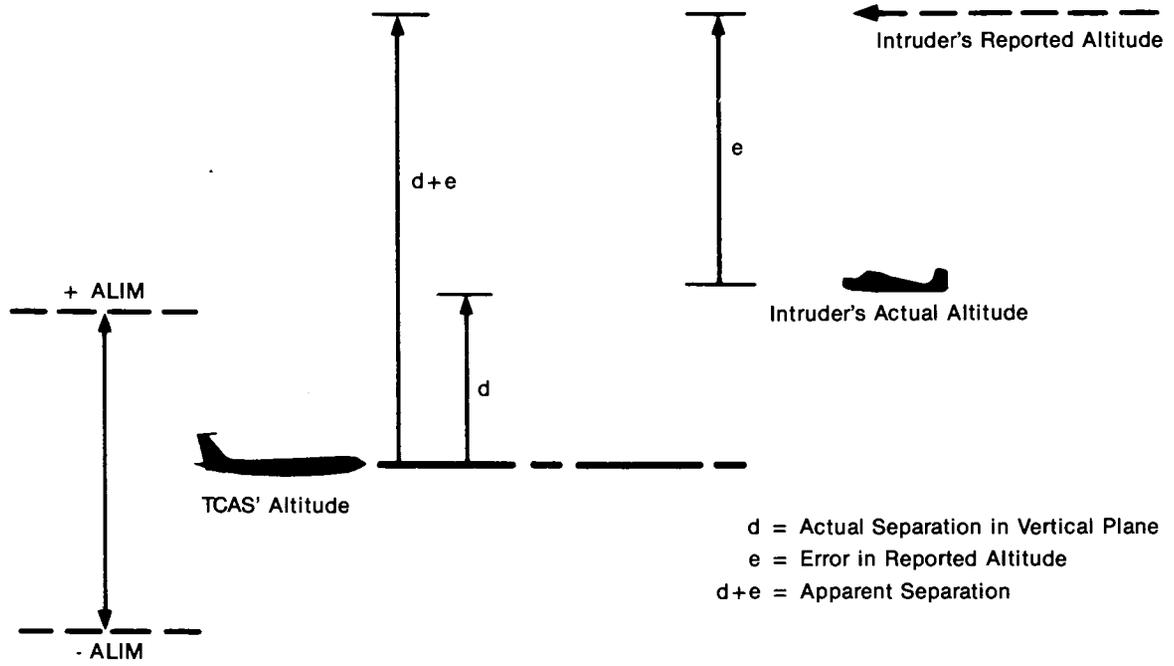
ALTIMETRY ERROR COMPUTATION

The Risk Ratios for unresolved and induced NMACs in IMC are computed in the same manner as the overall Safety Study. This Appendix reviews that methodology and describes the computation leading to the result for IMC.

Methodology. In the overall Safety Study, two variables were defined: d , the actual vertical separation between a TCAS aircraft and an intruder; and e , the error in the intruder's altitude report. These variables are illustrated in Figure A-1, which shows an intruder about to pass a TCAS aircraft with separation d (above the TCAS aircraft). The intruder is reporting altitude with error e (reporting higher than actual). The separation TCAS sees is thus $d + e$. If d is less than ALIM, a positive maneuver ("Descend") is called for to increase separation to $\text{ALIM} + 75$ ft, since advisories are maintained until separation of ALIM plus a small margin is achieved; however, in the presence of an error e which makes $d + e$ larger than ALIM, a positive RA would not be issued, since TCAS perceives that ALIM separation exists.

The areas of critical interest in the evaluation of the safety of TCAS are those combinations of actual separation and altimetry error which either cause TCAS not to give a corrective RA when separation is less than 100 ft, or cause TCAS to give an incorrect RA which moves the TCAS aircraft to within 100 ft of the intruder. These combinations are illustrated in Figure A-2, which shows the regions of susceptibility in the d - e plane. The diagonal lines define the regions where the intruder is perceived to be within ALIM of the TCAS aircraft ($-\text{ALIM} \leq d + e \leq \text{ALIM}$); TCAS will issue a positive RA ("Climb" or "Descend") until separation appears to be $\text{ALIM} + \text{DELTA}$. The regions for an unresolved NMAC are those in which d is between -100 and +100 but either no RA is given or the RA is inadequate (the lightly shaded areas). The regions for an induced NMAC are the dark, cross-hatched areas inside the positive RA region; the intruder aircraft will be perceived to be below when it is above (or vice-versa) and an RA will be generated which moves the TCAS aircraft toward the intruder's altitude, and is removed so as to leave it within 100 ft.

The probability of occurrence of these regions relative to the current probability of a critical NMAC is obtained by integrating the distributions of altimetry error and vertical separation over the regions which cause an unresolved or an induced NMAC. This is



NOTE: Level encounters are used as examples, encounters with vertical rates also apply with d being referred to predicted closest point of approach.

**FIGURE A-1
ENCOUNTER GEOMETRY**

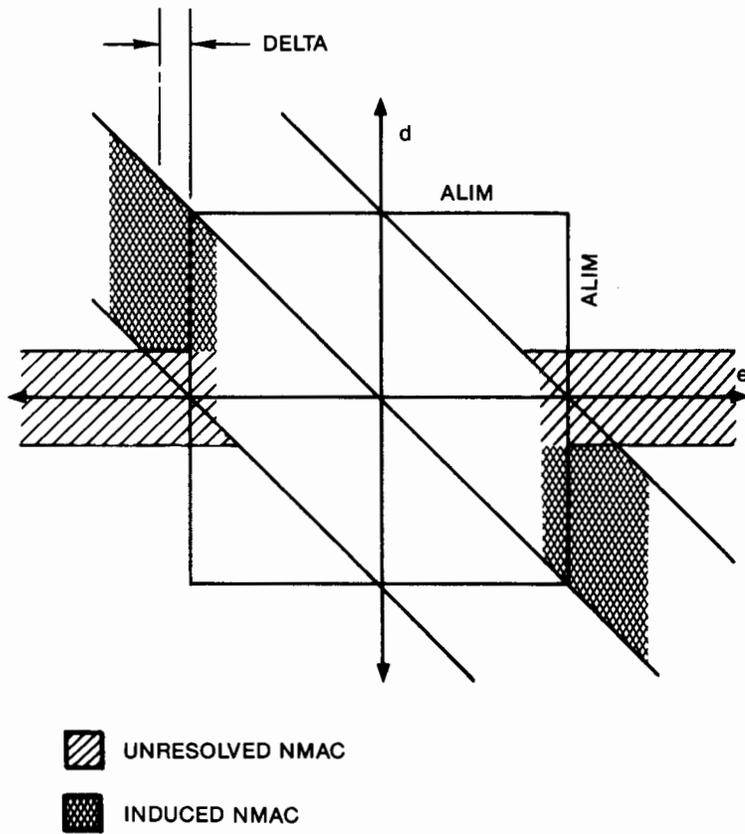


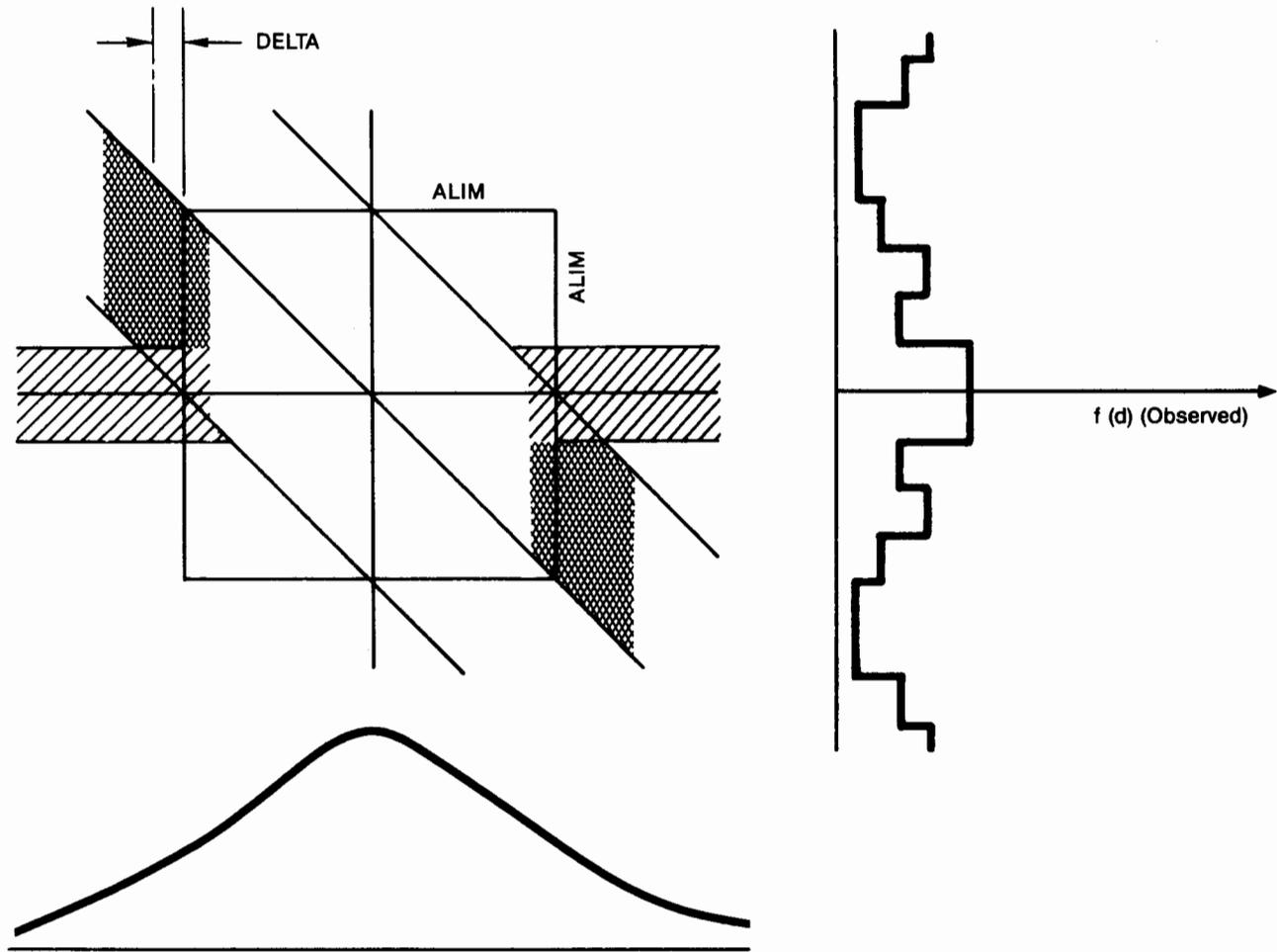
FIGURE A-2
REGIONS OF SUSCEPTIBILITY TO UNRESOLVED AND INDUCED NMAC

done by taking small intervals of d and integrating e over the regions shaded in the diagram. The standard deviation (s.d.) used in the error distribution is that for air carrier and GA altimetry combined in RSS fashion. Each integration result is multiplied by the probability of the d interval, which is taken from the vertical separation distribution. To convert this probability to a Risk Ratio, it is divided by the probability of an encounter with vertical separation of 100 ft or less.

