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A CONCEPT FOR REDUCING OCEANIC SEPARATION MINIMA THROUGH THE USE OF A TCAS-DERIVED CDTI

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16. Abstract

This report presents a concept for using a cockpit display of traffic information (CDTI), as derived from a modified version of the Traffic Alert and Collision Avoidance System II (TCAS II), to support reductions in air traffic separation minima for an oceanic track system. The concept, and the TCAS modifications required to support it, are described in detail. The feasibility of the concept is examined from a number of standpoints, including expected benefits, maximum alert rates, and possible transition strategies. Various implementation issues are analyzed. Pilot procedures are suggested for dealing with alert situations. Possible variations of the concept are also examined. Finally, recommendations are presented for other studies and simulation experiments which can be used to further verify the feasibility of the concept.

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SECTION 1

SUMMARY

This report presents and evaluates a concept for using a cockpit display of traffic information (CDTI) to potentially help support reductions in the air traffic separation minima for oceanic track systems. Such reductions could provide significant savings in flight costs. The CDTI would be derived from a modified version of the Traffic Alert and Collision Avoidance System II (TCAS II). Under the oceanic CDTI concept, primary reliance for the safe separation of aircraft would continue to be placed on planned separation using the oceanic track system. The CDTI system would only be used to detect and resolve conflicts where the planned separation minima had been violated. Under this concept, all pilots would monitor a single Very High Frequency (VHF) voice channel. Aircraft call signs would be encoded in TCAS air-to-air data exchanges to permit voice communication to be established between conflicting flights. The TCAS II surveillance range and traffic alert boundaries would be enlarged to provide at least two minutes of warning prior to the closest approach of two aircraft; this should provide sufficient time for the pilots to negotiate a resolution strategy over the air-to-air voice channel and perform routine resolution maneuvers.

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A theoretical evaluation of the feasibility of the oceanic CDTI concept was performed from a number of standpoints. The necessary modifications to TCAS II to support this concept were determined; it was concluded that these modifications were feasible, but possibly at significant extra cost. Pilot procedures were developed for dealing with alert situations. The ability of the system to maintain or increase safety levels was examined. Maximum alert rates from the pilot's viewpoint were estimated for various sets of reduced separation minima in a parallel track system. A number of implementation issues were investigated, including contention for the voice channel and oceanic multipath effects. It was concluded from these analyses that at least 50% reductions in the current separation minima for both the lateral and longitudinal dimensions should be possible with the oceanic CDTI system. The system also shows promise for supporting reductions in vertical separation on the basis of the analyses conducted in this study. Additional experimental evaluations are needed to validate this possibility.

Supplementary investigations included the development of possible transition strategies for the oceanic CDTI system. A number of variations and extensions of the concept were also considered. Finally, recommendations were made for further data collection efforts and cockpit simulation experiments which could be conducted to confirm the feasibility of the oceanic CDTI concept.

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SECTION 2

INTRODUCTION

For the past few years there has been a joint program between
the Federal Aviation Administration (FAA) and the National
Aeronautics and Space Administration (NASA) to investigate how a
pilot might use a display in the cockpit that shows the positions of
nearby aircraft in relation to his own aircraft. This presentation
of traffic to the pilot is called Cockpit Display of Traffic
Information (CDTI). Recently, there has been a review of the CDTI
program, in which several potentially needed improvements in air
traffic operations were considered. Those improvements that might
be supported through the use of CDTI were identified. One of these
potentially needed improvements is for a reduction in the separation
minima in oceanic areas so that aircraft can more often fly routes
and altitudes that are optimal from a fuel consumption point of view.

Purpose

The purpose of this study was to develop and analyze a concept
for using CDTI information, as derived from an airborne collision
avoidance system, to support reductions in separation minima in
oceanic areas. A primary goal of the study was to determine what
changes could be made to the current Traffic Alert and Collision
Avoidance System II (TCAS II) to permit it to provide the necessary
information for this purpose. Another important goal was to provide
an initial assessment of the feasibility of this oceanic CDTI
concept. It should be noted that the methods for transoceanic
control proposed in this document were developed solely to provide a
framework within which further research studies could be conducted
by NASA.

The benefits of reducing air traffic separation minima are
significant and have been well documented. For instance, SRI
International, under contract to the FAA, recently investigated the
potential benefits of reduced separation in the Oceanic Area System
Improvement Study (OASIS). The final report concluded that the
potential savings in flight costs over a twenty year period might
run into the hundreds of millions of dollars for the North Atlantic
alone (Reference 1). By capitalizing on the current stage of
development of TCAS, these benefits might be realized in the
relatively near future.

Objectives and Scope

The specific objectives of this study were as follows:

(1) Identify any changes to the current TCAS II design which
would be necessary to implement the oceanic CDTI concept.

(2) Develop possible pilot procedures for dealing with alert
situations.

(3) Identify candidate schemes for reducing separation minima
that might be supported by the oceanic CDTI concept.

(4) Estimate the maximum alert rates for the proposed concept
for each candidate scheme identified.

(5) Estimate the expected benefits of the proposed system.

(6) Investigate implementation issues surrounding the concept.

(7) Devise possible strategies for transitioning to the
proposed system.

(8) Consider possible variations to the proposed system.

(9) Make recommendations for additional in-depth studies and
experiments which might be used to validate the oceanic
CDTI concept.

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These objectives were met through engineering analysis and a review of current research literature; no cockpit simulations or extensive computer analyses were undertaken.

In general, this study was based upon the assumption of a high-altitude oceanic track system with parallel tracks. Although the oceanic CDTI concept might also provide significant benefits in non-track oceanic areas, it would be more difficult to develop operational procedures and to assess the value of the system for such an environment. Traffic data and baseline separation minima for this study were based upon current oceanic track systems, particularly the North Atlantic track system. A ground rule for this study was that any proposed changes to TCAS must not affect its normal operation over land areas.

Approach

To achieve the objectives of this study, the following approach was taken. First, a preliminary concept for using CDTI, as derived from a modified TCAS unit, was developed. This concept included a provision for the pilots of two aircraft to verbally coordinate, via VHF radio, a resolution of any situation causing an alert. The operations of current oceanic track systems were then reviewed, and several candidate approaches to reducing the separation minima were proposed. These were analyzed briefly for feasibility. Several were eliminated from further consideration at this stage.

The preliminary concept was then refined. The specific modifications that would be required of the TCAS II units (as currently defined) to support the oceanic CDTI concept were identified. Both equipment and logic modifications were studied. Then, possible pilot procedures for dealing with the alerts generated by the CDTI system, and for negotiating with other pilots,

were developed. These procedures included actions that would be appropriate for each of the candidate schemes for reducing separation minima.

Next, the operation of the CDTI system with each of the candidate schemes was studied in depth from a number of viewpoints. Maximum alert rates were estimated for each of the candidate approaches, and the effect of the alerts on pilot workload was assessed. The benefits of implementing each of the candidate schemes for reducing separation minima were then evaluated. Such benefits as reduced operating costs for users of the system, increased capacity of the track system, and improved safety of oceanic flight were considered. Transition strategies for converting from the current separation minima to those of the proposed new schemes were assessed for each of the candidates. Finally, with the preceding information in hand, a comparative evaluation of the overall merit of each candidate scheme was prepared.

Additional study was performed to identify and investigate implementation issues surrounding the oceanic CDTI concept. These included contention for the voice channel, oceanic multipath effects, and TCAS interference levels. Possible variations of the basic concept were then addressed briefly. These included variations to deal with unequipped aircraft, to handle aircraft crossing the tracks, and to permit cruise climb.

From the results of the above activities, recommendations were made for data collection efforts and simulation studies that could be used to confirm the feasibility of the concept proposed in this document.

Measurement Units

Calculation and measurement values used in this report are generally expressed in both SI units and in customary units (in parentheses following the SI units). In all cases, the customary units were used for the original measurements and calculations.

SECTION 3

BACKGROUND

In this section, background information is provided on the current TCAS II design and on the current operation of oceanic track systems.

Current TCAS II Design

TCAS II is an airborne system that makes use of air-to-air beacon transmissions for the purpose of aircraft separation assurance. The system is capable of detecting and tracking aircraft that are equipped with secondary surveillance radar (SSR) transponders. TCAS II can provide both traffic advisories and resolution advisories against intruders that are so equipped. The avionics for each TCAS II unit includes a Mode S transponder with data link capability. Whenever two TCAS-equipped aircraft come into conflict, their resolution actions are automatically coordinated via the Mode S data link.

Two versions of TCAS II are currently under development: Minimum TCAS II and Enhanced TCAS II. Minimum TCAS II is described in detail in the TCAS II Minimum Operational Performance Specification (MOPS) recently prepared by Special Committee 147 of the Radio Technical Commission for Aeronautics (RTCA). This document is listed as Reference 2. Minimum TCAS II is currently in the final stages of development and testing. Because of the limited accuracy of its bearing data, Minimum TCAS II can provide resolution advisories in the vertical dimension only (e.g., "climb" and "descend"). Enhanced TCAS II is a proposed version of TCAS II which would be capable of deriving more accurate bearing information, enabling it to provide resolution advisories in the horizontal

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dimension (e.g. "turn left" and "turn right"), in addition to the vertical.

In general, TCAS II will generate an advisory for each nearby aircraft whose projected separation is within certain predefined bounds. These alert boundaries may vary according to local traffic and airspace conditions. However, for high-altitude enroute airspace, the alert boundaries for Minimum TCAS II are defined essentially as follows: A resolution advisory is issued if an intruder is projected to come closer than 1.9 km (1.0 n. mi.) in range within 30 seconds and is projected to be within 290 m (950 ft) of own aircraft's altitude at the time of horizontal closest approach. Traffic advisories are of two types: threat advisories and proximity advisories. A threat advisory is issued if an intruder is projected to come closer than 2.2 km (1.2 n. mi.) in range within 45 seconds and is currently within 370 m (1200 ft) of own aircraft's altitude (or is projected to cross own aircraft's altitude within 45 seconds). A proximity advisory is issued if the intruder is currently within 7.4 km (4.0 n. mi.) of own aircraft in range and within 370 m (1200 ft) of own aircraft vertically, but does not meet the criteria for a threat advisory.

Because of the limited accuracy of its bearing data, the detection of large horizontal miss distances is difficult for the Minimum TCAS II system. (Horizontal miss distance is the range of a threat aircraft at the point of its horizontal closest approach.) Even though filtering on horizontal miss distance could eliminate some unnecessary alerts, the current logic for Minimum TCAS II does not specifically include a horizontal miss distance filter. However, some testing of such a filter has been performed as part of the TCAS program; this filter is referred to as "tau-dot logic." Although this filter is not included in the current TCAS design, it is mentioned here because of its potential value for the oceanic CDTI system.

The alert criteria for Enhanced TCAS II are expected to be basically the same as those used by Minimum TCAS II. However, more accurate bearing data should allow Enhanced TCAS II to use a true projection of horizontal miss distance to eliminate even more unnecessary alerts.

The oceanic CDTI concept described in this document is based upon a modified version of Minimum TCAS II (as specified in the TCAS II MOPS). The additional capabilities of Enhanced TCAS II, though potentially useful in this application, are not considered essential and have been ignored in the analyses presented here.

Current Operation of Oceanic Track Systems

The oceanic track systems in use today have a number of features in common. They are typically composed of parallel tracks, with a number of flight levels being used on each track. The systems operate at high altitudes (above 8800 m, or 29 000 ft), and flight levels are generally separated by 610 m (2000 ft). Aircraft separation for a track system is governed by an official separation standard, which specifies the minimum separation of tracks and flight levels, as well as the minimum longitudinal spacing between consecutive aircraft on the same track and flight level. The minimum longitudinal spacing is typically adjusted to account for any differences in Mach number between successive aircraft on the same track.

Control procedures for different track systems also have a number of similarities. Each aircraft must receive a clearance from the appropriate oceanic control center before entering the system. Among other things, the clearance specifies the aircraft's assigned track, flight level, and time of entry into the system. Except in an emergency, a pilot desiring to change tracks, flight levels, or

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filed Mach number must first negotiate a new clearance with oceanic
control. Radar surveillance is typically not available over most of
an oceanic track system. Therefore, oceanic separation minima are
comparatively large, and each pilot is required to periodically
report his position to the oceanic control center. Each track
system has its own reporting requirements. For instance, in
East-West systems, each aircraft is generally required to report its
position every ten degrees of longitude.

In oceanic track systems, High Frequency (HF) radio is used for
communication between pilots and oceanic control centers. As a
rule, pilots do not talk directly to controllers. Instead, messages
must be relayed through a communications center, which is generally
not co-located with the oceanic contol center. A pilot files a
position report or requests a change in flight plan by talking to
the communications center over HF radio. An operator then sends
this message to the oceanic control center (typically by teletype).
The reply from oceanic control follows a reverse process. An
exchange of messages between a pilot and controllers can take ten
minutes or more. Thus, a request for a change in clearance must be
planned well in advance, and quick response from controllers in
helping to resolve an urgent problem is not possible. VHF radio,
being limited to line-of-sight distances, is not generally used for
oceanic control purposes.

The two largest oceanic track systems, in terms of daily
operations, are the North Atlantic (NAT) track system and the
Central East Pacific (CEP) track system. Both are East-West
systems. The NAT track system, operating generally between
Newfoundland and Ireland, is the larger, in terms of both traffic
and length. The system is roughly 3700 km (2000 n. mi.) in length.
The CEP track system, operating generally between Hawaii and
southern California, is somewhat shorter than the NAT track system.

Some of the differences between the NAT and CEP track systems are worth mentioning.

The NAT track system is completely rebuilt twice each day to take best advantage of the existing meteorological conditions, prevailing winds, and traffic demand. Traffic is predominantly one way. Traffic moving opposite to the prevailing direction typically occupies one or two tracks separate from the prevailing flow. Opposite-direction traffic is seldom separated vertically from the prevailing traffic on the same track. Figure 1 shows the structure of a predominantly westbound NAT track system on a typical day.

The safety of current separation standards in the NAT track system is ensured by the enforcement of a Minimum Navigational Performance Specification (MNPS) for all aircraft using the system (Reference 3). The MNPS requires that each aircraft's lateral navigational accuracy have a standard deviation of error of no more than 12 km (6.3 n. mi.). Also, the fraction of time spent more than 56 km (30 n. mi.) off course must be less than 5.3×10^{-4}. The fraction of time spent between 93 km (50 n. mi.) and 130 km (70 n. mi.) off course must be less than 13×10^{-5}.

The CEP track system, in contrast to the NAT, uses fixed tracks which do not change. Unlike the NAT, alternate flight levels are used for opposite-direction traffic on all tracks in the CEP. One-direction traffic is not as prevalent in the CEP as in the NAT.

Because of the lack of radar surveillance, as well as the lack of direct pilot-controller communications, maintaining separation between aircraft in an oceanic track system depends solely upon

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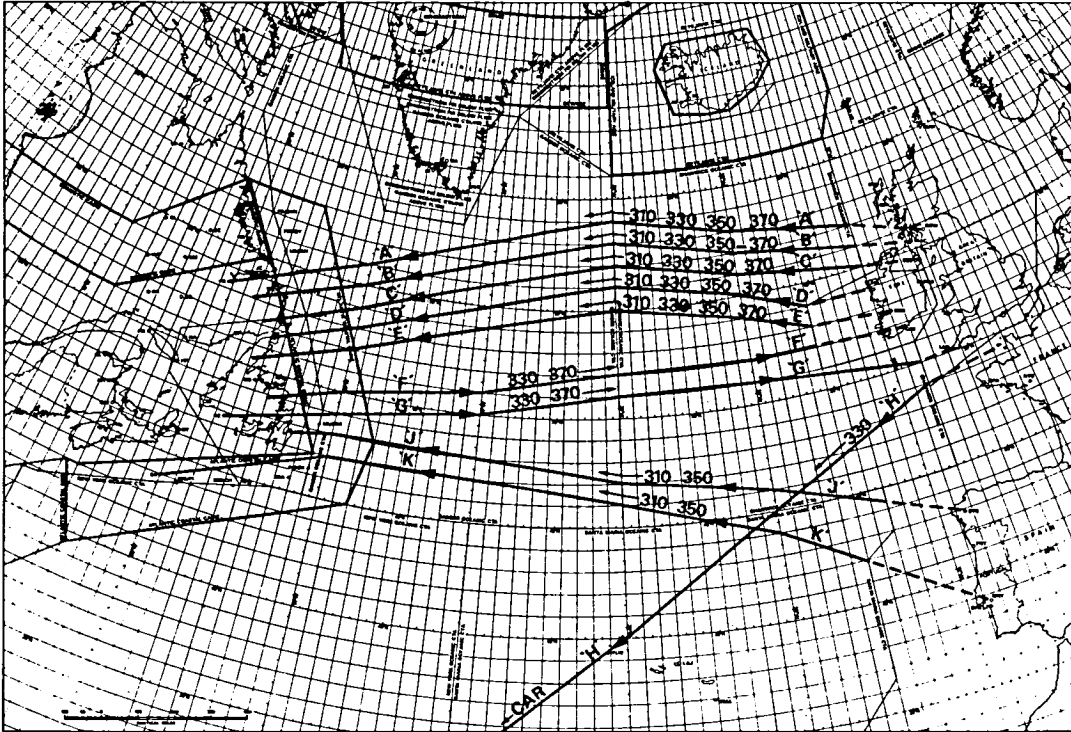
Figure 1.–Typical daytime westbound track
system for the North Atlantic.