As ALIM and the magnitude of the distribution of altimetry error both vary with altitude, the total Risk Ratio caused by altimetry error will be a numerical average over all altitudes at which air carrier NMACs occur. To obtain this average, the altitude range is divided into 5000 foot intervals, and the above calculation is performed using the ALIM and s.d. of altimetry for each altitude interval. The results are then averaged, with each result being weighed by the proportion of NMACs occurring in that altitude interval. Finally, the result is multiplied by the probability that the intruder encountered is a GA aircraft, that it is Mode C equipped, and that surveillance acquires the track.

Computation for the IMC Case. Two principal inputs to the altimetry error analysis have been observed to change in IMC. They are the distribution of vertical separation and the fraction of aircraft that are GA. No new information is available regarding the quality of GA altimetry in IMC, so the same error distribution will be used as in the overall case. It is expected that altimetry error is lower in IMC than in VMC due to the biennial checks required for IFR flight (a detailed description of these checks can be found in Appendix C); however, no data is available to estimate the magnitude of this difference, so it is not accounted for in the calculations.

Figure A-3 illustrates the distributions that apply to the d - e plane in IMC. The distribution of d is that taken from the Chicago ARTS data (Figure 3-2). The distribution of e is Gaussian with the same error s.d.'s used previously. As before, e is integrated over the regions of susceptibility for small intervals of d and factored by the probability of that interval. As shown in Table A-1, this calculation is performed for altimetry error s.d.'s and ALIMs at 5000 foot altitude intervals. Each Risk Ratio is the integration of d and e over the regions of susceptibility for the values of ALIM and altimetry errors given in columns 2 and 3. It is multiplied by the fraction of critical NMACs at that altitude to get a weighted Risk Ratio; note that for IMC, no NMACs occur in the higher altitude bands. The total Risk Ratio for IMC is .0239; 2/3 of this is unresolved NMACs, while only 1/3 is induced. This result differs significantly from that for overall conditions, which is also



$$f(e) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{e^2}{\sigma^2}\right)$$

FIGURE A-3
ALTIMETRY ERROR AND VERTICAL SEPARATION DISTRIBUTIONS
APPLIED TO THE D-E PLANE

TABLE A-1
CALCULATION OF RISK RATIO FOR ALTIMETRY ERROR FOR THE IMC CASE

ALT.	ALIM	RSS ERROR (SIGMA)	OVERALL CONDITIONS			I M C		
			FRACTION OF NMAC IN ALTITUDE BAND	RISK RATIO	WEIGHTED RISK RATIO	FRACTION OF NMAC IN ALTITUDE BAND	RISK RATIO	WEIGHTED RISK RATIO
5 Kft	400 ft	143 ft	.44	.0256	.0118	.43	.0195	.0084
10	400	156	.31	.0485	.0150	.36	.0436	.0125
15	500	175	.17	.0231	.0039	.21	.0147	.0031
20	640	190	.03	.0051	.0002	0.0	N/A	.0000
25	640	206	.01	.0117	.0001	0.0	N/A	.0000
30	640	220	.03	.0210	.0006	0.0	N/A	.0000
35	740	239	.01	.0125	.0001	0.0	N/A	.0000
			Total = .0317			Total = .0239		
			Unresolved = .0143			Unresolved = .0154		
			Induced = .0174			Induced = .0085		

9-A

provided in Table A-1 for comparison; in overall conditions unresolved and induced NMAC risk are about equal.

The final step in the process is to multiply this Risk Ratio, which is for an encounter with a Mode-C equipped GA aircraft, by the probability that an intruder is GA, that it is Mode C-equipped, and that surveillance acquires the intruder's track. From Table 3-3, GA and "other" aircraft constitute 64 percent of aircraft encountered in IMC NMACs; from Table 3-6, 84 percent of aircraft will be Mode C equipped; and from Section 3.4, 97 percent of intruders will be in track at the time of the RA. Multiplying the results of Table A-1 yields a Risk Ratio for an unresolved NMAC of .010, and a Risk Ratio for an induced NMAC of .0044.

APPENDIX B

MANEUVERING INTRUDER COMPUTATION

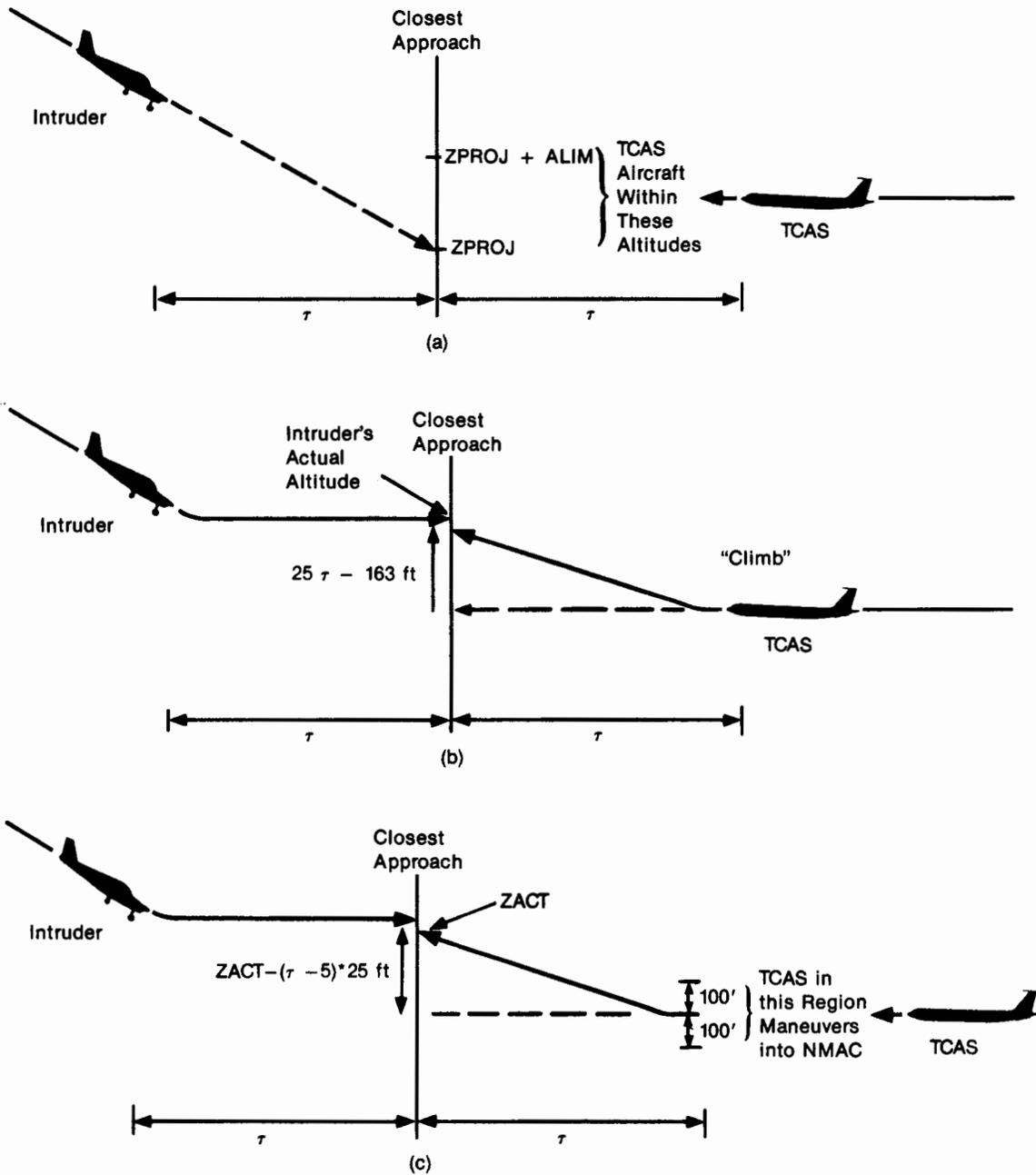
The probability that an intruder maneuver will lead to a critical NMAC is estimated by examining all TA- and RA-producing tracks in the Chicago ARTS data base. This Appendix describes the processing done to obtain this estimate. The calculation process involves two basic steps: 1) identification of relative altitudes and vertical rates for encountering track segments such that, if a TCAS aircraft encounters the track segment with these relative altitudes and vertical rates, it would maneuver into a critical NMAC with the aircraft; and 2) computation of the probability that a TCAS-equipped aircraft will encounter the track at the required relative altitude and vertical rate. Calculations are done separately for those cases in which TCAS is level and those in which TCAS has a vertical rate.

B.1 Identification of Track Segments Which Have Potential to Cause Critical NMAC

Identification of track segments with potential to cause a critical NMAC involves sampling from an aircraft track at regular intervals. Two variables are examined: intruder's altitude (ZINT) and intruder's altitude rate (ZDINT). ZINT and ZDINT are used to project an altitude (ZPROJ) for the track τ seconds later, where τ is the time before closest approach that TCAS issues Resolution Advisories. The correct τ value is selected using ZINT to determine the sensitivity level. The track is then examined τ seconds later for the actual altitude of the track (ZACT). The values of ZPROJ and ZACT provide the basis for determining whether the track contains a maneuver with the potential to cause a critical NMAC for two cases: 1) when TCAS is level, and 2) when TCAS has a vertical rate.

Case 1: Level TCAS

Figure B-1 illustrates the procedure used for the case where TCAS is level. It shows the case of an intruder descending toward TCAS; however, the conditions being described apply to the case of an intruder climbing toward TCAS as well. Since TCAS is assumed to be level, only the bounds on relative altitude need to be found.



**FIGURE B-1
IDENTIFICATION OF AIRCRAFT TRACKS WHICH CAN
INDUCE A CRITICAL NMAC WITH A LEVEL TCAS**

The relative altitudes required are bounded by these conditions:

1. The intruder must have a vertical rate. If not (ZDINT less than 480 fpm), then TCAS will track it as level. TCAS will not choose altitude crossing, so the critical NMAC cannot occur.
2. If the intruder has a vertical rate, then the intruder must be projected to cross own altitude, passing within ALIM ft so as to generate a positive RA. The TCAS-equipped aircraft must be at an altitude within ALIM of ZPROJ (Figure B-1(a)), where ALIM is a TCAS parameter that defines the altitude separation TCAS attempts to achieve or maintain.
3. A level off at or near TCAS' own altitude would not result in a critical NMAC since TCAS would continue the RA in order to achieve ALIM separation and would cross through the intruder's altitude, leading to separation greater than 100 ft. Thus, the relative altitude defined in (2) is further limited in that the TCAS altitude must be at least 500 ft away from the intruder's altitude (ZINT) at the time of issuance of the RA.
4. An intruder maneuver must occur such that the TCAS-equipped aircraft, in response to an RA, ends up within 100 ft of the intruder's altitude τ seconds later (Figure B-1 (b)). The TCAS aircraft can displace $25\tau - 163$ ft (163 ft of displacement will be lost in the 5 second delay and 1/4 g acceleration) as shown in Figure B-1 (c); thus, to end up within 100 ft of the intruder the TCAS aircraft must start its maneuver within 100 ft of an altitude this distance away from ZACT.

These conditions define a region of relative altitude in which a level TCAS-equipped aircraft is susceptible to a critical NMAC caused by an intruder's maneuver.

Case 2: Non-level TCAS

Figure B-2 illustrates the procedure used for the case where TCAS is not level. Again, the example illustrated shows the case of an intruder descending toward TCAS; however, the procedure applies equally to those cases in which the intruder is climbing or is level and changes rate (since a level intruder could initiate a maneuver which causes a critical

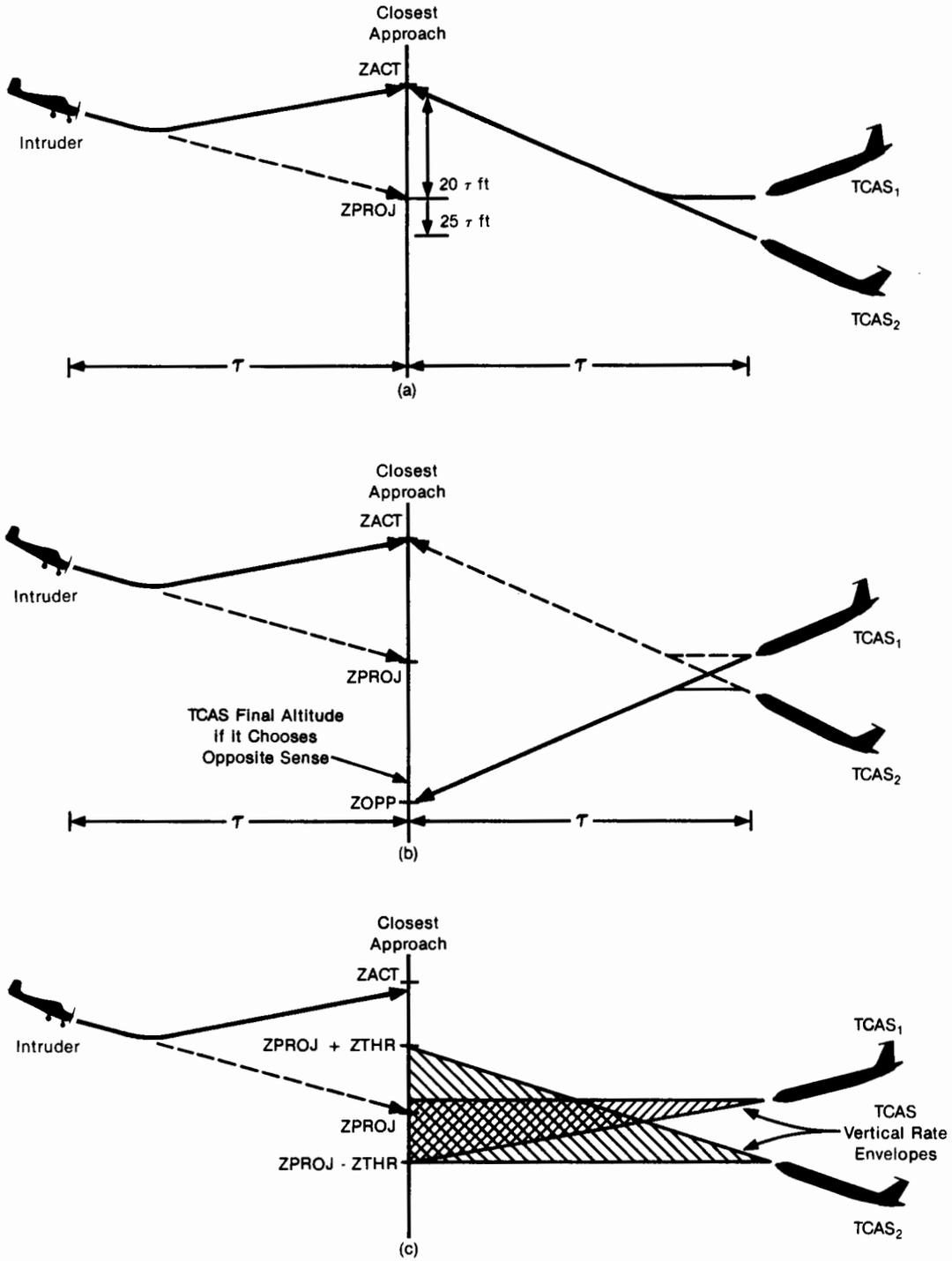


FIGURE B-2
IDENTIFICATION OF AIRCRAFT TRACKS WHICH CAN
INDUCE A CRITICAL NMAC WITH A NON-LEVEL TCAS

NMAC). Since TCAS is not level, bounds are needed on both relative altitude and vertical rate.

The relative altitudes and vertical rates required are bounded by these conditions:

1. An intruder maneuver must occur such that the TCAS equipped aircraft, in response to an RA, ends up within 100 ft of the intruder's altitude τ seconds later (ZACT), as shown in Figure B-2 (a). TCAS is assumed to displace 25τ ft (25 fps over τ seconds) if it is continuing its climb (or descent); 20τ ft if it will be changing from descend to climb, or vice-versa (25 fps over $\tau-5$ seconds, allowing delay to switch direction). This defines two altitudes such that if TCAS were at these altitudes and chose the sense leading to the intruder's actual altitude (ZACT), a critical NMAC would result.
2. If it is found that, for TCAS at an altitude defined in (1.), choosing the opposite sense results in greater separation from the intruder's projected altitude (Figure B-2 (b)), then TCAS would not choose the sense indicated in (1.). This reduces (or eliminates) those altitudes found in (1.) that would result in a critical NMAC.
3. The allowable vertical rates for TCAS that will cause it to issue an RA must be found for those altitudes remaining after step (2.). The shaded areas in Figure B-2 (c.) illustrate the vertical rate envelopes for both a descending and climbing TCAS. The rates must project the TCAS aircraft within ZTHR ft of the intruder's projected altitude (ZPROJ), where ZTHR is the TCAS parameter which defines the relative altitude for which TCAS will provide an RA. For a descending TCAS, allowable rates are from 0 to the lowest that will put TCAS within ZTHR below ZPROJ; for a climbing TCAS, it will be from 0 to the highest rate that will put TCAS within ZTHR above ZPROJ.

These conditions define regions of relative altitude and vertical rates in which a non-level TCAS-equipped aircraft is susceptible to a critical NMAC caused by an intruder's maneuver.

B.2 Probability Computation

The probability of an intruder maneuver that leads to a critical NMAC is computed by performing the process described in B.1 over many track segments from the Chicago ARTS data base, determining the relative altitudes and vertical rates (if any) for TCAS that would result in a critical NMAC, and evaluating the probability that TCAS would encounter each track at those altitudes and rates. The exact computation process is as follows:

A 25 second track segment is examined, using the identification process in B.1, to determine bounds on relative altitudes and, for the case in which TCAS is non-level, to determine vertical rates for a TCAS-equipped aircraft such that it would maneuver into a critical NMAC if it were at those altitudes with those rates. If there are no altitudes or vertical rates for the TCAS-equipped aircraft such that a critical NMAC could result (which is usually the case because the actual altitude for an intruder is usually close to that projected 25 seconds earlier), the hazard probability for that track is 0.0; if there are altitudes that meet the requirements of B.1, then there is a nonzero probability for that track. This nonzero probability is evaluated from the distribution of relative altitude at closest approach (Figure 3-2) and from the distribution of vertical rates for TCAS (Figure 5-16).

This process is repeated over all track segments that produced RAs or TAs from the Chicago ARTS data base. Tracks were sampled at 5-second intervals for the level TCAS case and 10-second intervals for the non-level TCAS case; thus segments overlap. The probability of a critical NMAC is the average of the computed probabilities (including those that are 0.0) for each track segment.

B.3 Results

This computation process yields a Risk Ratio for level TCAS of .0024, and for non-level TCAS, .00029--an order of magnitude below the level case. Table B-1 indicates the components of these Risk Ratios. Note that while there are three times as many tracks that could potentially induce a critical NMAC when TCAS is non-level, the restrictions on relative altitude of TCAS are such that the non-level Risk Ratio is an order of magnitude lower. This is due to the fact that under most circumstances, the sense opposite to the one that could induce a critical NMAC will be the sense that is chosen. The final Risk Ratio for maneuvering intruder is .0016, almost an order of magnitude lower than in overall conditions.