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aircraft maintaining their assigned tracks, flight levels, and Mach numbers using their on-board navigation systems and cockpit instruments. In the NAT, the aircraft are required by the MNPS to have duplicate navigation systems, but no direct, corroborating measurements of aircraft separation are made today. This open-loop approach to ensuring aircraft separation demands the very large separation minima that are in current use.

SECTION 4

CONCEPT DESCRIPTION

This section summarizes the concept for using CDTI to support
reductions in separation minima in an oceanic track system. The
concept described here is the result of the study reported in this
document. The remainder of this document records the steps taken in
developing this concept, and assesses the feasibility and
limitations of the concept.

In the track systems used in oceanic areas today, separation
between aircraft is achieved by assigning aircraft to specific
tracks, flight levels, and Mach numbers and then by requiring the
aircraft to adhere closely to these assignments. Since separation
is based solely upon onboard navigation systems without surveillance
data, very large separation minima must be applied. The concept
proposed here is for the use of TCAS equipment which has been
modified to provide long-range CDTI capability in oceanic areas.
The concept is designed to permit smaller separation minima to be
applied between aircraft which are so equipped. With these reduced
separation minima, airlines would be able to fly flight paths more
nearly approaching the optimal ones, and they would thus be able to
save time and fuel on their transoceanic flights.

The display generated from direct TCAS measurement of separation
permits recognition of the loss of separation caused by aircraft
drifting from their assigned flight paths and provides a means for
ensuring safe separation when this happens. The TCAS system tracks
all targets within its surveillance range and continuously tests to
see if any of them are converging to a close approach. If so, the
TCAS unit alerts the pilot with an aural alert; displays a symbol
and data block for that target on a plan view display that indicates

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the target's range, bearing and flight level; and flashes or otherwise highlights the position symbol of that target. This will be called a CDTI alert. The TCAS unit also determines if a target is close enough to be of concern to the pilot, even though it may not be converging rapidly. If so, it displays the target, but does not generate an aural alert and does not flash or highlight the position symbol. This will be called a CDTI proximity advisory.

An important element of this concept is that pilots would monitor a single, specially designated VHF frequency at all times when within the oceanic track system. If two aircraft were losing safe separation, the two pilots would make voice contact, exchange additional data about their situations, and negotiate a compatible set of actions to avoid a close approach. When the TCAS unit found a target converging, it would automatically acquire the Air Traffic Control (ATC) call sign of that target and display it with the target's position symbol on the CDTI display. This would permit the pilot to initiate voice contact with the pilot of the target aircraft on the designated voice frequency.

The TCAS unit which supports this CDTI concept requires several modifications to the normal Minimum TCAS II equipment. First, the effective transmitter power and receiver sensitivity of the TCAS unit must be raised to increase the surveillance range. This is required to provide the time necessary for voice coordination. The exact amount of the required increase in range depends on the way in which separation minima are reduced, as described later in this document. In no case would the surveillance range need to be greater than 74 km (40 n. mi.).

Provisions must also be made for the pilot to enter his call sign into his Mode S transponder, and the TCAS unit must be able to make an interrogation to solicit the call sign from another Mode S

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transponder. The TCAS unit must have a test capability, in addition to the self-test feature required of the Minimum TCAS II, that permits the pilot to receive, while airborne, a graphical or tabular display of all targets being tracked by his TCAS. The TCAS unit must have a switch that permits it to be manually switched between the oceanic mode and the normal mode. In the normal mode the TCAS unit must behave exactly like a Minimum TCAS II.

The TCAS display must be modified slightly to support the CDTI concept. It must have a scale suitable for displaying targets -- perhaps as much as 74 km (40 n. mi.) ahead and 37 km (20 n. mi.) behind own aircraft. It must also be capable of displaying the ATC call sign of a target aircraft.

The TCAS logic must also be modified to support the CDTI concept. The TCAS traffic alert parameters must be modified to give a CDTI alert approximately 120 seconds before the closest approach of a target aircraft. This logic should include a horizontal miss distance filter in some form. The TCAS logic must also be modified to give a CDTI proximity advisory for a target at a much greater range than the normal TCAS proximity advisory.

When the TCAS unit is switched to the oceanic mode, it is able to generate CDTI alerts, CDTI proximity advisories, or TCAS resolution advisories, if the corresponding logic criteria are satisfied. When the normal mode is selected, only TCAS threat advisories, proximity advisories, and resolution advisories may be issued. Note that resolution advisories may be issued in either mode.

The oceanic CDTI concept still depends primarily on the structure provided by the oceanic track system to keep aircraft separated. The CDTI system is designed to protect against hazards

caused by deviations from assigned flight paths. It is not intended
to be a primary separation mechanism.

In this concept, reduced separation minima would be applied only
between two aircraft which are CDTI-equipped. In the oceanic track
system as a whole, this might be achieved by setting aside
designated tracks to be used by CDTI-equipped aircraft only.
Whenever CDTI-equipped and unequipped aircraft operate on adjacent
tracks or flight levels, the present separation minima must be
applied. However, in the rare event that a CDTI-equipped aircraft
encountered an unequipped aircraft, a CDTI alert would be issued
against the intruder to provide additional safety. In this concept
it is proposed that the pilot not make voice contact with an
unequipped aircraft.

A gradual transition strategy for implementing the oceanic CDTI
concept is proposed. This strategy would provide early cost-saving
benefits for the first aircraft to acquire the CDTI capability.
Initially, only one or two tracks might be reserved for use
exclusively by CDTI-equipped aircraft. As more aircraft became
equipped, more tracks would be converted to CDTI-only tracks.

If vertical or longitudinal separation standards were reduced, a
single existing track could be converted initially to a CDTI-only
track. On this track, the vertical or longitudinal separations
between CDTI-equipped aircraft would be reduced. But the lateral
separations between these aircraft and aircraft on adjacent tracks
would remain unchanged. If only lateral separations were reduced,
it would be necessary to establish at least two adjacent tracks that
were CDTI-only tracks. The separation between these two would be
reduced, while the separation between either of these and the
adjacent normal track would be unchanged.

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The track(s) to be converted to CDTI-only tracks should be those
that are most heavily used. These are the ones where reduced
separations would have the greatest overall benefit. (Presumably
these tracks are the minimum-fuel tracks for a large number of
flights and are, therefore, popular tracks.) Other than offering
the incentive of receiving the preferred tracks or more nearly
optimal tracks to equipped users, no additional encouragement for
equipage should be required. No regulations mandating equipage are
envisioned. Tracks should be converted to CDTI-only tracks at a
rate to keep pace with the equipage rate of aircraft using the
oceanic track system. The period of time required to recover the
costs of the equipment through fuel savings should be short enough
to make the concept attractive on its own merits.

Pilot procedures for operating the TCAS unit and for responding
to CDTI indications are proposed. First of all, several
pilot-initiated tests of the TCAS equipment must be performed on
each flight prior to entering the oceanic track system. These tests
are intended to ensure that the TCAS unit is operating properly
before the aircraft is permitted to enter the oceanic track system
under reduced separation minima. Secondly, the pilot would probably
check his CDTI display periodically during his flight, even if he
has not been alerted, because there may be proximity targets
displayed. (Targets satisfying the CDTI proximity advisory criteria
would not be brought to the pilot's attention via an aural alert,
because they would not represent a threat at that time.) Finally,
procedures are proposed for dealing with CDTI alerts. These
generally involve assessing the situation and negotiating a
resolution strategy with the pilot of the threat aircraft over the
air-to-air voice channel. Procedures appropriate for specific
geometries are suggested. The proposed pilot procedures are
described in detail in Section 7 and Appendix A of this report.

The oceanic CDTI concept as described above is promising for the following reasons:

(1) The need for reduced separation minima in oceanic areas is real and immediate.

(2) TCAS can support this concept with relatively straightforward modifications to the currently-defined system.

(3) If it is assumed that an airline would install the Minimum TCAS II for midair collision protection, regardless of whether or not the oceanic CDTI concept were adopted, then the airline can realize the oceanic cost savings for only the incremental cost of the TCAS II modifications.

(4) Many of the objections to the use of CDTI in other contexts are not applicable here. For instance, pilot workload is not a primary limitation in oceanic areas. Also, there should be no controversy about the pilot's role and how responsibility is divided between the air traffic controller and the pilot.

(5) It would be easy to assign a single VHF frequency and permit voice contact, since pilots shouldn't need to monitor any other VHF frequencies (except the emergency frequency, 121.5 MHz).

(6) Possible limitations of the TCAS surveillance system in high-density airspace are not a factor in the low-density oceanic environment.

(7) The TCAS surveillance system is an independent monitor that can provide protection against navigation errors or blunders, whatever the cause. Today there is no independent check of navigation, and the separation minima have been established to protect against rare instances of very large navigation errors.

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(8) Uncertainties about the effects of undetected large altimetry errors are largely eliminated in this concept, because only CDTI-equipped aircraft are permitted on tracks which involve reduced separation minima. The TCAS MOPS requires that an aircraft which carries TCAS must have an altimetry system meeting more stringent requirements than those that are currently imposed for flight in U.S. airspace.

(9) Because reduced separation standards would be applied only when all aircraft are equipped, most encounters would involve two CDTI-equipped aircraft. This provides a natural redundancy which would mean a high degree of protection from isolated equipment failures and errors in human judgment.

While the CDTI concept offers these advantages, it has some limitations and some areas of uncertainty at the present stage of investigation. The most significant of these are:

(1) What maximum surveillance range is actually required to support this concept? Can this range be achieved reasonably in the TCAS unit?

(2) What will be the actual incremental cost in production equipment to provide the modifications required to support the concept? Can this cost be recovered via fuel and other cost savings in a reasonable period of time?

(3) Is the bearing accuracy attainable with the Minimum TCAS II equipment adequate to support pilot use of horizontal resolution maneuvers?

(4) Can the production TCAS system be built with sufficient reliability and fault monitoring capabilities to support this concept?

(5) Can altimetry system accuracies sufficient to support reduced vertical separation using the oceanic CDTI concept be achieved?

(6) Can a method be devised for providing adequate separation in the face of heavy turbulence if vertical separation is reduced?

(7) What will actual aircraft densities be in the oceanic track system at peak periods? Are these densities high enough that there would be a voice frequency saturation problem?

(8) Would the frequency of CDTI alerts, or the monitoring required when they occur, produce an unreasonable increase in pilot workload under any circumstances?

(9) Do pilots have the ability to make sound judgments in the variety of situations which they might experience?

(10) Can the voice procedures and phraseology be standardized? How difficult would it be for pilots to master them? Could the resolution negotiation process be successfully conducted by a pilot who had a native language other than English?

(11) Can the pilot successfully resolve blunder encounters with unequipped targets without voice coordination, as called for in this concept?

As recommended in the final section of this document, data collection efforts, cockpit simulation experiments, and further analysis may help to answer many of these questions.

SECTION 5

STRATEGIES FOR REDUCING SEPARATION MINIMA

In this section, the selection of candidate schemes for reducing separation is discussed. The selections start with current oceanic separation minima, which are then reduced in one or more dimensions. The selected separation minima represent logical next steps in reducing aircraft spacing, and are subsequently used in estimating both benefits and alert rates for the oceanic CDTI system.

Current Oceanic Separation Minima

Track systems in oceanic areas are generally composed of parallel tracks with multiple flight levels on each track. Separation minima for these track systems are typically expressed as a set of three numbers: lateral track separation, longitudinal spacing, and vertical flight level separation. Any two aircraft must be separated by the minimum spacing in at least one dimension. Lateral separation is usually expressed in nautical miles, longitudinal spacing in minutes, and vertical separation in feet. In this document, each set of separation minima will hereafter be designated by these three numbers, separated by slashes. For instance, 30/10/2000 will indicate lateral track separation of 56 km (30 n. mi.), longitudinal spacing of 10 minutes, and vertical separation of 610 m (2000 ft). Composite minima, in which certain minimum spacings must be applied in two dimensions simultaneously, have also been used in oceanic track systems.

The current separation minima for two oceanic track systems are pertinent to this study: the North Atlantic (NAT) track system and

the Central East Pacific (CEP) track system. For the NAT track system, the current separation minima are 60/10/2000. The current CEP separation minima are 50/15/2000. The latter is actually a composite separation standard, since the flight levels used on alternate tracks are separated by 300 m (1000 ft) in a staggered fashion. In both systems, the nominal longitudinal spacing is adjusted by Mach numbers to safely account for differences in speed between aircraft on the same track and flight level.

Candidate Schemes for Reducing Separation

For the oceanic CDTI study, the current separation minima for the NAT track system (60/10/2000) were selected as a baseline against which sets of reduced separation minima could be compared. This selection was made because the NAT is a larger system than the CEP (carrying about four times the traffic), and because more traffic data is available for the NAT. Candidate schemes for reducing separation were generated basically by halving the baseline spacing in each dimension. Of the candidate schemes thus derived, the following four were selected for further evaluation:

(1) Reduce spacing by a factor of one-half in the vertical dimension only (yielding separation minima of 60/10/1000). Restrict traffic on each track to one direction only.

(2) Reduce only lateral spacing by a factor of one-half (yielding separation minima of 30/10/2000).

(3) Reduce only longitudinal spacing by a factor of one-half (yielding separation minima of 60/5/2000).

(4) Reduce both lateral and longitudinal spacing by a factor of one-half (yielding separation minima of 30/5/2000).

The first of these candidate schemes (vertical reduction only) has great potential for reducing flight costs, as will be shown

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later. This scheme was restricted to one-way tracks in order to
hold the alert rate at a manageable level and to limit the potential
for opposite-direction encounters. As indicated earlier, the use of
one-way tracks is consistent with common practice in the NAT.

The remaining three candidate schemes represent all combinations
of horizontal spacing reductions by a factor of one-half. It was
felt that each of these schemes should be feasible, in terms of
alert rates and safety levels, for use with the oceanic CDTI
system. It was further felt that reductions in vertical spacing
would cause a greater increase in potential conflicts than
reductions in any other dimension. For this reason, it was decided
not to consider simultaneous reductions in both vertical and
horizontal separation.

In addition to the four candidate strategies listed above, a
number of other strategies were considered briefly and discarded.
For example, composite separation minima were considered, but were
deemed too complex for analysis in this limited study. Spacing
reductions of more than one-half were also briefly considered. In
the vertical dimension, the limited accuracy of today's altimetry
systems makes this idea implausible. Lateral spacing reductions of
more than one-half are probably not feasible because of the limited
ability of Minimum TCAS II to recognize, and avoid alerts for,
encounters having large horizontal miss distances. Reductions of
more than one-half in longitudinal spacing may be possible with the
oceanic CDTI system, but it was felt that such reductions could
result in a type of stationkeeping operation which is inappropriate
for transoceanic flight.

The four strategies listed above were subsequently evaluated in
terms of potential benefits, alert rates, and transition

strategies. The strategies were compared with each other and with
the baseline separation minima in terms of overall merit.

SECTION 6

MODIFICATIONS TO TCAS II

This section describes the modifications to TCAS II which would be necessary to implement the avionics portion of the oceanic CDTI concept. These modifications include increased surveillance range, new message formats and protocols for acquisition of CDTI-equipped intruders, logic modifications, and new display requirements. Unless otherwise noted, the changes described below apply only to the oceanic mode of operation.

New Message Formats and Protocols

As mentioned in the introduction, the oceanic CDTI concept calls for one CDTI-equipped aircraft to be able to identify another CDTI-equipped aircraft and to acquire its call sign. These requirements can be met by the use of an air-to-air interrogation and reply sequence using long (112-bit) Mode S message formats.

The current TCAS design already provides a means for TCAS II to identify another aircraft's TCAS equipage, if any. Dedicated bits in the Mode S air-to-air surveillance reply formats are reserved for this purpose. TCAS equipage inherently includes the ability to transmit and receive air-to-air interrogations and replies using long message formats. Therefore, a TCAS-equipped aircraft will always respond to an interrogation with a long reply if a long reply is requested. These facts help to simplify the addition of a CDTI message protocol.

Figure 2 shows the formats of the long Mode S air-to-air messages used by TCAS. Each long format contains a 56-bit field (designated MU for interrogations and MV for replies) which can be used for general-purpose messages. The first 8 bits of this field form a subfield (designated UDS for interrogations and VDS for replies) which indicates the type of message. The use of the remaining 48 bits depends on the message type.

The CDTI message protocol might work as follows: Once a CDTI-equipped aircraft has established a track on a TCAS-equipped intruder, it sends a long interrogation to the target aircraft with the RL field set to 1 (requesting a long reply). A special UDS code is used to designate the interrogation as a CDTI call-sign request. The remainder of the MU field is not used. The target aircraft, if CDTI-equipped, responds with a long reply containing a special VDS code to indicate CDTI equipage. (This special VDS code might be the same as that used in the UDS subfield of the interrogation.) The target aircraft's call sign is encoded in the remaining 48 bits of the MV field. The target aircraft uses an identical interrogation-reply sequence to obtain the call sign of own aircraft. If the target aircraft is not CDTI-equipped, it still sends a long reply, but the 56-bit MV field is left empty (is set entirely to zeros). All other fields in the interrogation and reply are set as specified in the TCAS II MOPS (Reference 2).