TABLE B-1
 COMPARISON OF COMPONENTS OF RISK RATIO DUE TO MANEUVERING
 INTRUDERS FOR LEVEL AND NON LEVEL TCAS IN IMC

CONDITION	PROBABILITY		TOTAL
	LEVEL TCAS	NON-LEVEL TCAS	
Track that could induce NMAC	2.11×10^{-2} X	6.05×10^{-2} X	
TCAS at required relative altitude	1.14×10^{-1}	1.24×10^{-2}	
TCAS with required vertical rate (given that it is non-level)	N/A	3.85×10^{-1}	
	2.41×10^{-3} X	2.89×10^{-4} X	
TCAS Level	.8		
TCAS with vertical rate		.2	
	1.92×10^{-3}	5.78×10^{-5}	$= 1.98 \times 10^{-3}$
Intruder Mode C Equipped			X .84
Surveillance Acquires Intruder			X .97
Probability that an Intruder Maneuver causes a Critical NMAC =			1.6×10^{-3}

APPENDIX C

ALTIMETRY BIENNIAL CHECK REQUIREMENTS

This appendix summarizes the sections of the Federal Aviation Regulations (FARs) which describe the requirements for tests and inspections of altimetry systems, including transponders. The sections of the FARs that apply are 91.171 and 91.172, which describe the requirements for tests of altimetry and transponders for all aircraft flying IFR. The nature of the tests is prescribed in Part 43, Appendices E and F (altimetry and transponders, respectively), with the exception of the static port leakage test, which is covered in Sections 23.1325 and 25.1325. Reference is made to other sections which are not discussed here; these sections either reference TSOs (Technical Standard Orders) under which equipment may be installed, or documentation that demonstrates that the tests have been performed.

Altimeter System Tests. Section 91.171 of the FARs prohibits IFR operation of an aircraft unless within the past two years the components of the altimeter system have been inspected and tested and found to comply with Part 43, Appendices E and F, of the FARs. These sections specify the following tests:

1. Static Pressure System. There are four tests:
 - The system must be free of entrapped moisture and restrictions.
 - Leakage must be within tolerances listed in Sections 23.1325 and 25.1325, which specify static system tests for pressurized and unpressurized aircraft. These tests call for evacuation of the static system to a certain pressure differential followed by a check to insure that losses are within tolerances of 100 ft of altitude difference at an equivalent altitude of 1000 ft for unpressurized aircraft, or 2 percent of the equivalent altitude at the maximum cabin pressure differential for pressurized aircraft.
 - The static port heater, if there is one, must work.
 - Airframe modifications and/or deformations must not affect the static port.

2. Altimeter. There are six tests:
 - Scale errors: Must be within tolerances specified in a table provided in Appendix E of the FARs. Typical tolerances are 20 ft at altitudes below 10,000 ft; 100 ft at 14,000; 205 ft at 35,000; 280 ft at 50,000.
 - Hysteresis: Simulate a descent of 3000 fpm approaching two test altitudes; hold the pressure at each test altitude for at least 1 minute; at the end of that time, the altimeter should read within 75 ft of the correct altitude.
 - After-Effect: After completing the hysteresis test, the system is returned to atmospheric pressure; the altimeter should read within 30 ft of the original altitude.
 - Friction: Simulate a descent of 750 fpm; take altitude readings at twelve altitudes specified in a table in Appendix E of the FARs, which also specifies the accuracy required. Required accuracies range from 70 ft at an altitude of 10,000 ft to 250 ft at 50,000 ft.
 - Case Leak: Generate pressure within the altimeter equivalent to an altitude of 18,000 ft; after 1 minute, loss should be no more than 100 ft.
 - Barometric Scale Error: Set the barometric scale to various settings provided in a table. The altimeter should read the correct altitude differences within 25 ft.
3. Automatic Pressure Altitude Reporting Equipment (Encoder) and ATC Transponder System Integration Test (Correspondence Check). This test requires that the output of the installed transponder, when interrogated on Mode C, be measured "at a sufficient number of test points to insure that the altitude reporting equipment, altimeters, and ATC transponders perform their intended functions as installed in the aircraft." The difference between the altimeter reading and the transponder reply must be no more than 125 ft.

Transponder Tests. Section 91.172 requires tests specified in Appendix F for transponders. These include radio reply frequency, suppression, and receiver sensitivity. None of these tests should have an effect on the magnitude of an error in reported altitude.

Other Requirements. In addition to the biennial test, section 91.171 also requires the following tests for IFR flight:

- If the static system is opened or closed, it must be retested.
- If the automatic pressure altitude reporting system is installed or maintenance is performed on them, the correspondence check must be performed.
- Altimeters and altitude reporting equipment approved and installed under TSOs are considered tested and inspected as of the date of manufacture.
- Operations are prohibited above the maximum altitude at which the equipment has been tested.

There are further specifications on who is authorized to do the testing (Section 91.171, para. (b)) and what documentation is required (Part 43, Appendix E, para. (d)).

APPENDIX D

FAULT TREE ANALYSIS FOR IMC

The fault tree developed for the overall Safety Study of Minimum TCAS II is designed to be applicable in all traffic situations and environmental conditions expected in normal air carrier operations. IMC represents a special limiting case; certain events provided for in the overall fault tree do not apply in this case and are not considered in the analysis. This Appendix describes the effect on the fault tree of limiting the analysis to IMC.

An appropriate point of departure from the analysis in the overall Safety Study is the fault tree reduced for analysis, which is shown in Figures D-1 and D-2. Recall that the overall Safety Study assessed the risk relative to today's level of risk. As a consequence, the fault tree was reduced by "cutting" those branches that have no TCAS-related events, that is by assigning probabilities for those branches of 1.0 at "AND" gates and 0.0 at "OR" gates as shown in Figures D-1 and D-2. The remainder of the analysis is performed on a relative risk basis (the Risk Ratio).

The effect of limiting the fault tree analysis to IMC is to continue the process of reducing the fault tree. Branches applying to visual acquisition (e.g., event 7-361 in Figure D-1) are assumed to fail with probability 1.0 (all the time). Figures D-3 and D-4 show the fault tree after all the branches applying to visual acquisition have had probabilities of 1.0 assigned, and carries the results through the tree to the junctures of branches which do not relate to visual acquisition. Discussion of the reduction process for each of these branches follows:

D.1 Unresolved Branch of Fault Tree

Pilot Cannot Select a Maneuver (Event 6-385 in Figure D-3). This event applies to the "see-and-avoid" process for resolving a conflict. In overall conditions, if the pilot is alerted to the presence at a threat by a TA and visually acquires it, he can make a maneuver to avoid it. Event 5-385 covers the reasons why a pilot, alerted by the TA, would not be able to maneuver. The principal reason identified is that visual conditions are inadequate to support visual acquisition (event 6-386), which is given a failure rate of 1.0 since in

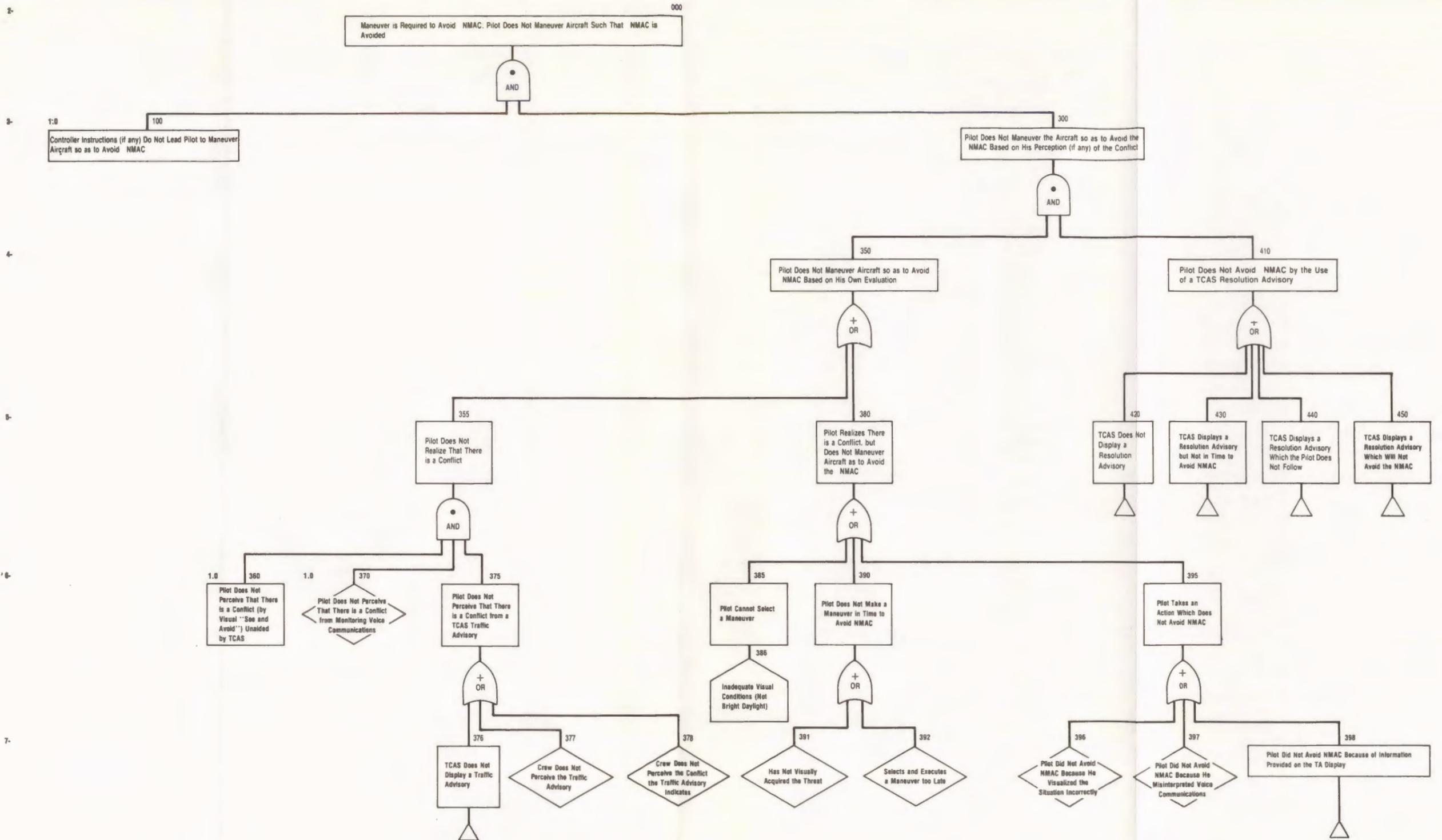


FIGURE D-1
000 BRANCH OF FAULT TREE REDUCED FOR
ANALYSIS IN SYSTEM SAFETY STUDY

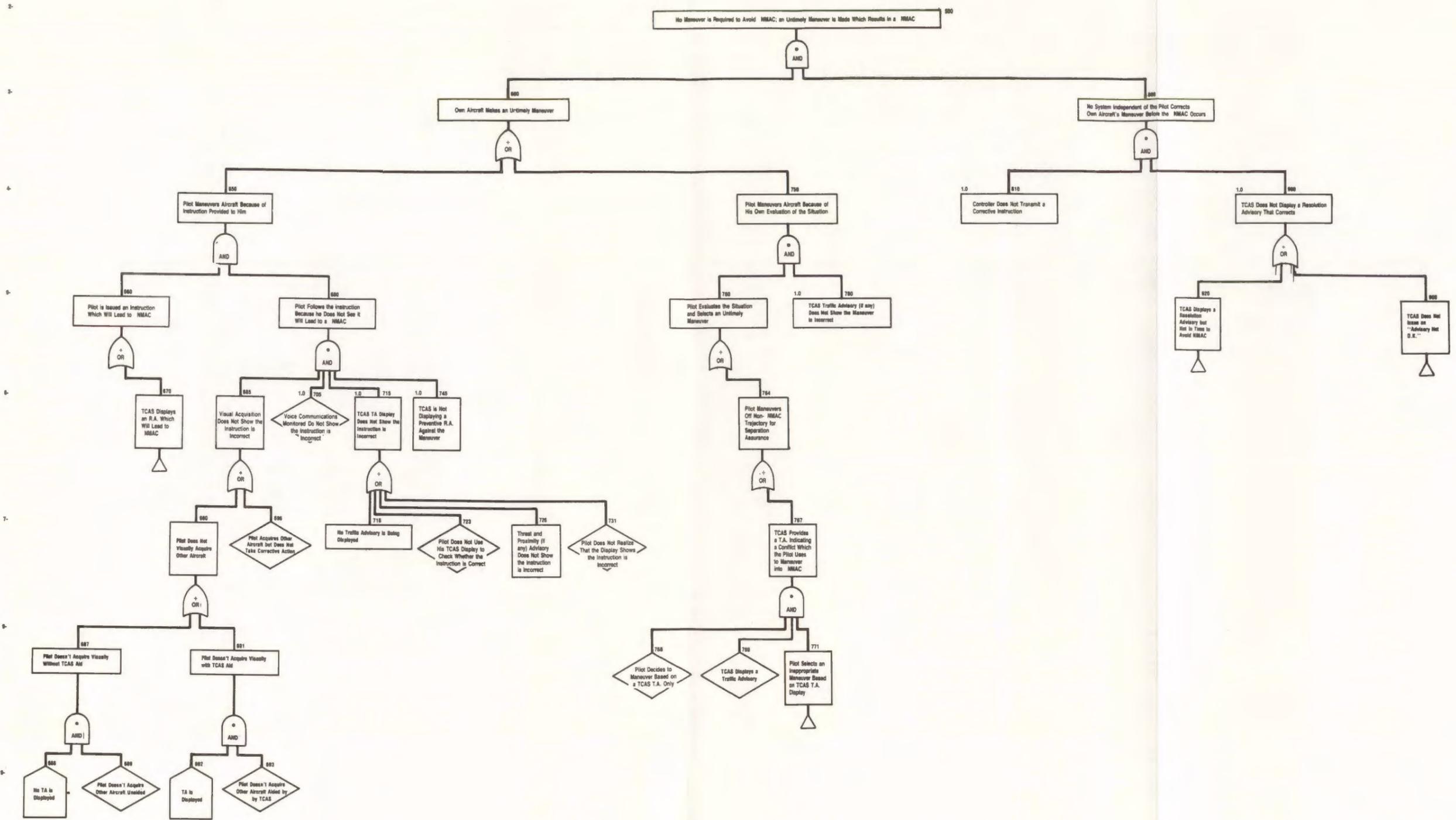


FIGURE D-2
500 BRANCH OF FAULT TREE REDUCED FOR
ANALYSIS IN SYSTEM SAFETY STUDY

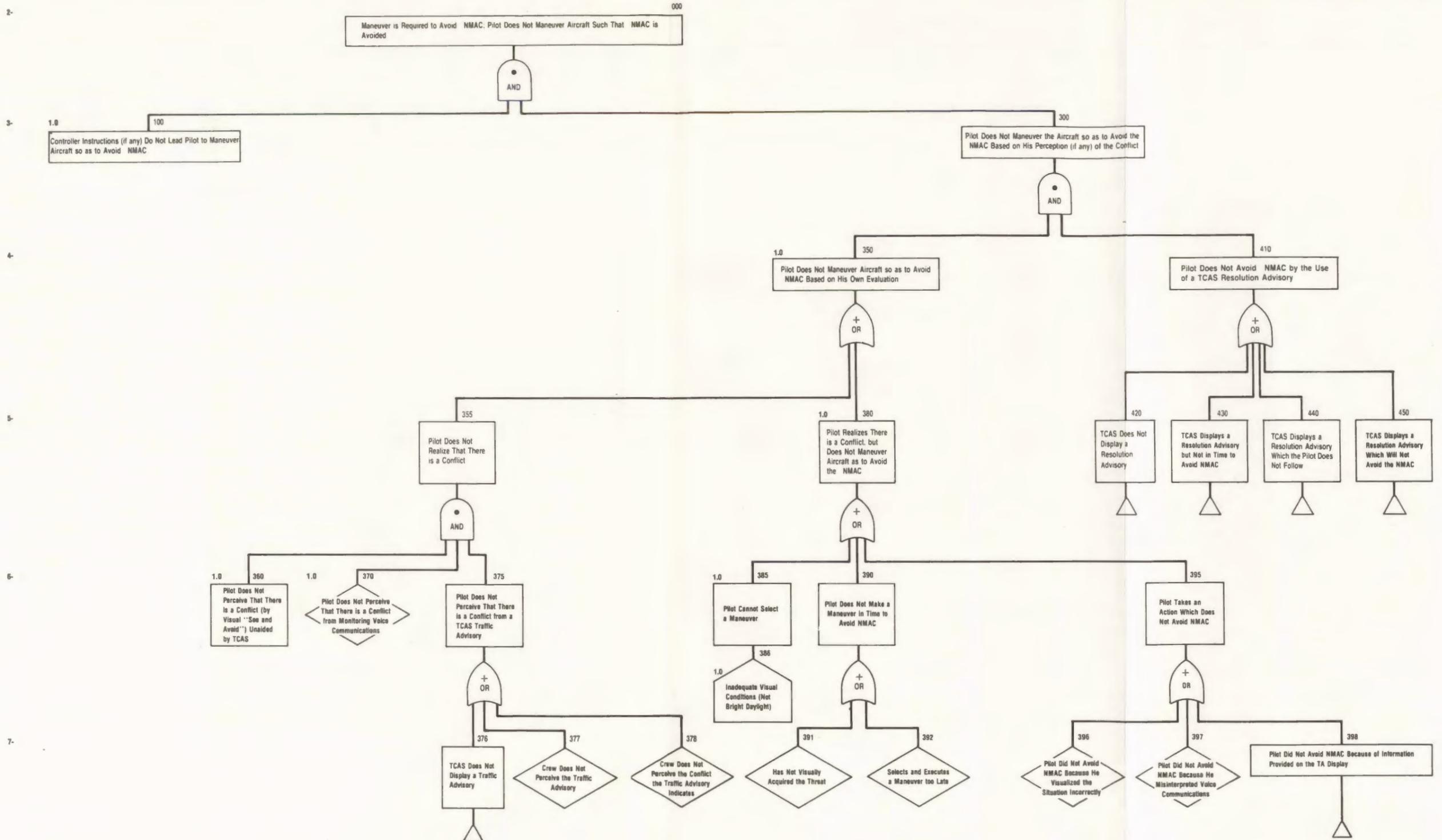


FIGURE D-3
000 BRANCH OF FAULT TREE FURTHER
REDUCED FOR IMC

IMC visual acquisition is assumed to be ineffective. As the pilot cannot make a "see-and-avoid" maneuver, events 5-380 and 4-350 automatically are assumed to fail and have probabilities of 1.0. This reduces the 000 branch of the Fault Tree (unresolved NMAC) to the events under 4-410 which relate to TCAS RAs; that is, failures occur should an RA (or lack of one) not resolve an NMAC. Events below these branches are contained in Appendix G of the overall Safety Study.

D.2 Induced Branch of Fault Tree

Pilot Does Not Visually Acquire Other Aircraft (Event 7-686).
This event applies to the process where a pilot, by visually acquiring the threat, avoids it even in the presence of an incorrect RA that would lead to an induced critical NMAC. Event 7-686 covers the situations wherein the pilot does not visually acquire the aircraft, either due to "No Traffic Advisory Is Displayed" (Event 9-688) or "Pilot Doesn't Acquire Other Aircraft Aided by TCAS" (event 9-683). In IMC, this latter event will always occur; thus, it is assigned a failure probability of 1.0; as a result, event 7-686 is assigned a probability of 1.0. Events 6-685 and 5-680 are calculated to be 1.0, with the final result that the probability of an induced critical NMAC is the probability that "Pilot is Issued an Instruction Which Will Lead to NMAC" (Event 5-660).

APPENDIX E

CHICAGO ENCOUNTER SIMULATIONS
STATISTICS AND PLOTS

Table E-1 contains the summary statistics for the RA-producing encounters simulated using the Chicago ARTS data. For each of the 14 encounters, the table lists the RA issued for each aircraft, whether it is preventive or corrective, the altitude of each aircraft, and the vertical rate tracked by TCAS at the time the RA is issued. The table also lists the vertical and horizontal miss distances at closest point of approach (CPA) for all but the parallel approach encounters.

Figures E-1 through E-14 are vertical and plan-view plots of these 14 encounters. The plots were generated from the simulations of each encounter. The tracks of Aircraft 1 are plotted with dashed lines, while those of Aircraft 2 are plotted with dotted lines. Each encounter was simulated twice; first with Aircraft 1 as TCAS-equipped, then as Aircraft 2 as TCAS-equipped. The plots of the two simulations are not significantly different; therefore, one set of plots is presented for each encounter.