The encoding of an aircraft's call sign could be done in one of several ways. One way would simply be to encode each character into a separate 6-bit subfield. An alternative method would be to encode the call sign according to the Unified Data Link (UDL) conventions which are currently under joint development by the FAA and Eurocontrol. Either method would allow up to eight characters

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INTERROGATION

FIELD	UF	--	RL	AV	AQ	--	MU	AP
LENGTH (BITS)	5	3	1	4	1	18	56	24

Definitions:

UF = Uplink format number (=16)
RL = Reply length
AV = TCAS maneuver advisory
AQ = Acquisition flag
MU = Interrogation message
AP = Address/parity

REPLY

FIELD	DF	VS	—	SL	—	RI	—	AC	MV	AP
LENGTH (BITS)	5	1	2	3	2	4	2	13	56	24

Definitions:

DF = Downlink format number (=16)
VS = Vertical status
SL = TCAS II sensitivity level report
RI = Air-to-air reply information
AC = Altitude code
MV = Reply message
AP = Address/parity

Figure 2. - Long Mode S air-to-air message formats.

to be encoded, which should be sufficient. (The International Civil Aviation Organization's model flight plan allows a maximum of seven characters to be used for aircraft identification.)

The entry and readout of an aircraft's call sign is an eminently practical idea. For commerical operations, an airline's two-letter designator and flight number could be keyed in by the flight crew at the beginning of the flight. For private aircraft, the registration marking (tail number) could be semi-permanently encoded via rotary switches or other means. The automatic readout of an aircraft's call sign is not a new idea, as it is already being planned as an option for Mode S ground stations.

Logic Modifications

A number of modifications to the TCAS II logic would be necessary to implement the oceanic CDTI concept. One change would be the enlargement of the boundaries for issuing a proximity advisory. This would be necessary to allow a pilot to take nearby traffic into account when considering a maneuver for any reason. Specific parameters for the CDTI proximity advisory have not been selected in this study; however, this subject is discussed later in this section under the heading of "Display Requirements".

The most important TCAS logic modification would be the creation of a "CDTI alert" by enlarging the boundaries for a TCAS threat advisory. Under the oceanic CDTI concept, the resolution of an apparent conflict should be an infrequent, but routine matter. Therefore, the boundaries for a CDTI alert should allow the pilots enough time to negotiate a resolution strategy and to make routine resolution maneuvers, when required. Parameter values should allow for a worst-case situation. Each of these requirements will be

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considered in the subsections which follow. Reasonable parameter
values for the CDTI alert will be determined.

   Time factors. — A CDTI alert must give the pilot sufficient time
to: (1) recognize the alert and consult the traffic display to
assess the situation, (2) establish voice contact with the pilot of
the threat aircraft, if necessary, and agree upon the action to be
taken, and (3) make a routine maneuver, if necessary, to ensure safe
separation. The time required for each of these activities will be
considered separately.

   An FAA study of pilot response delays to collision avoidance
advisories was conducted in 1979 (Reference 4) using cockpit
simulation. In this study, the mean response time was found to be
about 5.6 seconds, with a standard deviation of 2.1 seconds. To
allow for slow response, plus a few extra seconds for studying the
traffic display, a value of 15 seconds will be assumed for pilot
response to a CDTI alert.

   The time required for two pilots to establish radio contact and
agree upon a resolution strategy depends upon a number of factors,
including conflict geometry. For this limited study, a number of
sample conversations were enacted and timed with a stopwatch. On
this basis, it was estimated that 45 seconds would normally be
adequate for such a conversation. No particular accuracy is claimed
for this result, as only cockpit simulation could provide a more
accurate estimate of the actual time requirement.

   The time requirement for resolution maneuvers, based upon
worst-case geometry, is estimated in the following subsection.

Analysis of Worst-Case Geometry. - The time required for a routine resolution maneuver depends upon several things: the aircraft velocities, the conflict geometry, the desired minimum separation, and one's definition of a routine maneuver. For this study, it was decided somewhat arbitrarily that a routine vertical maneuver would consist of no more than 0.25 g acceleration to a final climb or descent rate of 2.5 m/s (500 ft/min). Likewise, it was decided that a routine horizontal maneuver would consist of a turn using a bank angle of no more than 0.35 radians (20 deg), achieved with a roll rate of 0.087 rad/s (5 deg/s). The desired minimum separation was chosen to be 9.3 km (5 n. mi.) laterally and 230 meters (750 feet) vertically. These values should allow safe passage, while helping to prevent the issuance of positive TCAS II resolution advisories in most cases. Finally, a maximum airspeed of 310 m/s (600 knots) was assumed for each aircraft.

Figure 3 illustrates the worst-case vertical and horizontal geometries selected for analysis. In calculating the time requirements, it was assumed that the aircraft perform complementary resolution maneuvers. The vertical case involves two coaltitude aircraft converging head-on. It was assumed that the descending aircraft can achieve the desired vertical rate of 2.5 m/s (500 ft/min), but that the climbing aircraft can achieve only half of this rate. The horizontal case also involves two head-on aircraft on a collision course. In this case, it is assumed that both aircraft can achieve the desired bank angle and roll rate. In the horizontal geometry, both aircraft were assumed to be flying at the maximum airspeed of 310 m/s (600 knots).

Analysis of the vertical case, as described above, indicates that approximately 60 seconds are required to achieve the desired separation of 230 meters (750 feet). In the horizontal case, it can

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VERTICAL

Aircraft #1

1.27 m/s
(250 ft/min)

Collision course

Aircraft #2

0.25 g
acceleration

0.25 g
acceleration

2.54 m/s
(500 ft/min)

HORIZONTAL

Aircraft #1
310 m/s
(600 knots)

Bank angle:
0.35 rad
(20 deg)

Aircraft #2
310 m/s
(600 knots)

Collision course

Roll rate:
0.087 rad/s
(5 deg/s)

Bank angle:
0.35 rad
(20 deg)

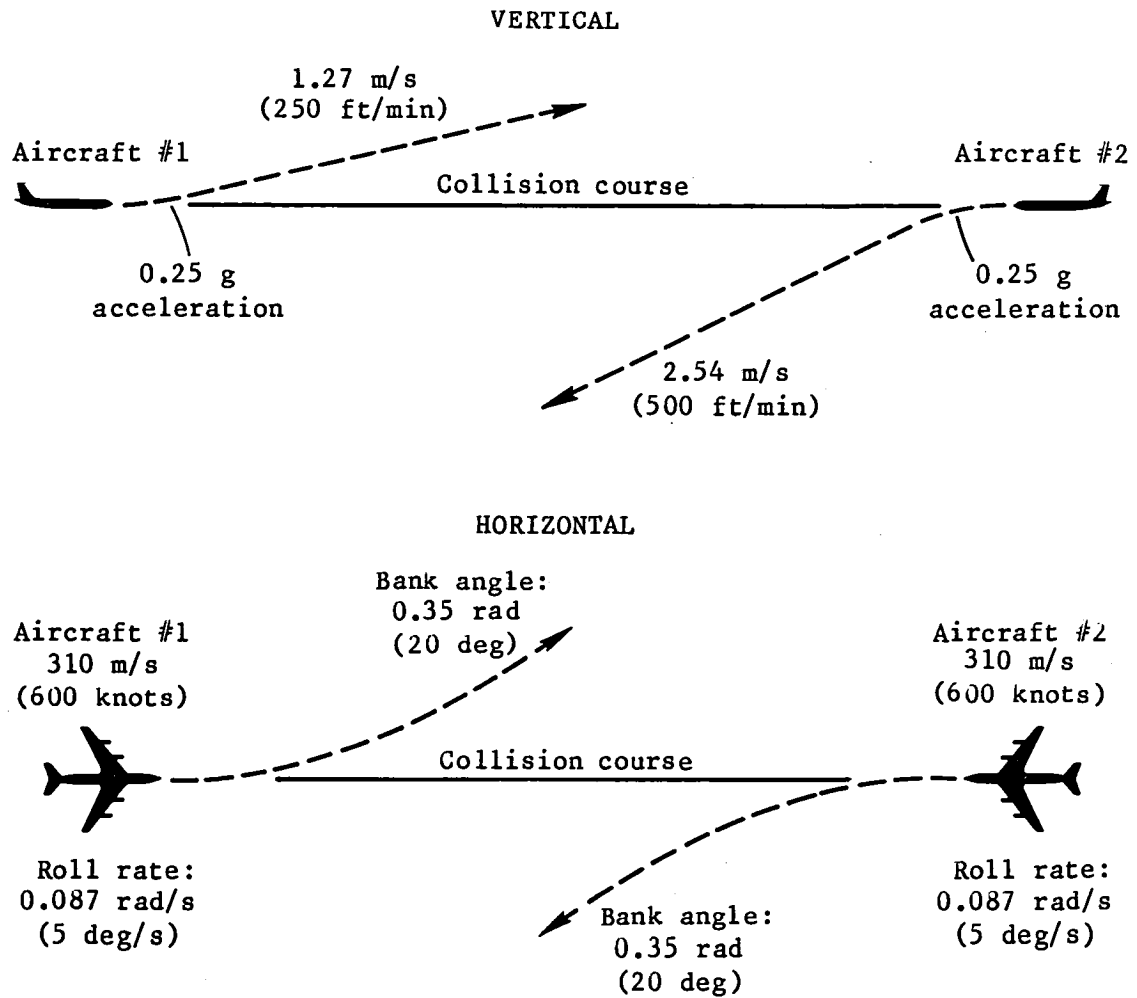Roll rate:
0.087 rad/s
(5 deg/s)

Figure 3.–Worst-case geometries.

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be shown that roughly 54 seconds are needed to achieve the desired lateral separation of 9.3 km (5 n. mi.). Choosing the larger of these two values yields a maximum maneuver time requirement of 60 seconds.

When the time requirements for pilot response, voice communications, and routine maneuvers are combined, a total warning time of 120 seconds is obtained for the worst-case geometry. Because of the very conservative selection of a worst-case geometry, this figure is believed to represent an upper bound on the required warning time. Simulation may show that a smaller warning time is adequate, especially in a one-way track system where the probability of a head-on conflict is very small.

Selection of CDTI Alert Parameters

In this subsection, parameters are derived for the CDTI alert in both the horizontal and vertical dimensions.

Horizontal parameters. - Horizontal boundaries for TCAS II advisories are usually expressed in the form:

$$\text{Tau (modified)} = \frac{R - D}{-V_R} \leq T_h \tag{1}$$

where R is current range to the target and V_R is range rate of the target. The formula includes two parameters, D and T_h. D is a distance modifier, and T_h is a modified-tau threshold. If all encounters involved a high closure rate, only the T_h parameter would be required. The distance modifier D provides extra protection against slow-closing intruders which may unexpectedly maneuver toward own aircraft.

For the CDTI alert a distance modifier of 9.3 km (5 n. mi.) was chosen. This value seemed to provide adequate protection against slow-closing intruders. Using this value for D, a value for the modified-tau threshold can be computed, based upon 120 seconds warning prior to closest approach for the worst-case horizontal geometry. For a collision course, true tau ($-R/V_R$) exactly equals the time to closest approach. Therefore, substituting D = 9.3 km (5 n. mi.) and V_R = -0.62 km/s (1200 knots) into equation (1), letting $-R/V_R$ equal 120 seconds, and solving for T_h yields a value of 105 seconds for the T_h parameter.

As pointed out earlier, Minimum TCAS II cannot readily filter out encounters with large miss distances based purely upon tau logic. This is why tau-dot logic has been tested for use with TCAS (see Appendix C). In a parallel track system, encounters involving large miss distances will be the rule rather than the exception. Therefore, it is considered important that a horizontal miss distance filter such as the tau-dot logic be used for filtering CDTI alerts. In the rest of this report, tau-dot logic with a threshold of 0.96 is assumed to be included as part of the CDTI alert logic.

Vertical parameters. - In the vertical dimension, the TCAS II threat advisory parameters include both a relative altitude threshold and a vertical tau threshold, as previously explained. For high-altitude encounters, an alert may be issued if two aircraft are within 370 m (1200 ft) of each other, or are projected to cross altitudes within 45 seconds. In the oceanic track system, the relative altitude threshold is the more important parameter, since most encounters will involve aircraft in level flight or with very modest vertical rates. The tau threshold becomes more important when one aircraft is transitioning to another altitude.

The existing TCAS II vertical alert parameters account for altimetry system errors, as well as Mode C quantization error. Since these errors are no different for over-ocean flight than for high-altitude flight in general, it seems reasonable that the current vertical parameters for threat advisories not be increased further for CDTI alerts. With these parameters, any vertical closure rate of 3.0 m/s (600 ft/min) or less would provide at least two minutes of warning in the vertical dimension.

Table 1 summarizes the CDTI alert parameters chosen for this study.

Increased Range and Power Requirements

The maximum surveillance range for TCAS II is currently about 37 km (20 n. mi.). The requirement for an increase in this range would depend on the manner in which separation minima were reduced. For the worst-case horizontal geometry (Figure 3), 105 seconds to 9.3 km (5 n. mi.) occurs at a range of 74 km (40 n. mi.). Therefore, if a method of reducing the separation minima is proposed which results in an increased likelihood of head-on encounters, then the effective range of TCAS would have to be approximately doubled. On the other hand, if reduced minima are proposed in a way that does not increase the likelihood of head-on encounters (for instance, reduced vertical spacing using only one-way tracks), then little or no increase in range may be required.

In the latter situation, a head-on encounter could only occur because of a major blunder. Such a blunder would be no more likely to occur than in today's system. While it would be desirable to have as much warning as possible in the event of such a blunder, it would not be necessary for the TCAS system to have a range of 74 km

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TABLE 1. - CDTI ALERT PARAMETERS

Horizontal Dimension

Distance modifier, D, km . . . . 9.3 (5 n. mi.)

Horizontal tau threshold, T_h, s 105

Tau-dot threshold, d 0.96

Vertical Dimension

Relative altitude threshold, A_r, m . . . . 370 (1200 feet)

Vertical tau threshold, T_v, s 45

(40 n. mi.). Even if the range of TCAS were not increased beyond 37 km (20 n. mi.), safety would be greater than today's system, since the TCAS unit would provide at least a one-minute warning in such a blunder situation.

From the viewpoint of the power and range required of TCAS, then, it is clearly advantageous to reduce separation minima in a way that does not increase the likelihood of head-on encounters. In order to help determine the feasibility of reducing separation minima in ways that do increase this likelihood, the prospects for increasing the range of TCAS will now be explored.

Since range is proportional to the square root of power, then doubling the range of TCAS would nominally require a fourfold (6 dB) increase in both the effective radiated power and the receiver sensitivity. (The idea of requiring increased transponder power or sensitivity over the ocean was rejected as being impractical because it would require modifications to transponders as well as to TCAS units.)

To determine the practicality of doubling the range of TCAS, several TCAS hardware design engineers were consulted. From these conversations, two important things were learned. First, an increase of 6 dB in receiver sensitivity should not be a major problem; TCAS receiver sensitivity is not maximized, but is adjusted to provide reliable operation at the maximum design range without allowing undue interference. Second, an actual increase of 6 dB in radiated power would present a serious design problem; the transmitters used on current TCAS engineering models are state-of-the-art, solid-state devices which operate near their design limits. An increase of more than 1-2 dB in transmitter output power is unlikely in the near future with a solid-state

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design. (A new transmitter and power supply design might provide greater output power, but size, weight, and especially cost might present major problems.)

In order to double the range of the interrogation link, then, it may be necessary to achieve an effective increase of 4-5 dB in radiated power over and above any increase in transmitter output power. One means of achieving this increase, at least in part, would be to reduce power losses between the transmitter and the antenna. A contribution of 1-2 dB of this amount could be achieved by using cable having less power loss. (Up to 3 dB of cable losses are tolerated with the current engineering models.) Another 1 dB might be achieved by reducing loss in the high level step of the whisper/shout attenuator.

Another means of increasing the effective radiated power is with increased antenna gain (using a narrower beam). It might be possible to achieve several decibels more antenna gain without introducing excessive cost and complexity.

Finally, in contrast to what was said above, it might not be necessary to increase the effective radiated power by a full 6 dB. The current TCAS design achieves its maximum design range with a link margin of about 6 dB. (Link margin is the amount by which the received power level exceeds the receiver sensitivity for the average transmission.) This link margin is designed into the system to provide high reliability at the maximum design range. It must account for such things as irregularities in antenna radiation patterns, manufacturing tolerances on transmitter and receiver components, and signal fades due to antenna shielding during banking maneuvers.

For the oceanic CDTI system, a smaller link margin might be acceptable for the following reasons:

(1) Reliability at maximum range is less important for CDTI alerts than for resolution advisories; a delay of several seconds in receiving a two-minute warning is less critical than the same delay in receiving a resolution advisory at 30 seconds before closest approach.

(2) The high-altitude cruise regime prevalent in an oceanic track system would very rarely have aircraft maneuvering with significant bank angles, meaning that very few deep antenna fades should be experienced.