The vertical plots show the altitudes for each aircraft and the slant range as they are tracked by TCAS. The altitude scale is on the left side and the range scale is on the right side. The horizontal scale represents time from the start of the encounter. The vertical line drawn through the tracks indicates the time that the RA is issued. This time is the same for both of the simulation runs of the encounter.

The plan-view plots show the smoothed ARTS tracks of the encounters. A scale, with each division representing one nautical mile, is drawn along the edge of the box. Labels are drawn every sixteen seconds that indicate the time from the start of the encounter and the Mode C altitude reports (in hundreds of ft). The RA each aircraft receives is indicated at the point at which the advisory is issued.

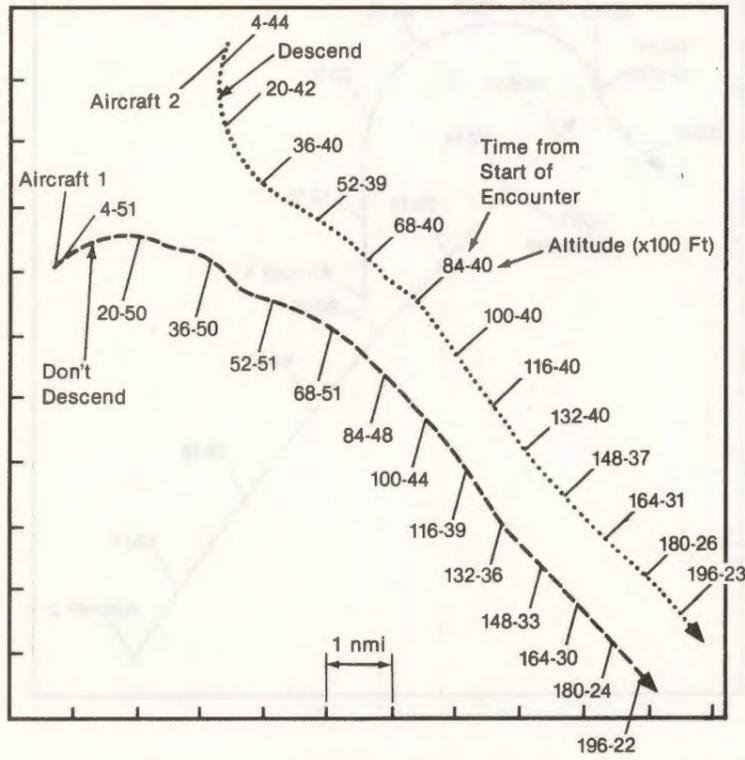
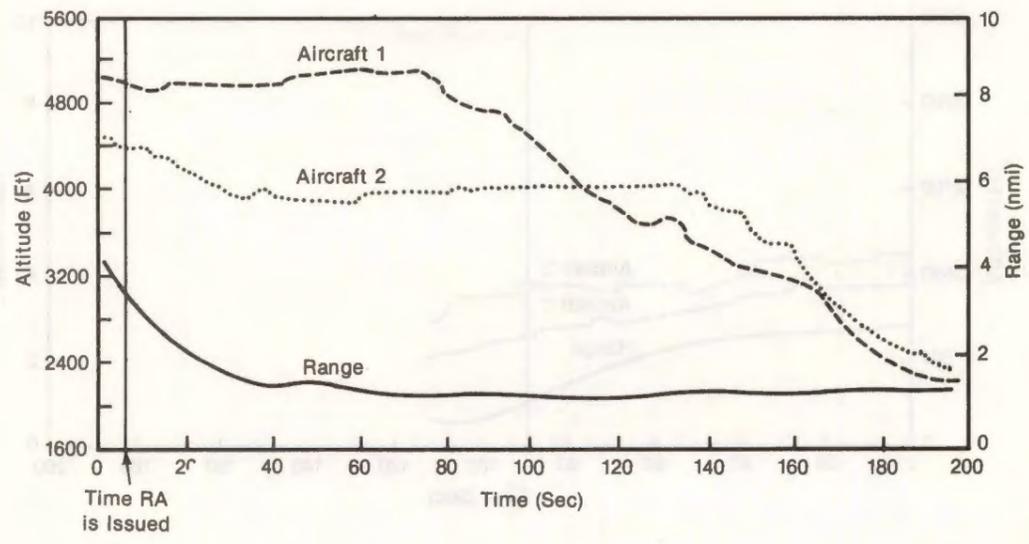


FIGURE E-1
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 1

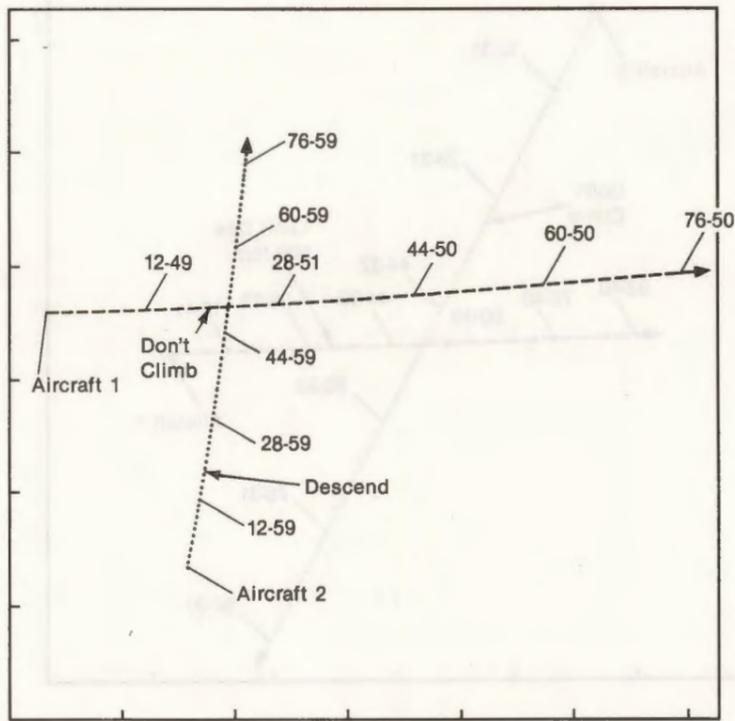
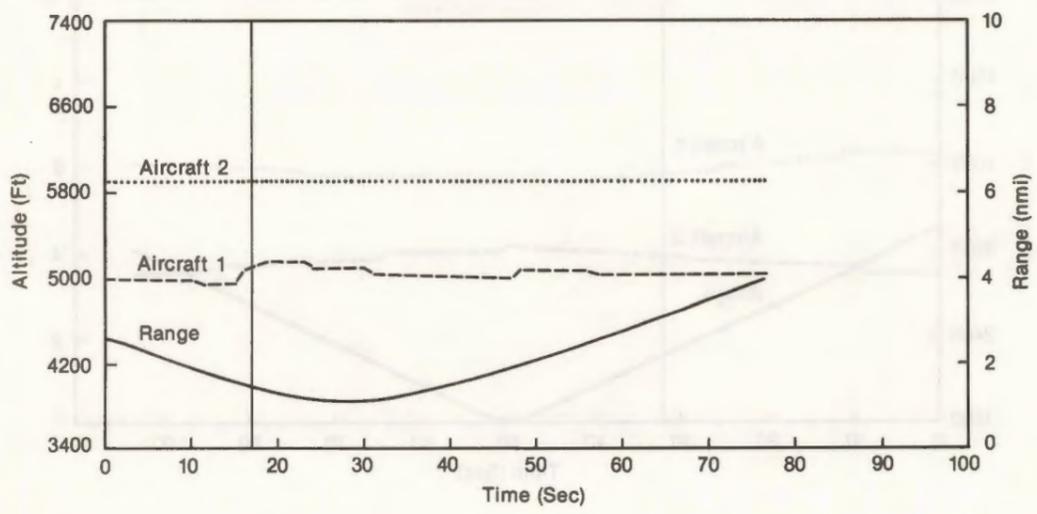


FIGURE E-3
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 3

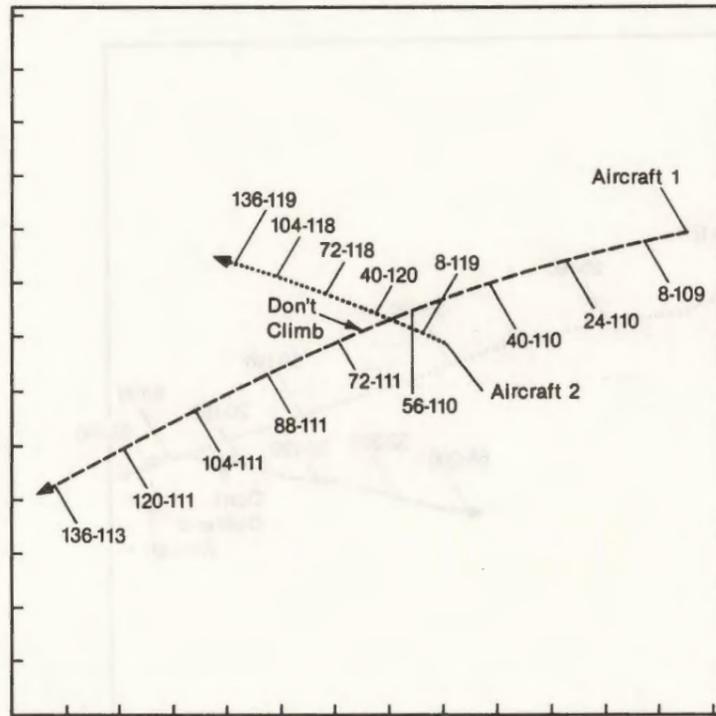
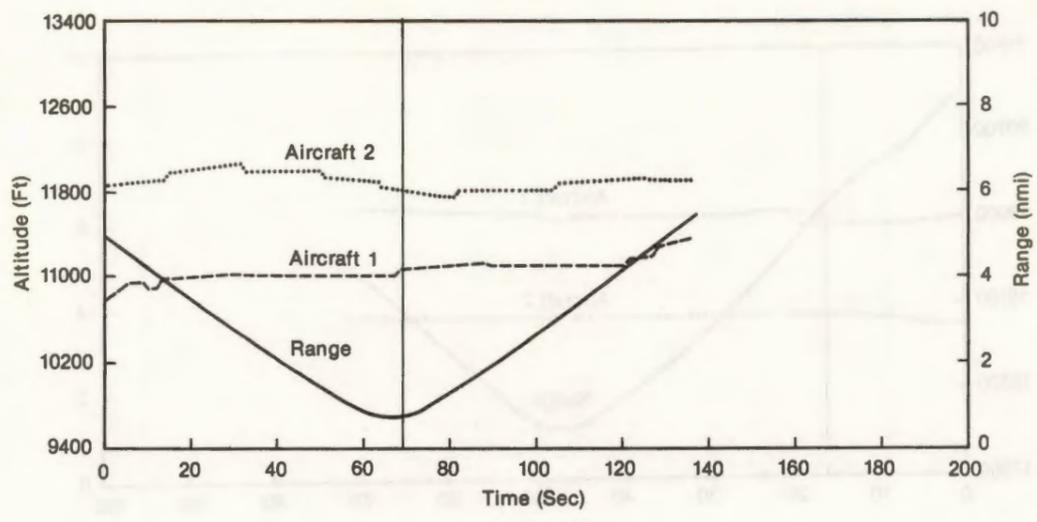