(3) In the baseline CDTI system being considered here, all aircraft operating on CDTI-only tracks would be TCAS-equipped, and therefore would be using both top and bottom-mounted antennas. A 1977 study by M.I.T. Lincoln Laboratory (Reference 5) indicated that diversity antennas on both aircraft improves link reliability significantly (1-3 dB less link margin required for the same level of reliability).

In summary, it is not entirely obvious how difficult or how costly it would be to double the range of the TCAS interrogation link. The near-term ability to increase transmitter power is limited. However, some combination of reduced power losses, increased antenna directivity, and decreased link margin might make up the difference at a reasonable cost. Further investigation is required in this area.

Display Requirements

This subsection discusses the content and form of information presented to the pilot. It is assumed that the basic pilot display

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would consist of a Plan View Display (PVD) of nearby air traffic on a Cathode Ray Tube (CRT) or other suitable device.

Display range. – The pilot's display must be designed to show not only aircraft for which a CDTI alert is issued, but also nearby aircraft which may affect the pilot's decision on maneuvers. To begin with, the range limits must allow the display of any aircraft for which a CDTI alert can be issued. This would mean as much as 74 km (40 n. mi.) ahead, 42 km (23 n. mi.) to each side, 22 km (12 n. mi.) behind, and 760 m (2500 ft) above and below. In addition, it is desirable to show aircraft which are nearby, but which are not closing rapidly enough to trigger a CDTI alert. This can be brought about by expanding the boundaries for the TCAS proximity advisory.

No specific parameters were developed for the CDTI proximity advisory in this study. However, these parameters should be limited, to some extent, to be consistent with the separation minima, in order to ensure that the screen is not cluttered with unimportant targets. For instance, if the lateral separation minimum is 56 km (30 n. mi.), then occasional separations of 46 km (25 n. mi.) or less may be common. Therefore, the logic for CDTI proximity advisories should limit lateral range to something on the order of 37 km (20 n. mi.) in this case. In the longitudinal dimension, a separation minimum of 5 minutes would mean a spacing of approximately 74 km (40 n. mi.) between aircraft. Therefore, range limits of 56 km (30 n. mi.) ahead and 37 km (20 n. mi.) behind might be appropriate for the CDTI proximity advisory. In the vertical dimension, it would be desirable to show aircraft which are one occupied flight level above and below own aircraft, so that the pilot will be aware of any aircraft in his vicinity at an adjacent flight level. In such instances, he could then monitor the heightkeeping performance of his aircraft particularly closely. Hence, a limit of 1.5 times the standard vertical spacing might be sensible.

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As an alternative to the fixed display limits, variable limits might be worthwhile to consider. The appropriate limits might be selected automatically upon the issuance of a CDTI alert, or manually, by the pilot, for routine monitoring.

Data blocks. - Each symbol on the display screen representing another aircraft should be accompanied continuously by a data block showing that aircraft's altitude and call sign. A special symbol (such as a question mark) should be used in place of the call sign to indicate an aircraft not equipped with CDTI. Altitude could be displayed either as an absolute flight level for the target or as a relative indication of the target's altitude with respect to own (i.e., hundreds of feet above or below own flight level). Each method has its advantages and disadvantages. The current consensus among TCAS designers is that relative altitude is superior for collision avoidance purposes. Because of the frequent need to exchange and compare assigned and actual flight level data, however, it seems that absolute values would be preferred for the oceanic CDTI application. Other items of information might be useful in the data block. For instance, an upward or downward arrow following the altitude could be used to indicate that a target aircraft has a significant vertical rate. It is also desirable that the data block flash, and/or be presented in a special color, during a CDTI alert for that aircraft. A final recommendation is that the display software should have provisions to prevent the overlap of data blocks.

Other display features. - The following additional display features should be given serious consideration for use with the oceanic CDTI system:

(1) Trails - It may be desirable to display a short trail of an intruder's previous positions as an aid in estimating speed

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and direction of flight. One potential problem with this idea is that the bearing accuracy of Minimum TCAS II is limited. (The standard deviaton of bearing error is roughly 8-9 degrees.) This could tempt a pilot to put more faith in the apparent heading of an intruder than he should.

(2) Range ring – It may be desirable to include a range ring of perhaps 9.3 km (5 n. mi.) radius about own aircraft's positon as an aid in estimating horizontal distances. Optionally, the size of the range ring could be selectable (automatically or manually).

(3) Aural annunciation – Current plans call for each new TCAS threat advisory to be accompanied by an aural annunciation of moderate urgency. This feature must be retained for CDTI alerts.

Figure 4 shows an example of a CDTI display screen. In this example, own heading is straight up, altitudes are presented as absolute flight levels, and position trails are used. Own flight level appears below the symbol for own aircraft.

Other Equipment Modifications

In normal operation over land areas, the TCAS II system serves only as a backup to the regular air traffic control system for ensuring aircraft separation. In the oceanic CDTI concept, however, more routine use is made of the TCAS system. This increased dependence calls for a high degree of reliability. Several self-test and monitoring features are already required of Minimum TCAS II to help assure that failures are recognized. One additional requirement is placed on the TCAS unit for supporting oceanic CDTI. This requirement is for a push-to-test switch which the pilot can activate while airborne to provide a momentary display of all targets being tracked by his TCAS. These can be displayed in either
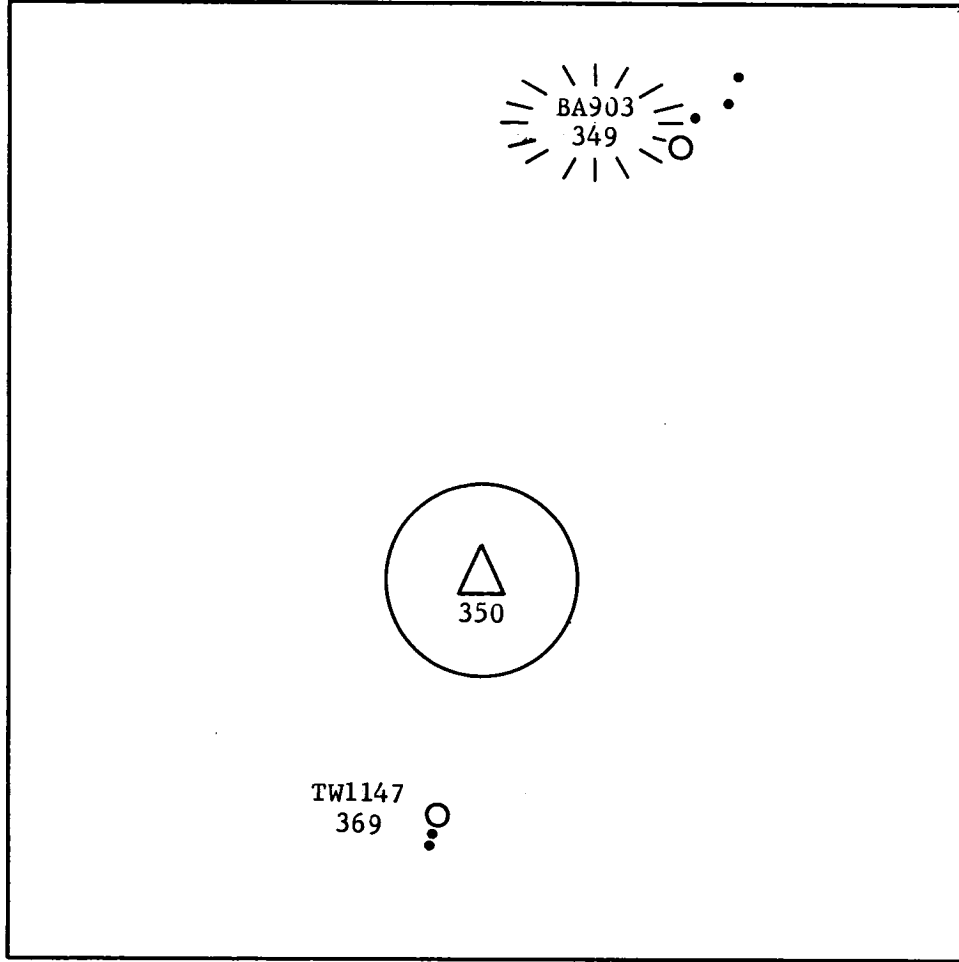
Figure 4.–Example of CDTI display screen.

a tabular form or with position symbols on the CDTI display. The pilot would be required to activate this switch before entering the oceanic track system and to observe that his TCAS actually had one or more targets in track.

Reliability might also be enhanced by providing redundancy for critical system components. It must be remembered, however, that in the baseline CDTI system, all aircraft operating on CDTI-only tracks would be CDTI-equipped. It is extremely unlikely that the CDTI systems on both aircraft in a conflict would fail simultaneously. This natural redundancy adds a great deal to system reliability.

In addition to the above modifications, the CDTI unit (or perhaps the Mode S transponder, if it is a separate unit) must have a provision for the pilot to enter his ATC call sign once per flight, or else the call sign must be permanently encoded.

SECTION 7

PROPOSED PILOT PROCEDURES

Possible procedures for use of a CDTI system in oceanic areas
are described in this section. These procedures are considered
feasible and reasonable by the authors; of course, if CDTI were to
be adopted for oceanic use, final procedures would be developed by
an ICAO committee after extensive study and review.

Possible procedures to be used prior to reaching oceanic
airspace are described first. Those used within oceanic airspace
follow.

Procedures Undertaken Prior to Reaching Oceanic Airspace

Greater dependence is placed upon a TCAS unit supporting a CDTI
service of the type described in this report than on a TCAS unit
used in airspace subject to radar control. This is true because the
separation minima have been reduced due to the use of TCAS in the
former case, whereas they have not been changed in the latter.
Ensuring proper operation of TCAS units supporting over-ocean CDTI
service is important because of this greater dependence on the
equipment. For this reason, the pilot would be required to perform
a pre-flight test of the TCAS unit and to observe the correct
results as indicated by the manufacturer's procedures. (Such a test
capability, called a self-test, is required to be implemented in a
TCAS unit by the TCAS MOPS (Reference 2).) If the TCAS unit were to
fail the pre-flight test, the pilot would be prohibited from flying
an oceanic track using reduced separation.

Prior to takeoff the pilot would be required to enter the call
sign for the flight into his TCAS avionics (or into the associated

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Mode S transponder if the transponder is a separate device). The call sign would be the same as that used in filing flight plans and in voice communications with air traffic control (ATC).

Just prior to or immediately after takeoff the pilot would switch his TCAS unit to normal TCAS operation. (This is assuming that the country from which he departs permits operation of TCAS in its airspace.) Normal TCAS operation means use of the standard power levels and conditions spelled out in Reference 2. Assuming that the pilot departs from airspace where radar control is being exercised, the pilot would observe normal ATC procedures appropriate for a radar control environment.

A second test to provide a further indication of correct operation of the TCAS unit would be required after takeoff. The pilot would be required to activate the pust-to-test switch while his TCAS was operating in the normal mode (as opposed to the oceanic mode) and to observe that some targets were in track.

Once the pilot had been released on his assigned track and had been given clearance to leave the ATC VHF voice frequency, he would configure for oceanic CDTI operation. He would switch his TCAS unit to the oceanic mode and would tune his VHF radio to the CDTI monitoring frequency. He would then observe the procedures described in the following subsections.

Procedures Used Within Oceanic Airspace

Most of the discussion in the following subsections deals with the procedures to be followed when a target is displayed that is CDTI-equipped and when both own aircraft and the target are flying assigned tracks. There is some possibility of the pilot encountering a target under other conditions, and procedures to cover these situations are also discussed briefly.

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Procedures When the TCAS System Has Not Given a CDTI Alert

In routine conditions, the pilot may wish to glance at his CDTI display periodically. From time to time it may happen that there will be a CDTI proximity advisory displayed for a target. The most likely circumstance giving rise to this display is one in which own aircraft and the target are flying the same track in the same direction at adjacent flight levels. In this situation, the target may remain on the display for an extended period. The pilot may want to check the other aircraft's position periodically. If the target is at a very close horizontal range, the pilot will want to ensure that his own aircraft remains close to its assigned flight level and will want to confirm that the target is also following its assigned flight level closely.

During times of heavy turbulence when it may be difficult to prevent significant excursions from assigned flight level, it should be helpful for the pilot to know of the presence of another aircraft. Using the CDTI display, the pilot might want to offset his course just slightly to the right or left of the track centerline to provide an extra dimension of protection against an extreme excursion from assigned flight level.

Although the pilot is not required to make voice contact for a proximity advisory, the pilot may still wish to do so and to confirm that the target's flight level shown on his own display is the same as that being displayed in the target's cockpit. (There are certain types of altimeter and encoding system errors that can result in the flight level reported by the target's transponder being different from the flight level displayed on the altimeter in the target's cockpit.) Care should be taken to avoid excessive conversation on the designated VHF frequency, but brief conversations when the channel is otherwise clear could be permitted.

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The display of a proximate target can also be useful for monitoring the target after action has been taken as the result of a CDTI alert for that target. The CDTI alert occurred because the target was close or converging. Once action has been taken and the aircraft are separating, the CDTI alert condition will be taken away, but the CDTI proximity advisory will keep the target displayed until it is out of range.

Procedures When a CDTI Alert Occurs

There are a variety of situations that may exist when a CDTI alert occurs. There are several steps which should be taken initially in any of these situations.

The first step following the CDTI alert should be to assess the urgency of the situation. In the great majority of cases there should be sufficient time to make voice contact with the other pilot and to mutually agree on a resolution. But in a few cases, immediate action may be required. If this is the case, the pilot should take whatever action appears to be warranted and should immediately make a call on the designated VHF frequency in the clear to indicate his call sign and the actions he is taking. As soon as possible he should try to contact the other pilot and agree on the next steps to be taken.

Assuming that the situation is not critical, the pilot should attempt to make voice contact with the pilot of the target aircraft. He should first establish whether or not the target's TCAS also is providing a display of his own aircraft in the target's cockpit. If so, he should proceed to work out a resolution with the other pilot. Depending upon the nature of the encounter, it may be helpful in this process to exchange information about the assigned track, flight level, Mach number, or heading.

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If the target's TCAS does not have own aircraft displayed, the pilot of own aircraft should query the other pilot for his assigned track, flight level, and Mach number, and should then develop a suggested course of action for his own aircraft. This should be communicated to the target aircraft along with a suggested course of action for the target aircraft, if appropriate. A pilot should not view himself as giving instructions to the other aircraft, since the CDTI display on own aircraft may not show all traffic in the vicinity of the target aircraft. He would only offer a suggestion when there was an obvious course of action for the target aircraft. An example would be when the target aircraft was observed to be 300 feet below its assigned altitude. In this case, the suggestion could be made that the pilot of the target aircraft climb to his assigned altitude.

If the target's TCAS does have own aircraft displayed, the pilots should agree on the resolution and then begin to carry it out. As they do so, they may wish to confirm that each TCAS has the same view of the situation. This can be done by verbally exchanging the flight level of the target and the range of the target as seen by each TCAS.

If the pilot is unable to contact the pilot of the target aircraft on the designated frequency, he should determine his best course of action using the available information. He should then communicate his intentions along with his call sign in the clear. He should monitor the progress of the resolution on his CDTI display and should continue to try to establish voice contact with the target aircraft.

The discussion thus far has assumed that own pilot was the one to initiate voice contact. Often, the other pilot may be first to make contact. When this happens, own pilot should check his CDTI

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display to see if the other aircraft is displayed. If not, the
pilot should.respond to all communications from the other pilot and
should check his current flight level, Mach number, and position
against their assigned values. If own aircraft is off the assigned
values, own pilot should suggest that he return to the assigned
values and should do so after the other pilot agrees. In most
cases, the target will appear shortly after the other pilot has
initiated voice contact, and own pilot will be able to monitor the
progress of the actions.

If the target aircraft is displayed at the time the other pilot
initiates voice contact, own pilot should respond to questions and
should check his own position against his assigned flight path. He
should mutually agree to a course of action and monitor the progress
of the resolution.

Once the situation has been restored to normal, the pilot should
attempt to understand why the TCAS provided a CDTI alert in this
situation. If a navigation error is involved, the cause could be
flight technical error, measurement error, or a combination of the
two. Flight technical error is when the basic position, flight
level, or Mach number measurements are correct, but the aircraft,
because of autopilot or manual error, has not closely followed the
assigned flight path. In this case the cockpit instruments will
show that the aircraft is not on the assigned flight path.
Measurement error is when the navigation instruments indicate that
the aircraft is on the correct flight path, but they are actually in
error. In most cases, the actual cause of the CDTI alert should be
evident to the pilots of the two aircraft if they exchange
additional information such as latitude/longitude coordinates, TCAS
range, or other cockpit indications. If the cause can be attributed
to measurement error in one aircraft, the pilot should make a note
of the particulars and have the appropriate equipment inspected at

his destination. Depending upon the nature and severity of the problem, the pilot may also consider coordinating a change of flight plan with the oceanic control system in order to fly on tracks using normal rather than reduced separation, or to depart from the track system altogether.

Appendix A contains additional pilot procedures appropriate for specific encounter geometries.