FIGURE E-5
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 5

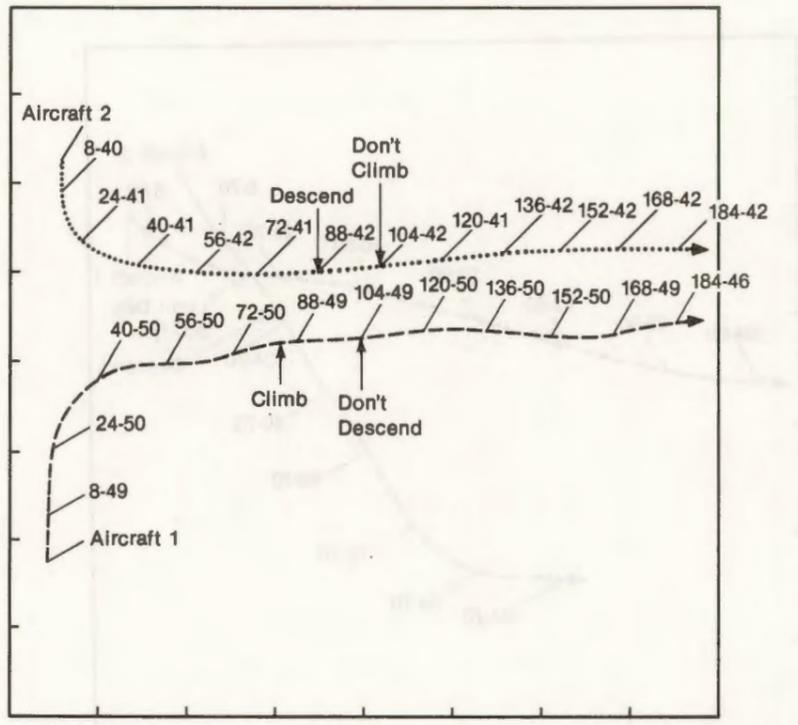
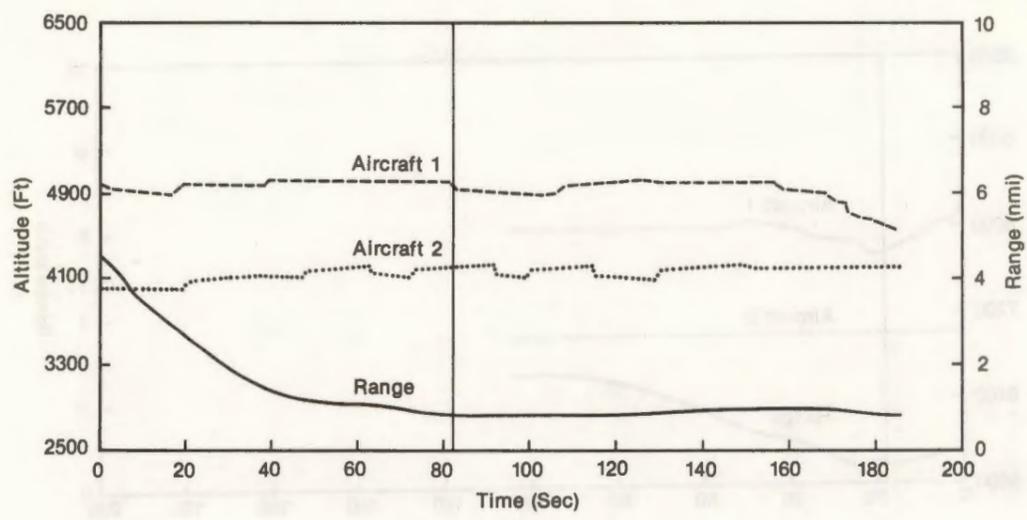


FIGURE E-7
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 7

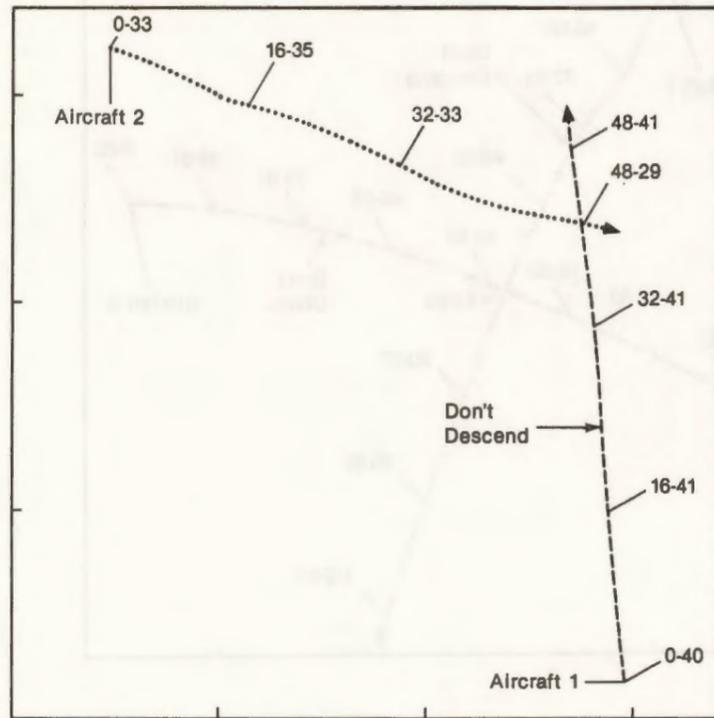
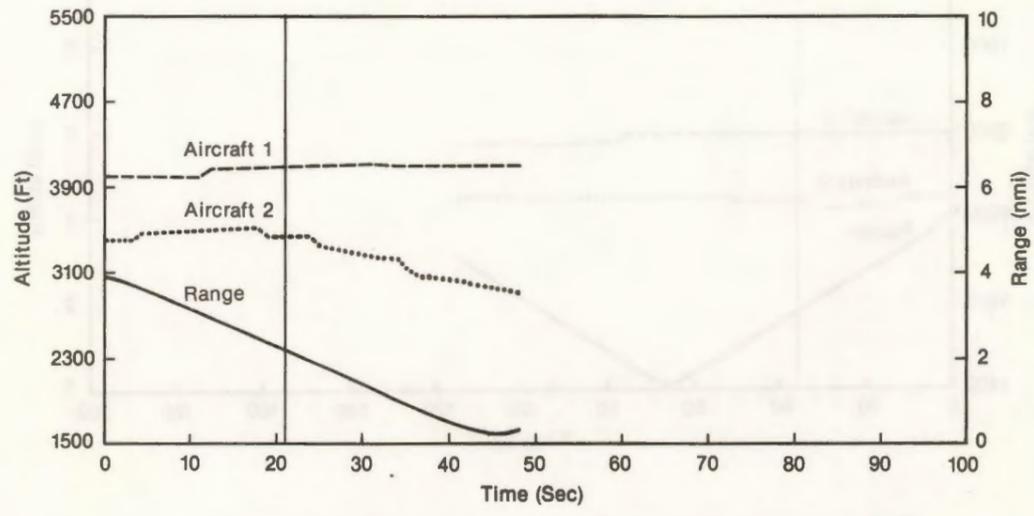


FIGURE E-9
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 9

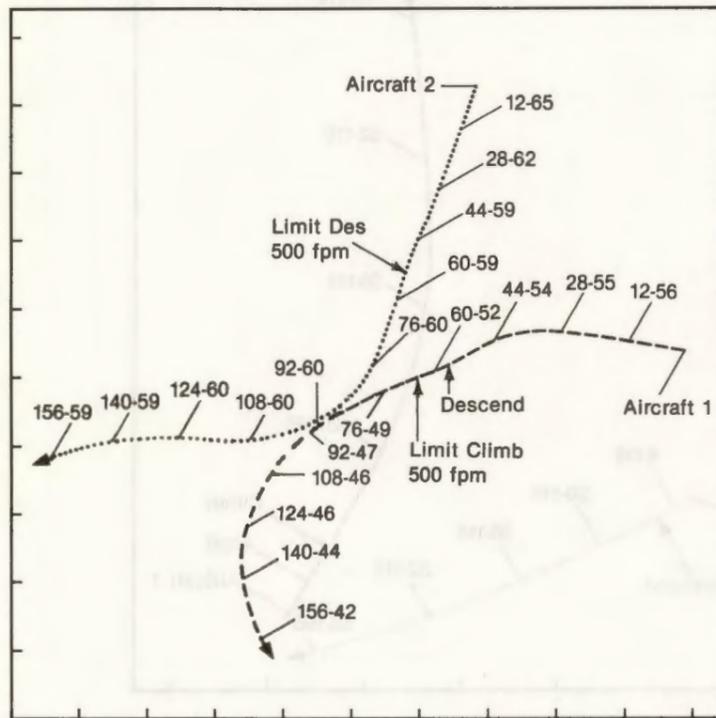
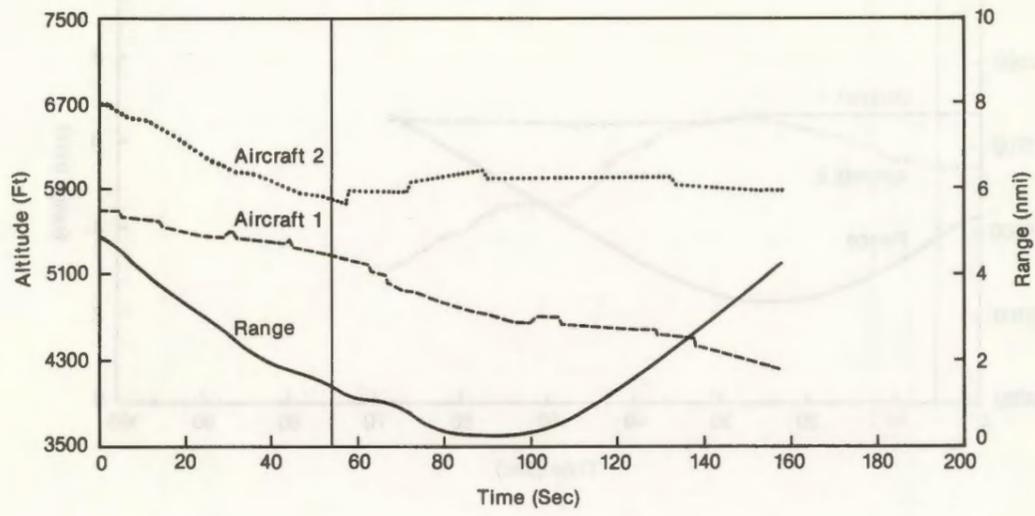