Procedures for an Encounter With a Target Not Equipped With CDTI

The TCAS unit is able to track aircraft which have only an operating ATC beacon transponder, as well as aircraft which are equipped with TCAS. The former will be referred to as CDTI – unequipped or just unequipped aircraft. (There is the possibility that some aircraft could operate on the oceanic track system with TCAS II equipment that does not have the oceanic mode implemented. Such equipment would be technically interoperable with the TCAS unit having the oceanic mode. If this normal TCAS II equipment were operated in the oceanic track system, additional procedures to handle these interactions would have to be developed. For the moment, this possibility is overlooked.) All aircraft operating within the oceanic track systems are required to carry beacon transponders and, as a matter of practice, the airlines keep them turned on throughout their oceanic flight. Thus, all aircraft operating in the oceanic airspace are potentially able to be tracked by TCAS.

In the concept described in this document, reduced separation would not be used between CDTI-equipped and unequipped aircraft. Nonetheless, there could be large navigational errors that cause an unequipped aircraft to generate a CDTI alert or CDTI proximity advisory. The TCAS unit would use the same criteria to determine

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when a target qualifies for a CDTI alert or a CDTI proximity
advisory for both equipped and unequipped targets. However,
different symbols could be used to represent equipped and unequipped
targets on the display. There would be no call sign displayed for
unequipped targets.

It has been a deliberate decision not to make provisions for
dealing with unequipped aircraft in the baseline concept for oceanic
CDTI. The idea of extending the concept to include unequipped
aircraft is briefly explored in Section 13 of this report. However,
it is felt that the advantages of positive voice contact and of the
pilots in both aircraft being able to view the encounter geometry
independently would be extremely important in allowing users to gain
confidence in the concept. Once experience with the concept as
presently proposed has been gained, the decision to include
unequipped features in the concept can be revisited.

Trying to establish voice contact with an unequipped target
would be awkward at best. Trying to communicate via a query such as
"Aircraft in the vicinity of 51 degrees North and 54 degrees West at
flight level 330, this is XYZ 53, do you read?" would require a long
time for a response and would preoccupy the pilot of the
CDTI-equipped aircraft. It is felt that the advantage of
coordinating actions through such a voice procedure might be
outweighed by the complexity of the procedure. However, it is
thought that there is a safety advantage to displaying an unequipped
target when it satisfies the CDTI alert or CDTI proximity advisory
criteria. Because the normal separation minima would be applied
between equipped and unequipped aircraft, the appearance of an
unequipped target on the display implies that there has been a
larger navigation error or blunder than would be the case for an
equipped target.

No detailed procedures for responding to a CDTI alert against an unequipped target can be suggested. In general, the pilot should study the display for a brief time, if possible. If it appears that the target is maintaining level flight, the pilot may prefer to change altitude. Otherwise, the pilot should choose an action that would appear to provide the most positive separation in view of the target's observed position and velocity history. The pilot should notify the oceanic control system of the encounter and convey the details as soon as the encounter has been resolved.

Procedures if a TCAS Resolution Advisory Appears

When the oceanic CDTI system is operated in the oceanic mode, it would use the previously described logic to determine CDTI alerts and CDTI proximity advisories. It is also proposed that the resolution advisory logic that is used in the normal TCAS mode continue to be used without modification in the oceanic mode. Under these conditions, the appearance of a TCAS resolution advisory in the oceanic mode would be a very uncommon event. It is even less likely that such a resolution advisory would contradict pilot-negotiated resolution actions. The following describes the suggested procedures to be used when a TCAS resolution advisory appears in the oceanic mode.

If a TCAS resolution advisory appears, there would usually have been a CDTI alert on the same target at an earlier time. In this case, it is likely that the pilot has already made voice contact with the other pilot and has agreed on a course of action. If so, the pilot may have more information available than the TCAS system. Also, if the pilot of either aircraft had made a maneuver as a result of voice coordination just at the time that the TCAS unit selected a resolution advisory, the TCAS resolution advisory could

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be invalid because it was based on the geometry before the maneuver. For these several reasons, the pilot would not be bound to strictly observe the TCAS resolution advisories. However, at the time the resolution advisory first appeared the pilot would be required to quickly reassess the situation, taking into account the resolution advisory being displayed and all other information available to him. He should realize that it is likely that the TCAS in the other aircraft has also displayed a resolution advisory. The two TCAS units have conducted electronic coordination to ensure that one aircraft has displayed a "climb" advisory and the other has displayed a "descend" advisory. He should consider whether some other course of action is now required. The fact that the resolution advisory came up at all may imply that the previous resolution action is not producing adequate separation. It certainly implies that the aircraft are close or are converging rapidly and that immediate attention is required.

In unusual situations, a TCAS resolution advisory might appear with no previous warning. (An example of such a situation might be when another aircraft initiates a sudden rapid descent from an altitude of 760 m (2500 ft) or more above own aircraft. By the time the TCAS unit has recognized the rapid descent, the criteria for both a CDTI alert and a TCAS resolution advisory could have been satisfied.) If this happens, the pilot should quickly assess the CDTI display and the resolution advisory and, if the resolution advisory seems reasonable, should immediately initiate a maneuver in compliance with the resolution advisory. As he initiates the maneuver, he should check his display to verify that the maneuver will not place him in conflict with another aircraft. As soon as he has taken these actions he should make a call in the clear on the designated VHF frequency, giving his call sign and the action that he is taking. When the immediate threat has been eliminated, the

pilot should make voice contact with the pilot of the target aircraft and agree on a safe way to return to his assigned flight path.

The chance of TCAS resolution advisories occurring which contradict pilot-negotiated resolution maneuvers is explored further in Section 12 of this report.

Procedures If TCAS Fails While in the Oceanic Track System

The TCAS unit is required by Reference 2 to have a failure monitor function which provides essentially continuous monitoring for failure of key elements of the TCAS equipment. When this monitor senses that the TCAS is not capable of performing its required functions, it provides a warning to the pilot. If the pilot becomes aware, as a result of this warning or in some other way, that the TCAS has failed, he would be required to contact the oceanic control system and receive clearance to another track or altitude that will separate his aircraft from other aircraft by the normal rather than the reduced separation minima. The pilot should maintain his assigned track, flight level, and Mach number until he has received a new clearance. If the Mode S transponder supporting the TCAS unit is still serviceable, it should be kept in operation. If not, and the aircraft carries a backup Mode S or ATC transponder, this should be activated.

Procedures for Notifying the Oceanic Control System of an Encounter

It is suggested that it would not normally be necessary to notify the oceanic control system of a CDTI alert, or of action taken as a result of it, if the pilot were to return immediately to his assigned track, flight level, and Mach number.

There would normally be no reason from an air traffic control point of view to contact the control system, because the control system has no surveillance capability and has no direct communication with the aircraft. (There might, however, be a requirement to report each encounter in order to generate data that could support analysis of navigation accuracy or estimates of the safety of the oceanic track system with its reduced separation minima.) However, there are certain situations in which the pilot should be required to contact the control system. They are:

(1) There has been an encounter between two CDTI-equipped aircraft which were flying the same track in the same direction at the same flight level. The trailing aircraft has closed on the lead aircraft, and the pilots are not able to resolve the discrepancy in Mach number. The pilot of the trailing aircraft must contact the control system and receive a clearance to a new altitude or track.

(2) Following an encounter, the pilot realizes that, due to a blunder, he has crossed an adjacent track or flight level. Before returning to the correct track or flight level, the pilot should contact the oceanic control system.

(3) The pilot must receive clearance from the oceanic control system before making any permanent change in track, flight level, or Mach number.

(4) If, as the result of an encounter, the pilot suspects faulty navigation equipment, he must contact the oceanic control system.

(5) The pilot should report the specific information related to any encounter with an unequipped target.

Illustrative Voice Conversations

In this section, four situations giving rise to CDTI alerts are described, and voice conversations that might take place to negotiate resolutions of these situations are presented. In the following, the fictitious call sign XYAIR 62 is used to represent own aircraft and UVLINES 137 is used to represent the target.

Situation 1. - Reduced vertical separation of 300 km (1000 ft) is being applied. Both own aircraft and the target are eastbound on track V, own aircraft at flight level 310 and the target at flight level 320. Own aircraft has been slowly overtaking the target. Own pilot observes the target on his CDTI display as a proximity target 15 n. mi. ahead and initiates voice contact.

Own: "UVLINES 137, this is XYAIR 62, do you read?"

Target: "Calling UVLINES 137, say again."

Own: "UVLINES 137, this is XYAIR 62, I show you as a CDTI target 15 miles ahead at flight level 317. What track and flight level are you flying?"

Target: "XYAIR 62, this is UVLINES 137, my CDTI also shows you 15 miles at my six o'clock at flight level 310. We are flying track Victor at flight level 320. Our altitude has drifted low. We will climb back to 320 and hold that."

Own: "Roger, UVLINES 137, we are also on track Victor. It looks like we are closing on you and will pass below. We will keep our altitude close to 310."

Situation 2. - Reduced lateral separation of 56 km (30 n. mi.) is being used. Own aircraft and the target are westbound on

adjacent tracks at the same flight level. Own aircraft is assigned track C and the target is assigned track D, both at flight level 330. Track D is to the left of own aircraft.

Target: "XYAIR 62, this is UVLINES 137, do you read?"

Own: "UVLINES 137, XYAIR 62, go ahead."

Target: "XYAIR 62, I just got a CDTI alert on you. I show you at about three o'clock at 8 miles. What track are you flying?"

Own: "UVLINES 137, I also show you at 8 miles at my nine o'clock. We are flying track Charlie and are within 5 miles of centerline. What is your track and heading?"

Target: "We are on track Delta, heading 268. Our nav shows us on course. I suggest we turn left and you turn right until we get this straightened out."

Own: "UVLINES 137, I agree. We are turning right to 270. We'll check our nav system."

(After a pause)

Own: "Our nav coordinates show us on course at 56 39 north, 35 12 west. What is your position?"

Target: "UVLINES 137 is currently at 56 29 North, 35 15 West."

(After a Pause)

Own: "UVLINES 137, your coordinates plot well north of Track Delta. Have you checked your waypoints?"

(After a Pause)

Target: "XYAIR, we're sorry. We had a bad waypoint entered.
         The new one has been entered and it shows us well
         right of course. We will take a heading of 240 to get
         back on course."

Own: "O.K. we'll come back to 260 for a while.

Situation 3. – Reduced lateral separation of 56 km (30 n. mi.)
is being applied. Own aircraft is westbound on track E at flight
level 350 and the target is eastbound on track F at flight level
350. Track F is south of track E and is to the left of own
aircraft. Own TCAS does not have a display for the target at the
time that the target's pilot initiates voice contact.

Target: "XYAIR 62, this is UVLINES 137, do you read?"

Own: "Calling XYAIR 62, I read you loud and clear."

Target: "This is UVLINES 137, I have a CDTI alert on you,
         nearly dead ahead at 35 miles, at my altitude. We are
         on track Foxtrot. What is your track?"

Own: "We are on track Echo. I have no display on you."

Target: "XYAIR 62, it looks like we will pass with about 10
         miles separation. We are turning right. Suggest you
         turn right, also."

Own: "UVLINES 137, we have you now. We are turning right
         to 280. We show you at 10 o'clock, 25 miles."

Target: "Our display shows you at 25 miles at about 9 o'clock."

(After a pause)

Target: "XYAIR, we were a little left of course, we're coming
         back to centerline now."

Own: "We were a little left ourselves. We are clear now
         and are coming back to a heading of 260."

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Situation 4. - Reduced longitudinal separation is being applied. Both own aircraft and the target are assigned track W eastbound at flight level 330. The target has entered the track first, and own aircraft has been cleared behind it. Own aircraft is overtaking the target slowly. Own pilot has observed the target as a proximate target on his display and has noticed that the target is closing.

Own:	"UVLINES 137, this is XYAIR 62, do you read?"
Target:	"XYAIR 62, UVLINES 137, go ahead."
Own:	"Our CDTI shows you 15 miles ahead at flight level 330. Are you flying track Whiskey?"
Target:	"That's affirmative. We also show you 15 miles at six o'clock."
Own:	"We have been closing on you. What Mach number are you flying?"
Target:	"We filed for .80 and have been holding that. What is your Mach?"
Own:	"We filed for .82 and have been holding that. What is your ground speed?"
Target:	"530."
Own:	"We have 558. At that rate we will overtake in half an hour. 137, we will try to get a new altitude from ATC. We'll slow to 530 ground speed in the meantime."
Target:	"Roger."

These sample voice exchanges should help to show that the pilots are not being asked to memorize complex procedures or resolution rules. It should be evident that, in most cases, the pilots can achieve a full image of the situation very quickly and that the proper resolution actions are quite evident and natural. The conversation very quickly focuses on exchanging the items of

information that are required for that particular situation. Items which might be useful in another context, but which are irrelevant in the current one are not discussed. From these examples it is clear that pilots continue to use phraseology familiar to them from their everyday interactions with air traffic control.

SECTION 8

ESTIMATION OF ALERT RATES

In this section, maximum CDTI alert rates are estimated for various separation minima.

Approach

The technique used to estimate maximum CDTI alert rates is based on theory developed for determining collision risk (see Reference 6). The technique, as used here, accounts for all alerts except those caused by the loss of longitudinal separation between aircraft on the same track at the same flight level. This type of conflict is discussed separately at the end of this section.

The collision risk model used in this analysis represents an aircraft by a rectangular box that encloses it, as shown in Figure 5. The frequency with which another aircraft enters the box is then estimated using the following equation:

$$R_A = P_y P_z N_x + P_x P_z N_y + P_x P_y N_z \qquad (2)$$

where N_x is the expected frequency with which the along-track separation shrinks to less than L_x. N_y and N_z are similarly defined for the across-track and vertical directions.

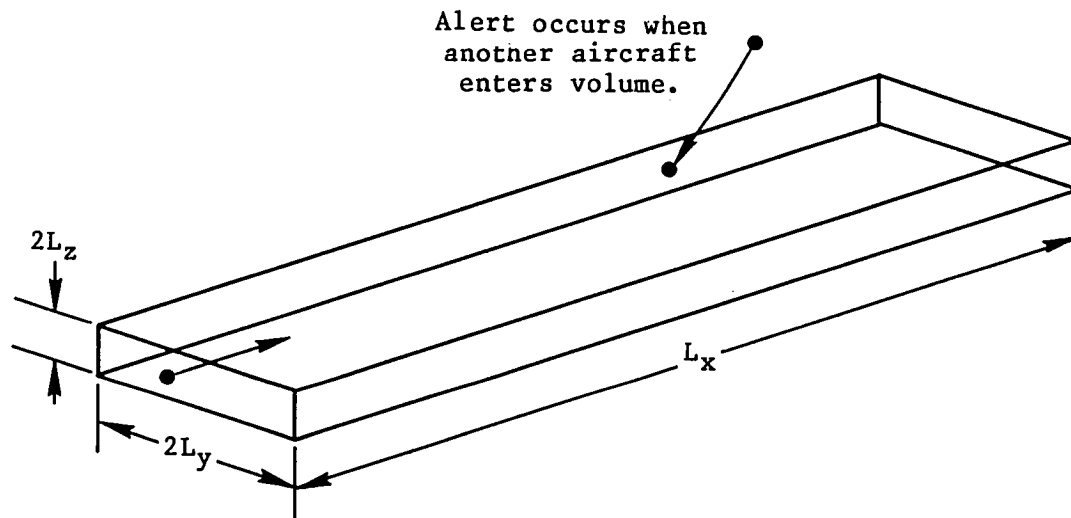P_x is the probability that the along-track separation is less than L_x, i.e., the

Figure 5.–Maximum CDTI alert volume.

proportion of time the aircraft spend in this condition. P_y and P_z are similarly defined for the across-track and vertical directions.

The first term in equation (2) can be interpreted as giving the frequency with which another aircraft approaches to less than L_x in the x-direction times the probability that the separation in the y and z directions is simultaneously less than L_y and L_z. The other two terms can be interpreted similarly for the cross-track and vertical directions. This approach assumes that the events of overlap in each of the three directions are statistically independent, and that the total alert rate can be determined as the sum of the alert rates resulting from the three directions individually.

For this model, the size of the box is chosen based on distances at which an alert can occur. It is assumed that the horizontal criteria for an alert will be met if the following inequality (the tau criterion) is satisfied as the aircraft pass:

$$\frac{R - D}{-V_R} \leq T_h \tag{3}$$

where   R   = radial distance between the aircraft

          V_R = range rate

          D   = 9 km (5 n. mi.)

          T_h = 105 s

In addition, the miss distance must be less than that determined by the tau-dot criterion. (The tau-dot criterion only affects the y-direction parameters, and is not covered in detail here. See Appendices B and C for more information).

To relate the box dimensions to the various parameters, adjacent
routes are assumed with traffic traveling at the separation
minimum. Same and opposite direction route pairs are separately
considered, as are horizontal and vertical encounters.
Opposite-direction aircraft are each assumed to be traveling at 310
m/s (600 knots), while for the same direction, one aircraft is
assumed to be traveling at 260 m/s (500 knots) and overtaking
traffic traveling at 240 m/s (460 knots).

X-Direction. - In the x-direction, the length of the box is
determined by computing the maximum distance at which an alert could
occur, based on worst-case closing speeds of 20 and 620 m/s (40 and
1200 knots) for the same and opposite direction route pairs; that is:

$$L_X = T_h |V_R| + D \tag{4}$$

where $|V_R|$ is the closing speed of the aircraft pair.

A method of determining P_x is described in Reference 6. The
approach uses what is sometimes called the "streaming aircraft"
model, where a constant flow of aircraft traveling at the same speed
on parallel routes through a sector is assumed. The number of
passings per sector hour is multiplied by twice the time that the
boxes representing each aircraft are in longitudinal overlap during
each passing (giving the total flight time in longitudinal overlap
per sector hour), and this is then divided by the total flight hours
per sector hour. When applied to the oceanic CDTI scenario, the
following equation results:

$$P_x = \frac{L_X N}{V} \tag{5}$$

where   N is the aircraft entry rate for each route
         V is the average ground speed on each route.

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As long as the box length and aircraft entry rates are such that each aircraft is in overlap with no more than one other aircraft (as occurred in the cases examined), this number can be interpreted as a probability. The x-direction parameters are the same for both horizontal and vertical encounters.

Reference 6 also gives a method of determining N_x, dividing the fraction of time that an aircraft is in overlap by the average duration of overlap. When adapted to the oceanic CDTI scenario, application of equation (5) gives the following result:

$$N_x = \frac{P_x}{L_{x}/|V_R|} = \frac{|V_R| \, N}{V} \qquad (6)$$

Z-Direction. — For the vertical direction, separations of 610 and 300 m (2000 and 1000 ft) are considered. It is assumed that aircraft at 300 m (1000 ft) spacing will always meet the criteria for a vertical alert, i.e., $P_z = 1$. This is a conservative result, as an aircraft pair separated by more than 370 m (1200 ft) will not meet the criteria. For this case, $N_z = 0$; that is, as the aircraft are always in vertical overlap, the frequency of entering into vertical overlap is 0. Aircraft at 610 m (2000 ft) spacing are assumed never to meet the vertical alert criteria, i.e., $P_z = 0$. A value of 0 for N_z also applies here. These values apply to aircraft on parallel routes at the same flight level and at flight levels separated by 300 m (1000 ft).

Y-Direction. — The method used to determine y-direction parameters is more complicated than that described for the x and z directions. In order to determine P_y, a distribution often used to model cross-track pathkeeping in the North Atlantic (NAT), the double-double exponential (Reference 6), is used. That distribution is of the form:

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$$f(y) = \frac{(1 - a)}{2\ b_1}\ \exp\ (-|y|/b_1) + \frac{a}{2\ (b_2)}\ \exp\ (-|y|/b_2) \qquad (7)$$

where $a = .0014246$

             $b_1 = 3.7$ km (2 n. mi.)

             $b_2 = 56$ km (30 n. mi.)

are parameters that will yield lateral deviation statistics that correspond to aircraft in compliance with the Minimum Navigational Performance Specification (MNPS) for the NAT.

As $f(y)$ is the distribution of each aircraft's deviation from route centerline, P_y can be found by convolving $f(y)$ with route-spacing + $f(y)$ and integrating over P_y from $y = -L_y$ to $+ L_y$.

To determine L_y, a blunder scenario is modeled, with an aircraft on each route proceeding towards the other route at an angle of 0.17 rad (10 deg), representing a waypoint insertion error of 1 degree of latitude at typical NAT latitudes. The tau and tau-dot criteria are used to determine the maximum cross-track distance at which a CDTI alert can be given. In this way, L_y is determined separately for the same and opposite direction cases. More details of this procedure are given in Appendix B.

Taking into account the values assumed by P_z and N_z, equation (2) simplifies to:

$$R_A = P_y\ N_x + P_x\ N_y \qquad (8)$$

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when the aircraft on the adjacent track have differences in assigned altitudes of 300 m (1000 ft), and R_A = 0 when the difference in assigned altitude is 610 (2000 ft).

When determining the alert rate due to aircraft on the same track at adjacent altitudes, P_y = 1 (the aircraft are always in overlap in the y direction) and N_y = 0 (the frequency of entering into lateral overlap is 0). For 300 m (1000 ft) vertical separation, equation (8) then further reduces to:

$$R_A = N_x \qquad\qquad (9)$$

Stated simply, the CDTI alert rate becomes a measure of the frequency at which the aircraft pass in this particular case.

The resultant parameters for various separation minima are shown in Table 2.

Results

Table 3 shows alert rates for route pairs with all combinations of the following spacings:

lateral separation: 110 and 56 km (60 and 30 n. mi.)
longitudinal separation: 10 and 5 min
vertical separation: 610 and 300 m (2000 and 1000 ft).

The results show the maximum alert rate as seen by a pilot on one of a pair of routes with the given separation. Results are presented separately for same and opposite direction tracks, and separately for horizontal and vertical route pairs (i.e., separately for traffic on adjacent coaltitude tracks and for traffic on the

TABLE 2. - VALUES OF ALERT RATE PARAMETERS

Separation Minimum	Route Pair			
	Same Direction		Opposite Direction	
Lateral	110 km (60 n. mi.)	56 km (30 n. mi.)	110 km (60 n. mi.)	56 km (30 n. mi.)
L_y	18.4 km (9.91 n. mi.)	18.4 km (9.91 n. mi.)	29 km (15.8 n. mi.)	29 km (15.8 n. mi.)
$|V_y|$	85.8 m/s (167 knots)	85.8 m/s (167 knots)	107 m/s (208 knots)	107 m/s (208 knots)
P_y	1.30×10^{-4}	4.84×10^{-4}	2.13×10^{-4}	2.45×10^{-3}
N_y	1.10×10^{-3}/hr	4.08×10^{-3}/hr	1.40×10^{-3}/hr	1.62×10^{-2}/hr
Longitudinal	10 min	5 min	10 min	5 min
L_x	11.4 km (6.17 n. mi.)	11.4 km (6.17 n. mi.)	74 km (40 n. mi.)	74 km (40 n. mi.)
$|V_x|$	20.6 m/s (40 knots)	20.6 m/s (40 knots)	617 m/s (1200 knots)	617 m/s (1200 knots)
P_x	0.0771	0.154	0.4	0.8
N_x	0.5/hr	1.0/hr	12./hr	24./hr
Vertical	610 m (2000 ft)	300 m (1000 ft)	610 m (2000 ft)	300 m (1000 ft)
L_z	370 m (1200 ft)	370 m (1200 ft)	370 m (1200 ft)	370 m (1200 ft)
P_z	0	1	0	1
N_z	0	0	0	0

TABLE 3. - ALERT RATE FOR ROUTE PAIRS

Separation Minima	Same-Direction Routes			Opposite-Direction Routes		
	Alerts Per Hour	Hrs. Betw. Alerts	Flts. Betw. Alerts	Alerts Per Hour	Hrs. Betw. Alerts	Flts. Betw. Alerts
Horizontal*						
110 km (60 n. mi.)/10 min	1.50×10^{-4}	6670	1670	0.00312	321	80.1
110 km (60 n. mi.)/5 min	2.99×10^{-4}	3340	836	0.00624	160	40.1
56 km (30 n. mi.)/10 min	5.57×10^{-4}	1800	449	0.0359	27.9	6.96
56 km (30n. mi.)/5 min	1.11×10^{-3}	901	225	0.0717	13.9	3.49
Vertical**						
10 min/300 m (1000 ft)	0.5	2.0	0.50	12.0	0.0833	0.0208
5 min/300 m (1000 ft)	1.0	1.0	0.25	24.0	0.0417	0.0104

* Vertical separation of adjacent tracks = 0 or 300 m (1000 ft).

** Horizontal separation of adjacent flight level tracks = 0 m.
Routes separated vertically by 610 m (2000 ft) or more experience zero alert rate.

same track but at different flight levels). Alerts per hour and the number of hours between alerts are shown, as well as the number of flights between alerts, assuming four hours of flight time in the track system. For example, for a pair of routes spaced 110 km (60 n. mi.) apart with 10 min longitudinal separation, a CDTI alert would occur at most once every 1670 flights for same-direction traffic, and every 80 flights for opposite-direction traffic. For vertical route pairs, the alert rate at 610 m (2000 ft) vertical separation is zero, while at 300 m (1000 ft) spacing the maximum alert rate is equal to the rate of passing of the aircraft. As a result, the alert rate for this vertical route pair is more than an order of magnitude greater than the alert rate for a horizontal route pair for any given flow rate.

Given the data in Table 3, a composite alert rate can be computed for an aircraft in any desired scenario for various combinations of separation minima. In Table 4 the alert rates for vertical and horizontal route pairs are summed to give a composite alert rate for both a "same-direction" scenario and an "opposite-direction" scenario. Both scenarios assume that the subject aircraft is surrounded on all sides by aircraft on adjacent tracks and flight levels. The same-direction scenario assumes that all aircraft are moving in the same direction. The opposite-direction scenario assumes that traffic on one of the adjacent tracks is moving in the opposite direction from the subject aircraft. For example, for an aircraft in the same-direction scenario with 60/10/2000 separation minima, the total alert rate would be twice the value of the 60/10 horizontal route pair shown in Table 3, since no alerts for vertical route pairs would be detected. However, for the 60/10/1000 case, the total alert rate is the sum of twice the vertical 10/1000 rate (for the flight levels just above and below the subject flight level) plus six times the

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TABLE 4. – ALERT RATE FOR AIRCRAFT IN TRACK SYSTEM

Separation Minima	Same-Direction Scenario			Opposite-Direction Scenario		
	Alerts Per Hour	Hours Between Alerts	Flights Between Alerts	Alerts Per Hour	Hours Between Alerts	Flights Between Alerts
60/10/2000	3.00×10^{-4}	3330	833	0.00624	160	40.1
60/5/2000*	5.98×10^{-4}	1670	418	0.0125	80.0	20.0
30/10/2000*	1.11×10^{-3}	901	225	0.0717	13.9	3.49
30/5/2000*	2.22×10^{-3}	450	113	0.143	6.99	1.75
60/10/1000*	1.00	1.00	0.250	1.01	0.990	0.248
60/5/1000	2.00	0.500	0.125	2.02	0.495	0.124
30/10/1000	1.00	1.00	0.250	1.11	0.901	0.225
30/5/1000	2.01	0.498	0.124	2.22	0.450	0.113

* Principal candidate for reduced separation

horizontal 60/10 rate (since the traffic on adjacent tracks at altitudes 300 m (1000 ft) above and below the subject flight level will also be included).

This same-direction case is representative of a worst-case scenario for the North Atlantic; that is, almost all of the NAT traffic will be one-way, but the loading rates will rarely be as high on all tracks surrounding an aircraft as are specified (i.e., 6 or 12 aircraft/hour at 10 or 5 minute spacing). At 610 m (2000 ft) vertical separation, even the smallest separation minima in the other two dimensions will only result in one alert every 113 flights. With 300 m (1000 ft) vertical separation, the number of alerts caused by traffic at adjacent flight levels on the same track dominates the alerts caused by traffic on adjacent tracks.

In the opposite-direction scenario, it has been assumed that opposite-direction alerts will only occur in the horizontal dimension, and only from one side. In the case of 300 m (1000 ft) vertical spacing, the vertical alerts (i.e., alerts caused by traffic above and below the subject aircraft, and proceeding in the same direction) will dominate the horizontal alerts (i.e., alerts caused by traffic on adjacent routes), in a similar fashion to the same-direction case.

In general, then, there will be few alerts from traffic on adjacent routes traveling in the same direction: one every 113 flights is predicted at the closest separations considered. Even opposite-direction traffic at 56 km (30 n. mi.) lateral separation and 5 minute headways would only result in an alert approximately every other flight. If 300 m (1000 ft) vertical separation is used, every aircraft passing on the same track will cause an alert. For 60/10/1000 separation minima, both the same-direction scenario and

the opposite-direction scenario result in a maximum of approximately one alert per hour.

For the four principal schemes for reducing separation, the following estimates, from Table 4, should represent upper bounds on the CDTI alert rate:

Reduced Vertical Spacing
   with One-Way Tracks   - 4 Alerts per Flight

Reduced Lateral and
   Reduced Longitudinal Spacing - 1.7 Flights per Alert

Reduced Lateral Spacing   - 3.5 Flights per Alert

Reduced Longitudinal Spacing   - 20 Flights per Alert

Peak Vs. Average Alert Rates

The maximum alert rates estimated here represent peak conditions which may be approached under heavy route loading in a localized area of the track system. Under normal route loading, however, the average CDTI alert rates should be substantially less than the maximum values. Although detailed route loading data is not available, some inferences can be made based on the occurrence of various conditions in the North Atlantic.

The effect of the mainly unidirectional traffic flow in the NAT is that there are very few opposite-direction route pairs (some days, during one of the major flows, there may be no tracks at all in the opposite direction). It is unlikely that efficient routes in opposite directions would be situated near each other, even when there is a minor flow in the opposite direction. Even if

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same-direction route spacing were to be narrowed to 56 km (30 n. mi.) there should be little need for such close spacing for opposite-direction routes. The same is even more true for the need for opposite-direction traffic at alternate altitudes, particularly at 300 m (1000 ft) intervals.

Another characteristic of actual system operations is that, in general, minimum longitudinal separation will be applied only during higher density operations, and then only for short periods of time. For example, if the allowable spacing is 5 minutes, but there is a 15 minute gap at one point, the efficient cruise speeds are in such a narrow range that it is unlikely that the extra 10 minute gap will be eliminated by the time of exit. In fact, a single route pair, fully loaded with aircraft at 10 minute longitudinal spacing, could carry all of the traffic of the July 1979 sample day described in the OASIS report (Reference 7). Except for brief periods during the day, then, the maximum entry rate will not actually be attained. The OASIS simulation predicted that with a 10 minute minimum headway standard, less than 15 percent of the eastbound clearances (10 percent westbound) would actually use the minimum spacing and that 40 percent of the eastbound clearances (50 percent westbound) would have greater than 30 minute headways. Even when 5 minute headways were simulated, fewer than 25 percent of the entries had headways of 10 minutes or less.

For these reasons, it is believed that the maximum alert rates projected here represent very conservative upper bounds on the CDTI alert rate that a pilot might normally encounter.

Alerts Caused by Loss of Longitudinal Separation

The preceding analysis of alert rates did not consider alerts caused by the loss of longitudinal separation between aircraft on

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the same track and flight level, since no current data is available on longitudinal navigational performance in the NAT. The best available data on longitudinal performance was collected over the Central East Pacific (CEP) track system in 1973-1974, and is analyzed in Reference 8. This study showed that for aircraft equipped with an inertial navigation system, the probability of an unexpected loss or gain of 10 minutes or more in longitudinal separation was approximately 0.41%. For a loss or gain of 5 minutes or more, this figure increased to 7.97%.

This longitudinal performance data is not considered representative of current aircraft flying in the NAT track system for the following reasons:

(1) The data is nearly ten years old.

(2) The NAT track system is longer than the CEP system; however, position reports are presumably required at about the same intervals (every 10 degrees of longitude).

(3) During the CEP data collection, the average longitudinal spacing was much greater than the minimum allowed spacing. None of the aircraft pairs in the study actually got closer to each other than 9 minutes. For a more heavily loaded system, oceanic traffic controllers would presumably become more involved in recommending speed adjustments to ensure continued safe separation. Such involvement could affect the probability distribution, especially if separation minima were reduced.

If longitudinal encounters were factored into the results shown in Table 4 (based upon the CEP data), the alerts per hour would increase by roughly 0.001 for 10 minute longitudinal separation and roughly 0.02 for 5 minute longitudinal separation (both scenarios). For the NAT track system today, however, these added values are probably too large.