FIGURE E-11
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 11

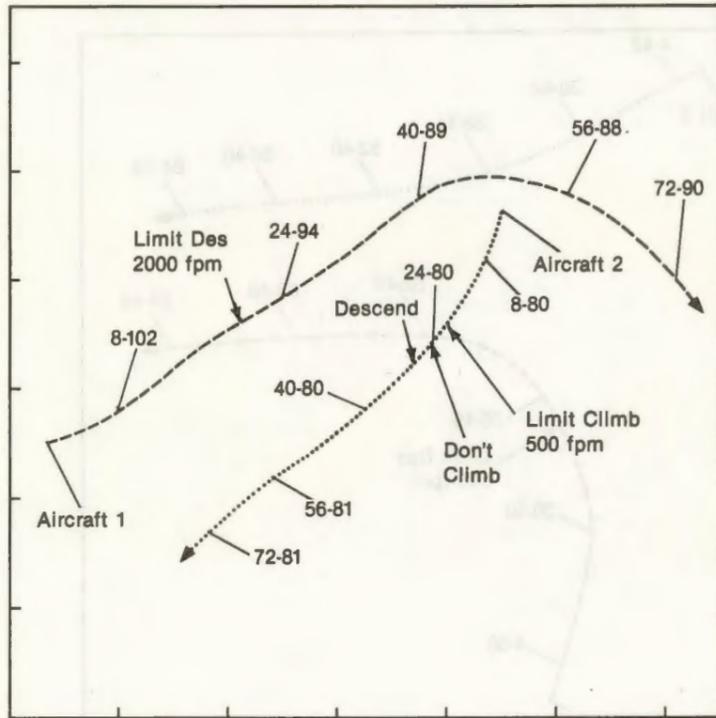
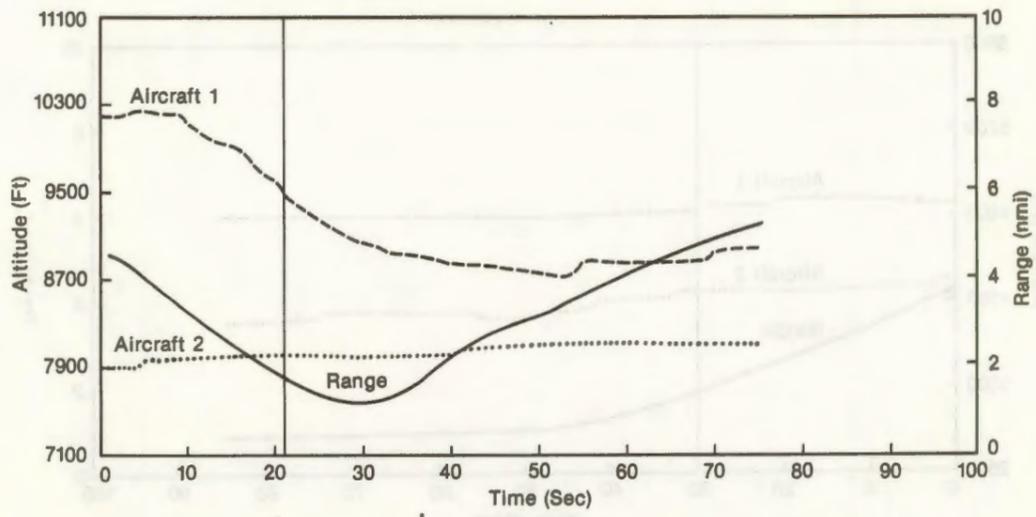


FIGURE E-13
VERTICAL AND PLAN-VIEW PLOTS OF ENCOUNTER 13

APPENDIX F

GLOSSARY

Active BCAS - A predecessor system that, like TCAS, used active interrogation of transponders to detect threats and issue alerts.

Air Carrier - As used in this study, major airline (Part 121) aircraft. This study evaluates the risk for these aircraft, since they are the type expected to carry TCAS.

Altitude Crossing Maneuver - A maneuver specified by an RA that requires the TCAS-equipped aircraft to cross the threat's altitude in order to achieve safe separation.

ARTS Extractor Tapes - The recordings of Secondary Surveillance Radar (SSR) data for aircraft tracked by the Automated Radar Terminal System (ARTS).

Avionics Critical Failure - A failure in the TCAS avionics that causes an incorrect RA to be issued in the presence of a proximate aircraft, resulting in a critical NMAC.

Beacon Collision Avoidance System (BCAS) - A predecessor airborne collision avoidance system that used transponder replies for threat detection. See Active BCAS and Full BCAS.

C-bit Error - A persistent error in an intruder's encoded altitude report.

Closest Point of Approach (CPA) - The point in an encounter at which the slant range between the two aircraft is at a minimum.

Coasted Track - A track that is continued based on previous range and altitude reports in the absence of current surveillance data.

Corrective Resolution Advisory - An advisory that requires a change in the TCAS-equipped aircraft's vertical rate for compliance (e.g., "Climb" for a level aircraft, "Don't Descend" for a descending aircraft).

Critical NMAC - As defined by the FAA, "a situation where collision avoidance was due to chance rather than an act on the part of the pilot." In this study, an event in which a TCAS-equipped aircraft comes within 100 ft (vertically) of a threat with close horizontal proximity (approximately 500 ft).

Instrument Conditions - Same as Instrument Meteorological Conditions.

Instrument Flight Rules (IFR) - The rules applying to aircraft flying in IMC or on IFR flight plans. These rules are contained in the Federal Aviation Regulations, Airman's Information Manual, the ATC Handbook, and other sources.

Instrument Meteorological Conditions (IMC) - The weather conditions described by cloud ceilings, cloud clearances, or visibilities that are less than the minima prescribed for VFR flight. In controlled airspace, these will typically be visibility of 3 nmi and ceiling of 1000 ft.

Instrument Weather Conditions - Same as Instrument Meteorological Conditions.

Intruder - An aircraft tracked by TCAS with potential to generate a Traffic or Resolution Advisory.

Intruder Maneuver - A change in the vertical rate of an aircraft being tracked by TCAS.

Invalid Advisory - An advisory issued by TCAS when it perceives that the RA maneuver currently displayed will no longer be adequate to generate 100 ft of vertical separation at closest point of approach. It can be caused either by a threat's vertical maneuver or by not following a displayed RA.

Maneuvering Intruder Hazard - Risk of an induced NMAC due to an intruder's vertical maneuver.

Minimum TCAS II - A version of TCAS which issues RAs in the vertical dimension only.

Multiaircraft Logic - The logic invoked by TCAS to resolve simultaneous conflicts involving two or more threat aircraft.

Near Midair Collision (NMAC) - An event in which two aircraft come close to each other in flight. There are several classes of NMACs based on how close the aircraft come to each other. In this study, the "critical" class is used (see Critical NMAC).

Negative Resolution Advisory - An advisory to inhibit the vertical rate of the TCAS-equipped aircraft ("Don't Climb" or "Don't Descend"). A negative RA can be either preventive or corrective, depending on the TCAS-equipped aircraft's vertical rate when the RA is issued.

Threat - An aircraft that is currently or is projected to be sufficiently close to the TCAS-equipped aircraft that a TA or RA is necessary.

Traffic Advisory (TA) - An advisory providing range, bearing, and relative altitude information to aid the pilot in visually acquiring a threat aircraft.

Traffic Alert and Collision Avoidance System (TCAS II) - An airborne collision avoidance system that actively interrogates aircraft transponders, advises the pilot of potential collision threats, and advises maneuvers when required to avoid threat aircraft. See Minimum TCAS II and Enhanced TCAS II.

Unresolved NMAC - An NMAC occurring today that would not be resolved by TCAS because of factors such as a non-Mode C intruder or error in an intruder's altitude.

Unresolved Risk Ratio - The risk of an unresolved NMAC expressed relative to the present risk of an NMAC without TCAS.

Vertical Miss Distance - The relative altitude difference between two aircraft in an encounter at closest point of approach.

Visual Conditions - Same as Visual Meteorological Conditions.

Visual Flight Rules (VFR) - The rules that apply to flight in VMC, where reference to navigation instruments, use of a filed flight plan, and contact with ATC is optional.

Visual Meteorological Conditions (VMC) - The weather conditions defined by minimum ceilings, visibilities, or cloud covers, at or above which reference to navigational instruments, use of a filed flight plan, and contact with ATC are optional.

Visual Weather Conditions - Same as Visual Meteorological Conditions.

APPENDIX G

ACRONYMS AND ABBREVIATIONS

AC (A/C)	Aircraft
ALIM	Altitude threshold for positive Resolution Advisories
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ASRS	Aviation Safety Reporting Service
ATC	Air Traffic Control
BCAS	Beacon Collision Avoidance System
BEU	BCAS Experimental Unit
CGT	Chicago Heights VORTAC
Clm	Climb
CPA	Closest Point of Approach
Des	Descend
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
fpm	Feet per minute
ft	Feet
GA	General Aviation
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IPC	Intermittent Positive Control
NASA	National Aeronautics and Space Administration
NMAC	Near-Midair Collision
nmi	Nautical miles
NTSB	National Transportation Safety Board
RA	Resolution Advisory
RSS	Root-Sum-Square
s	Seconds
SAR	System Analysis Recording
s.d.	Standard Deviation
SSR	Secondary Surveillance Radar

APPENDIX H

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