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SECTION 9

EXPECTED BENEFITS

This section discusses the potential benefits of the oceanic
CDTI concept. The first benefit considered is the expected savings
in user operating costs due to reduced separation. The second
benefit examined is the increased traffic capacity that would be
brought about by reduced separation. These benefits will be
discussed with reference to the ability of the oceanic CDTI system
to maintain or improve current safety levels in spite of reduced
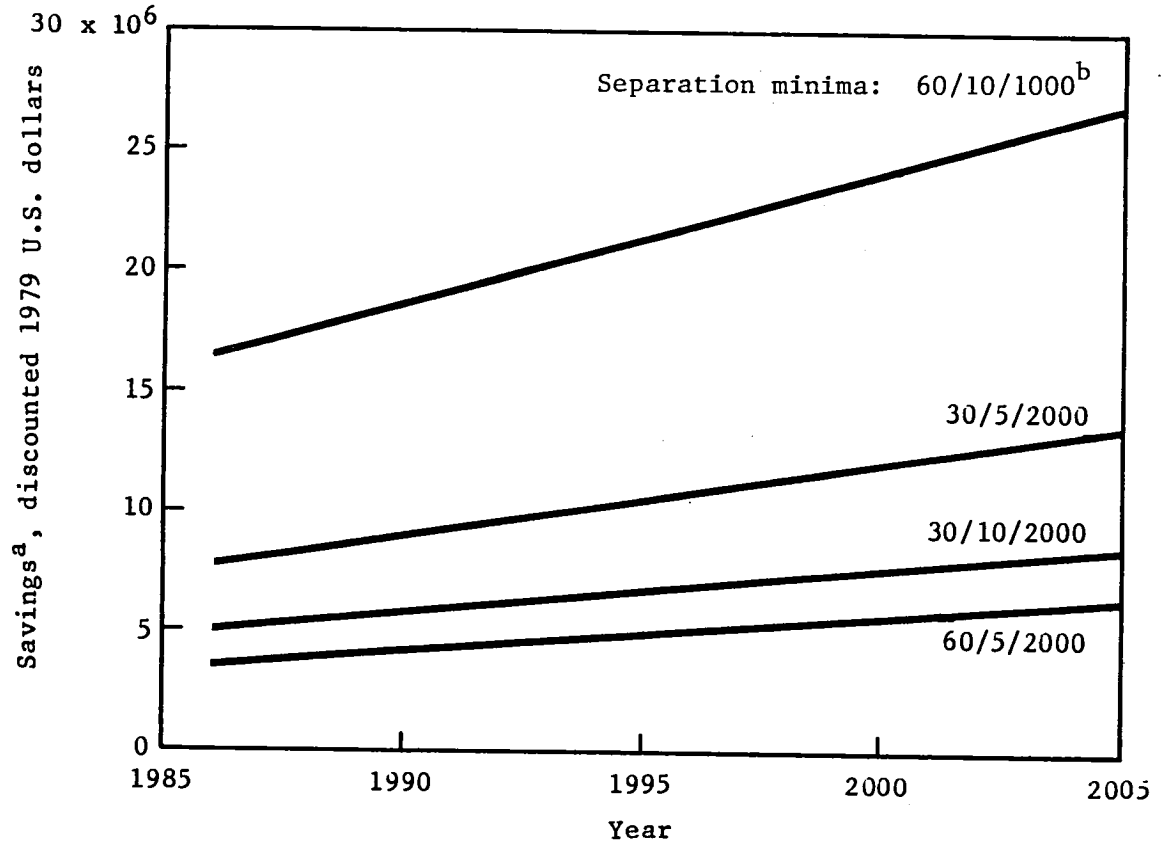separation.

Savings in Operating Costs

The principal benefit for reduced separation over the ocean lies
in lower flight costs. As previously mentioned, reduced separation
would allow aircraft to fly more fuel-efficient routes and
altitudes. Reduced flight time would also mean lower crew and
maintenance costs. In recent years, much study has gone into
reducing air traffic separation, not only over the ocean, but over
land areas as well. The implementation of a Minimum Navigational
Performance Specification (MNPS) in January 1978 has allowed reduced
separation over the North Atlantic. Special Committee 150 of the
Radio Technical Commission for Aeronautics (RTCA) is currently
attempting to develop a minimum performance standard for reducing
separation to 300 meters (1000 feet) above an altitude of 8800
meters (29 000 feet). The Soviet Union is also conducting
theoretical studies on the reduction of vertical spacing at high
altitudes. SRI International, under contract to the FAA, recently
investigated reduced separation in the Oceanic Area System
Improvement Study (OASIS). In short, it is widely recognized that
the potential savings due to reduced separation are substantial.

As part of the OASIS study, a sophisticated flight cost model was used to estimate user costs for various sets of separation minima for the North Atlantic (NAT) and for the Central East Pacific (CEP) track systems for future years. The model included projected future traffic increases. Costs were measured in discounted 1979 U.S. dollars, assuming an annual user discount rate of 12%. Fuel costs were assumed to increase at an annual inflation rate of 10%, while other costs were assumed to rise at 8% per year.

Figure 6 shows plots of dollars saved in flight costs vs. year, assuming reduced separation minima for all traffic in the NAT track system. Curves are shown for various sets of reduced separation minima when compared to the baseline minima of 60/10/2000. The plots are based upon data taken from the OASIS report (Reference 1). Table 5 compares the total savings for the years 1986-2005 for each set of reduced separation minima. The OASIS study did not estimate flight costs for simultaneous reductions in both vertical and horizontal dimensions; it can be assumed, however, that the savings for any reductions in this category would be somewhat less than the sum of the savings for vertical and horizontal reductions computed separately.

It is evident from Figure 6 and Table 5 that the biggest potential payoff by far comes from reducing vertical separation. The next largest saving can be achieved by a reduction in lateral separation. Reductions in longitudinal spacing result in slightly lower savings than for lateral reductions. Results for the CEP were similar to these results for the NAT, but with proportionately lower figures.

The savings indicated in Figure 6 and Table 5 do not account for capital cost increases associated with advanced avionics. The OASIS study estimated these costs at 32 million dollars for aircraft

30 x 10⁶

Separation minima: 60/10/1000ᵇ

30/5/2000

30/10/2000

60/5/2000

Savingsᵃ, discounted 1979 U.S. dollars

1985   1990   1995   2000   2005

Year

ᵃCompared to the separation minima 60/10/2000

ᵇ300 m (1000 ft) vertical separation for oceanic areas only

**Figure 6.–Savings in flight costs for the North
Atlantic for future years.**

TABLE 5. – TOTAL SAVINGS[a] FOR THE NORTH
ATLANTIC FOR THE YEARS 1986–2005

(Millions of discounted 1979 U.S. dollars)

Separation minima	Fuel savings	Crew and maintenance savings	Total savings
60/5/2000	91.82	6.24	98.06
30/10/2000	112.95	22.72	135.67
30/5/2000	189.34	26.82	216.16
60/10/1000[b]	432.00	5.48	437.48

[a] Compared to the separation minima 60/10/2000

[b] 300 m (1000 foot) vertical separation for oceanic areas only

separation assurance devices for the North Atlantic fleet, assuming 50% cost allocation. This cost would undoubtedly be somewhat higher for CDTI equipage.

Capacity Increases

A spacing reduction of one-half in any separation dimension would result in approximately a twofold increase in traffic capacity. The actual increase might be less, depending upon the number of tracks, flight levels, etc., which are actually added. For instance, in the current NAT track system, four flight levels are used with 610 meter (2000 foot) spacing. If a one-half reduction in spacing resulted in the addition of only three new flight levels, then only a 75% increase in capacity would result. Reductions in more than one dimension, of course, would result in multiple increases in traffic capacity. For instance, separation minima of 30/5/1000 could mean as much as an eightfold increase in capacity.

Obviously, no track system is operated near its theoretical capacity. Rather, a system must have adequate capacity to prevent long entry delays and large diversions from desired entry points. In this way, adequate capacity contributes to lower flight costs. The flight cost model for the OASIS study utilized traffic projections developed by the International Aviation Review Committee (ARC) for future years. These projections showed about an 80% increase in traffic for the NAT and approximately a 170% increase for the CEP by the year 2005.

Capability for Improving Safety

The oceanic CDTI system has potential for maintaining or increasing current safety levels, even with reduced separation. To

begin with, TCAS surveillance provides a totally independent check on navigational performance. No such independent and direct measurement of aircraft separation exists in oceanic areas today. Furthermore, in the baseline CDTI system all aircraft would be CDTI-equipped; this natural redundancy would provide a great deal of protection against isolated failures of the CDTI system and would improve safety levels even further.

In order to assess the safety of the CDTI system in a statistical sense, it would be necessary to compare the increase in conflicts brought about by reductions in separation with the decreased probability of a conflict turning into a collision. Although there is insufficient data for a full analysis of this sort, the available data on horizontal navigational performance is adequate to at least provide an idea of how effective the oceanic CDTI system must be in order to maintain current safety levels.

Consider first the conflicts which might arise as a result of reduced lateral separation. In Section 8, a probability density function was used to represent the MNPS for the North Atlantic. Convolving this distribution function with itself yields a distribution function for the total lateral error for an aircraft pair. It is reasonable to assume that the number of potential collisions due to loss of lateral separation is roughly proportional to the value of this convolved function at the spacing minimum being considered. (The term "potential collision" is being used here to mean any conflict which will result in a collision without an adequate resolution maneuver.) Although the actual collision risk cannot be calculated, this function can be used to estimate the change in collision risk due to a reduction in the minimum separation. Evaluation of the convolved function indicates that a reduction in lateral spacing from 110 km (60 n. mi.) to 56 km (30 n. mi.) would increase the number of potential collisions by about a factor of 3.

Let the probability of a collision be an inverse measure of
safety for a track system. Also, let F be the average failure rate
of the oceanic CDTI system over an extremely long period of time.
That is,

$$F = \frac{\text{number of actual collisions}}{\text{number of potential collisions}} \qquad (10)$$

Restating what was said previously, the failure rate for the CDTI
system must be sufficiently small to offset the increased collision
potential caused by reduced separation. On this basis, it can be
shown that the failure rate F must be less than or equal to the
reciprocal of the factor of increase in potential collisions.
Assume, as a worst case, that all potential collisions are caused by
the loss of lateral separation. Then in order for safety levels to
be maintained with reduced lateral spacing, the oceanic CDTI system
must reduce the probability of a collision by a factor of 3, or have
a failure rate F of less than 33%.

Next, consider the effect of reduced longitudinal spacing. In
the longitudinal dimension, the only available data was collected
for the CEP track system in 1973-1974 and is analyzed in Reference
8. This longitudinal data may not adequately represent longitudinal
performance in today's NAT, for reasons stated in Section 8. It
should serve here, however, for gross approximations. This data,
presented earlier, gave the approximate probability of overtake for
nominal separations of 10 and 5 minutes. Assume that the number of
potential collisions is proportional to the probability of
overtake. The data indicates that a 2:1 reduction in longitudinal
spacing would increase the number of potential collisions caused by
overtake by roughly a factor of 20. Thus, in order for safety
levels to be maintained with reduced longitudinal spacing, the
oceanic CDTI system must reduce the probability of a collision by a
factor of 20, or have a failure rate F of less than 5%.

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For track systems with reduced separation in more than one
dimension, it can be shown that the increase in collision potential
for the system as a whole is equal to or less than the greatest
increase in collision potential for any single dimension. Thus,
the result obtained for longitudinal reductions above applies to
simultaneous spacing reductions in both horizontal dimensions. It
is not known, of course, what the actual failure rate of the oceanic
CDTI system would be. It is not being overly optimistic, however,
to expect that the failure rate would be far less than 5%.

In the case of reduced vertical separation, comparable data for
aircraft heightkeeping performance is not available. A direct cal-
culation of the increase in likelihood of a collision with a halving
of the vertical separation minimum is not possible. Nevertheless,
arguments suggesting that safety would be at least maintained can be
offered.

First, the oceanic CDTI system ensures that the pilots of both
aircraft will be alerted every time there is a passing at 300 m
(1000 ft) separation. The pilots can ensure that their flight
levels are very close to their assigned values so that a 300 m (1000
ft) difference in indicated altitude can be practically guaranteed.
Thus, TCAS can ensure that flight technical error is driven to
nearly zero for the period of passage. Because the current
separation procedures over the ocean are completely open-loop, with
no monitoring of heightkeeping performance and with the pilots not
always being aware of the presence of another aircraft, the 610 m
(2000 ft) separation minimum has had to include a liberal allowance
for flight technical error.

Where the pilot may not always be able to control his altitude
precisely, as for instance in encounters with heavy turbulence, the
pilot can establish a lateral offset using his CDTI display. Both

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pilots can agree to maintain an offset of about 9.3 km (5 n. mi.) which will provide a margin of safety in the event of a sudden large altitude excursion. Such an offset from track centerline would provide a negligible effect on the lateral separations from adjacent tracks, which are spaced with at least 74 km (60 n. mi.) separation. The accuracy of the 9.3 km (5 n. mi.) separation can be confirmed by comparing the readings of the TCAS units on both aircraft.

Next, the TCAS MOPS requires that the altimetry system on an aircraft carrying minimum TCAS II meet a 285 feet three-sigma error tolerance at flight level 400. (This figure applies to the error between the altitude reported by the aircraft's transponder and the aircraft's actual pressure altitude.) If two aircraft meet this requirement, and the altimetry errors have a Gaussian distribution, then the probability that the aircraft have a vertical separation of less than 150 m (500 ft) when their indicated flight levels show 300 m (1000 ft) separation is 0.0001.

It is realized that large altimetry errors generally occur with a frequency greater than that indicated by the Gaussian distribution. This is because large errors generally result from a specific failure or error in one component of the altimetry system. However, there are several means available for detecting such large errors. All of the modern commercial jet aircraft are provided with dual static pressure systems. (This means that there are two completely independent static pressure systems, served by different static pressure ports.) There is generally a means to observe the altitude indicated by each of these systems in flight. The pilot could compare the results from the two systems in flight before entering the oceanic track system. If the two agree to within a given tolerance, it is unlikely that a static pressure source

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error exists. If they do not agree, the pilot would be prohibited from flying in the track system using reduced vertical separation.

The pilots can also perform an in-flight correspondence error check for each passage at 300 m (1000 ft) separation. They can exchange the transponder-reported flight levels as observed by their TCAS units, and they can exchange the flight levels indicated on their cockpit altimeters. Such a correspondence check could detect a dangerous situation caused by the fact that one pilot forgot to reset the altimeter setting to 29.92 when climbing through flight level 180.

While additional data relative to this subject needs to be collected and analyzed (such data collection efforts are currently being conducted in conjunction with the work of RTCA Special Committee 150), the factors mentioned above suggest that reduced vertical separation could probably be achieved without a sacrifice in safety. The role of CDTI in limiting the size of the flight technical error would be critical in this process.

SECTION 10

TRANSITION STRATEGIES

In this section, the question of how to transition to an
all-CDTI track system is considered. The basic assumption here is
that over some period of time, more and more aircraft would become
equipped with CDTI and more of the track system would be reserved
for use by CDTI-equipped aircraft. The goals and tradeoffs of such
a transition strategy are first explained. With these in mind, some
specific strategies are then suggested.

Goals and Tradeoffs

The goals for a good transition strategy would include the
following:

(1) Allow gradual equipage; i.e., do not require CDTI equipage
     all at once for the entire track system.
(2) Provide immediate positive benefits for the first aircraft
     to equip with CDTI.
(3) Do not unduly penalize aircraft which do not equip with
     CDTI right away.

The rate of transition to an all-CDTI track system would have to be
determined by economic constraints. If the oceanic CDTI concept can
be implemented at a per-aircraft cost that can be paid off through
fuel savings in a reasonable time (say five years or less), then the
concept should be attractive and equipage should take place
voluntarily.

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An oceanic track system could be converted to an all-CDTI system on either a track-by-track basis or on a flight-level-by-flight-level basis. Since the fuel-efficiency of specified flight levels depends to a large degree on aircraft type, converting to an all-CDTI system on a flight-level basis would not affect all users of the track system uniformly. Also, step climbs might be ruled out for unequipped aircraft if CDTI-only flight levels were interspersed with mixed-equipage flight levels. Therefore, it seems more sensible for an oceanic track system to transition to an all-CDTI system on a track-by-track basis.

Possible Strategies

Figure 7 shows three ways in which CDTI-only tracks could be added to an oceanic track system: namely, in groups of one, two, or three tracks. A reduced lateral spacing of 56 km (30 n. mi.) track spacing is assumed for CDTI-only tracks in these examples. The advantages and disadvantages of each strategy are relatively straightforward. Obviously, the penalty for non-equipage increases as the number of CDTI-only tracks in a group increases, since the average diversion from the optimal point of entry into the system becomes greater. On the other hand, if lateral spacing is reduced for CDTI-only tracks, then more economic benefits are realized by CDTI-equipped aircraft as the number of CDTI-only tracks in a group increases. For instance, if each CDTI-only track is flanked by mixed-equipage tracks (Figure 7a), then the total number of tracks has not increased and immediate positive benefits are achieved by equipped aircraft only if vertical or longitudinal spacing is reduced on CDTI-only tracks. If CDTI-only tracks exist in pairs or in groups of three (Figures 7b and 7c), then immediate benefits can be realized by equipped aircraft through a greater choice of tracks

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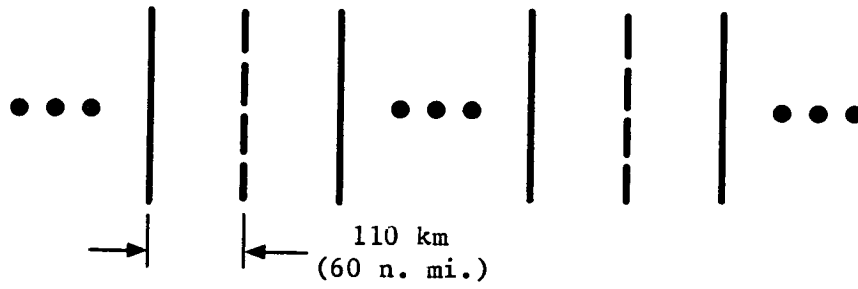
(a) Single CDTI-only tracks.
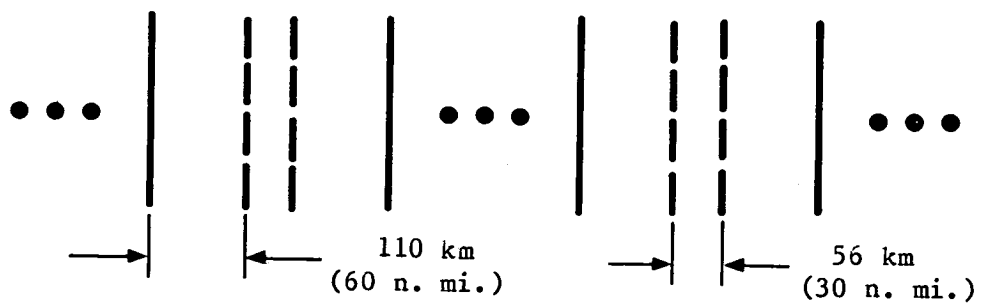
(b) Groups of two CDTI-only tracks.
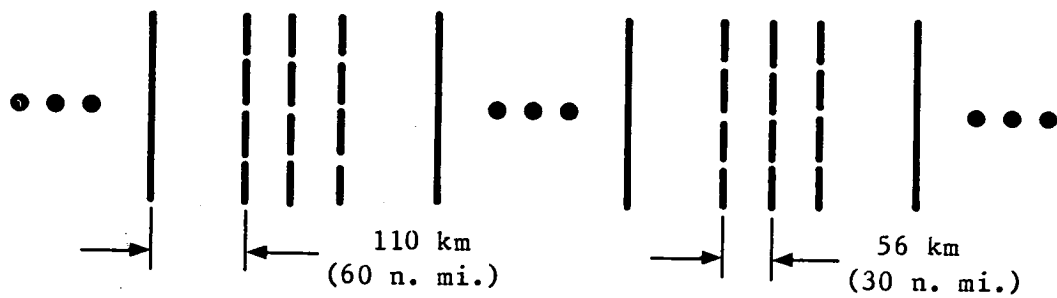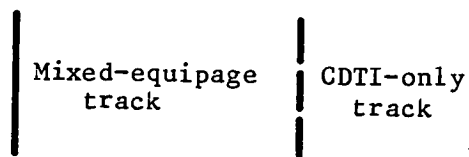
(c) Groups of three CDTI-only tracks.

Figure 7.–Track-by-track transition strategies.

(irrespective of any benefits which may be achieved through vertical and longitudinal spacing reductions).

Of course, the transition strategies described above assume that reduced spacing is allowed on CDTI-only tracks, but not on mixed-equipage tracks. These strategies provide little benefit, other than increased safety, for an equipped aircraft which is not frequently able to use CDTI-only tracks. By easing the spacing restriction slightly, a new alternative can be considered. This alternative, illustrated in Figure 8, would allow a CDTI-equipped aircraft on a mixed-equipage track to follow any other aircraft with reduced longitudinal spacing (5 minutes in the example). This alternative is worth considering for the following reasons:

(1) An overtake encounter is the easist type of conflict for the pilot of a CDTI-equipped aircraft to deal with. If an unequipped aircraft is being overtaken, a slight reduction in speed should give the pilot of the equipped aircraft sufficient time to contact air traffic control (ATC) for a report of status.

(2) Immediate benefits are realized by CDTI-equipped aircraft, even if no CDTI-only tracks are conveniently available.

(3) The transition to an all-CDTI track system could be more gradual; CDTI-only tracks would not necessarily have to be created initially.

It should be noted that the reliability of the transponders on unequipped aircraft becomes more critical for safety with this alternative strategy.

The following enhancements would make the alternative transition strategy even more attractive:
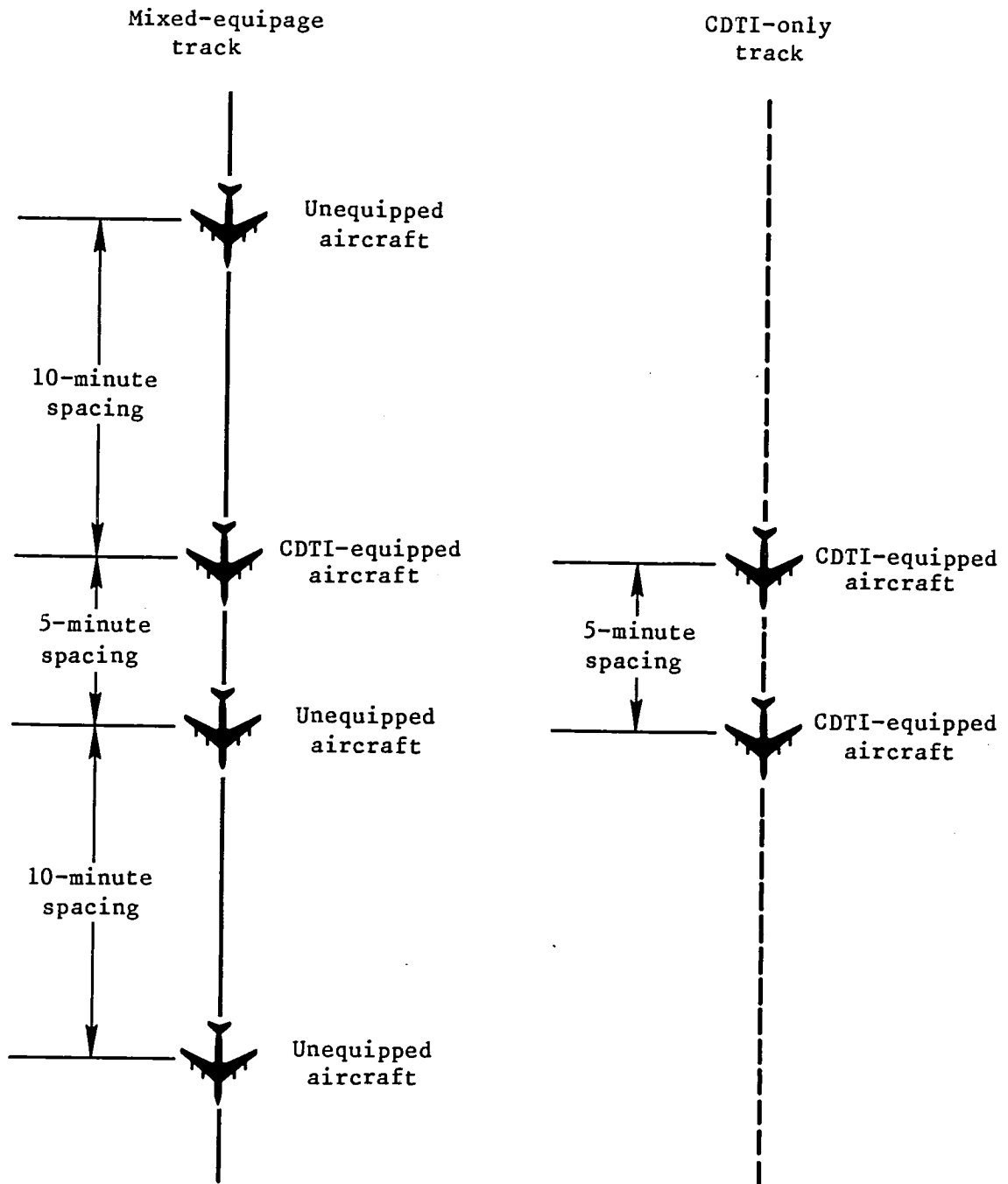
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Figure 8.—Alternative transition strategy with reduced longitudinal spacing.

(1) Require the flight crews of unequipped aircraft operating in the oceanic track system to also monitor the CDTI air-to-air voice channel.

(2) Whenever a CDTI-equipped aircraft is following an unequipped aircraft on the same track and flight level with reduced longitudinal spacing, have ATC give the call sign of the unequipped aircraft to the pilot of the equipped aircraft.

These enhancements could make pilot-negotiated resolution feasible for all overtake encounters.

As a final remark, it should be noted that no transition strategy would be ideal for all users of a track system. The choice of a transition strategy must be based upon maximizing long-term benefits without over-penalizing individual users of the airspace in the short term.

SECTION 11

COMPARISON OF STRATEGIES FOR REDUCING SEPARATION

In Section 5, a number of candidate strategies were proposed for reducing oceanic separation minima. Use of the oceanic CDTI system with each of these strategies was analyzed in subsequent sections from a number of viewpoints. In this section, a comparative evaluation of the overall merit of each of these candidate schemes is performed.

Reduced Vertical Spacing

The first candidate strategy called for a one-half reduction in separation in the vertical dimension only, with only one-way tracks allowed. For the North Atlantic (NAT), this would mean separation minima of 60/10/1000. This strategy has the following advantages:

(1) This strategy achieves by far the biggest payoff, in terms of reduced flight costs, of any of the strategies considered.

(2) Because of the one-way traffic, this approach may not require the 74 km (40 n. mi.) range proposed for other schemes; since opposite-direction encounters would happen no more frequently than today, even a range of 37 km (20 n. mi.) would provide an improvement in safety compared to today's system.

(3) The maximum alert rate, as estimated in Section 8, would be high, but should not represent a burden to the flight crew; for the NAT, there should be no more than 2 or 3 alerts per crossing of the ocean. Most of these alert situations

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would merely be routine passings at 300 m (1000 ft) separation.

(4) Devising transition strategies is easy with this approach. The total number of tracks would not change, and initially one CDTI-only track could be assigned. More CDTI-only tracks could be assigned later, one at a time.

(5) The TCAS II MOPS (Reference 2) specifies minimum altimetry requirements for all aircraft carrying TCAS II. This means that vertical navigational performance on CDTI-only tracks should be better than for the aircraft population as a whole.

(6) It should be easy for aircraft on adjacent flight levels to maintain 300 m (1000 ft) of indicated vertical separation, except during severe turbulence. In this case, however, pilots can agree to fly at an offset from the track centerline to ensure 9 km (5 n. mi.) of lateral separation. This would be easy to do with the CDTI display. With 110 km (60 n. mi.) spacing between adjacent tracks, this would not represent a significant deviation from the assigned track.

On the other hand, the vertical reduction strategy has the following disadvantages:

(1) Every vertical passing of two aircraft on adjacent flight levels would result in a CDTI alert. During the time of horizontal proximity (which could last for half an hour or more), continuous monitoring of the CDTI display would be required.

(2) Because of the lack of data on the altimetry system errors of today's transoceanic aircraft, and because of the lack of a suitable failure model for the proposed CDTI system,

it is impossible to accurately determine collision risk with this strategy. Such a determination would require new data and more in-depth analysis.

Reduced Lateral Spacing

The strategy of reducing lateral separation calls for a one-half reduction only in the minimum spacing between adjacent tracks. For the NAT, this is equivalent to separation minima of 30/10/2000. This strategy has the following advantages:

(1) The maximum alert rate, as estimated in Section 8, would be the lowest for any of the proposed strategies. For the NAT, it is likely that most crossings of the ocean would not experience any CDTI alerts.

(2) It should be easy to demonstrate, without a great deal of analysis, that this strategy significantly reduces collision risk in comparison with current system operations.

(3) Since vertical spacing is not reduced, the vertical dimension would be available for resolving many of the conflicts that occur.

The strategy of reducing lateral separation also has the following disadvantages:

(1) The potential savings in flight costs are far less than with a reduction in vertical spacing.

(2) It would be difficult to devise smooth transition strategies, since CDTI-only tracks would have to be added in groups of two or three in order to provide cost benefits to equipped aircraft.

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Reduced Longitudinal Spacing

The strategy of reducing longitudinal separation calls for a one-half reduction only in the minimum along-track separation between successive aircraft on the same flight level. For the NAT, this would mean separation minima of 60/5/2000. This strategy has the following advantages:

(1) The alert rate would be low, with perhaps only one CDTI alert occurring for every few crossings of the ocean.

(2) Of all encounter geometries, overtake encounters are the slowest to develop and among the simplest to deal with.

(3) It should be relatively easy to demonstrate, without a great deal of analysis, that this strategy significantly reduces collision risk in comparison with current system operations.

(4) Devising transition strategies is easy with this approach. The total number of tracks would not change, and initially one CDTI-only track could be assigned. More CDTI-only tracks could be assigned later, one at a time.

(5) Since neither vertical nor lateral spacing is reduced, pilots would have a great deal of freedom in selecting resolution strategies for any conflicts which occur.

The strategy of reducing longitudinal separation also has the following disadvantages:

(1) This strategy results in the lowest payoff, in terms of reduced flight costs, of any of the alternatives considered.

(2) With reduced longitudinal spacing, speed adjustments would sometimes be necessary to ensure safe separation; there is

some potential for a domino effect back along the track from an aircraft flying more slowly than its filed Mach number.

(3) If an alert occurs because the trailing aircraft is overtaking, it may be difficult to achieve a permanent resolution of the conflict. Such resolution may require the trailing aircraft to fly at a slower-than-desired Mach number, thus incurring an additional cost penalty.

(4) It is felt by some observers that using a collision avoidance device to support a reduction in longitudinal spacing would require more frequent position reports, perhaps every 5 degrees of longitude for east-west systems; if so, this would represent an increase in workload for both controllers and ground communications staff.

Reduced Lateral and Longitudinal Spacing

This strategy calls for a one-half reduction both in the minimum track spacing and in the minimum along-track separation between successive aircraft. For the NAT, this would be equivalent to separation minima of 30/5/2000. This strategy would have the following advantages:

(1) With this approach, the potential savings in flight costs are second only to those estimated for the vertical reduction strategy, among the alternatives considered.

(2) The alert rate would be low (perhaps only one CDTI alert for every few crossings of the ocean) and would not represent a burden to the flight crew.

(3) Devising transition strategies would be easy with this approach. Initially, one CDTI-only track could be

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assigned. Full cost benefits would not be achieved, however, until a large number of CDTI-only tracks were available.

(4) This approach provides a greater increase in traffic capacity than any of the alternatives studied. This could be important, depending on the projections of future traffic growth for a particular track system.

(5) It should be relatively easy to demonstrate, without a great deal of study, that this strategy significantly reduces collision risk in comparison with current system operations.

(6) Since vertical spacing would not be reduced, the vertical dimension would be available for resolving many of the conflicts that occur.

This strategy also has the following disadvantages:

(1) The potential savings in flight costs are still far less than with a reduction in vertical spacing.

(2) With reduced longitudinal spacing, adjustments in Mach number would sometimes be necessary to ensure safe separation, resulting in a less fuel-efficient speed for the overtaking aircraft. As previously explained, there is some potential for a domino effect back along the track.

(3) Reduced longitudinal spacing, as previously explained, might require more frequent aircraft position reports, with a resultant increase in workload for controllers.

Comparison of Alternatives

Obviously, the choice of one of the proposed strategies for
reducing separation would require a great deal of analysis based
upon the requirements of the particular track system being
considered. The proper choice would be the strategy which provided
the greatest cost benefits, while ensuring minimum safety levels and
adequate capacity for future traffic growth. It is also likely that
other strategies, such as combinations of those proposed here, would
be considered.

Primarily because of the size of the potential cost benefits,
the scheme involving reduced vertical separation would be the
preferred strategy among the alternatives considered. However,
there are more uncertainties (such as collision risk and pilot
workload) associated with this strategy than with any of the other
proposed schemes. This strategy would therefore require the
greatest amount of study to confirm its acceptability.

The strategy of reducing both lateral and longitudinal spacing
would be an obvious second choice, both because of the potential
benefits and the relative ease of confirming its feasibility.
Reducing only lateral separation would be the third choice of the
alternatives studied. Reducing only longitudinal separation would
be the least preferred because of its relatively low payoff and the
potential problems associated with maintaining in-trail spacing.

SECTION 12

IMPLEMENTATION ISSUES

In this section we consider a number of implementation issues which need to be addressed for the oceanic CDTI concept. These include contention for the voice channel, oceanic multipath effects, compatibility of pilot-negotiated resolution actions with TCAS II resolution advisories, the impact of the CDTI system on pilot workload, and TCAS interference levels.

Contention for the Voice Channel

One possible limitation on the oceanic CDTI system is contention for the voice channel. This potential limitation is closely related to the CDTI alert rate and is influenced by the same factors which affect the alert rate. Without an estimate of the total system alert rate, contention for the voice channel cannot be determined precisely. However, enough information is available to estimate an upper bound on the probability of voice communication being required simultaneously for a second conflict within the radio range of an existing conflict.

To derive a formula for this probability, we begin with the assumption that the fraction of time that each aircraft requires voice communication is no more than t_c x R_A, where t_c is the length of the average conversation, and R_A is the maximum alert rate for an aircraft. Given that one pair of aircraft requires voice communication for a conflict, the probability of a specified third aircraft requiring voice communication simultaneously for another conflict is no more than $2t_c$ x R_A. If there are a total of N_A aircraft within the radio range of a conflict pair,

including the two aircraft in conflict, then the upper limit on the probability of contention for the voice channel is given by:

$$P_c \leq 1 - [1 - 2(t_c)(R_A)]^{N_A - 2} \qquad (11)$$

Since $2\ t_c \times R_A$ is much less than 1, this inequality can be simplified by a binomial expansion to give:

$$P_c \leq 2(N_A - 2)(t_c)(R_A) \qquad (12)$$

The values of the variables in this formula will now be approximated for the North Atlantic. First, the value of N_A will be estimated. According to FAA sources, a VHF radio receiver used at altitudes above 4600 m (15 000 ft) must have sufficient sensitivity to receive a 10-Watt ground station at a range of 300 km (160 n. mi.). The VHF transmitters used on large aircraft generally operate at power levels of 18-25 Watts. Range is proportional to the square root of power. Thus, ignoring any differences in the gains of ground and airborne antennas, the reliable air-to-air range of a VHF radio should be between 390 and 460 km (210-250 n. mi.). Using 460 km (250 n. mi.) as a baseline value, this represents a coverage area of 673 000 km^2 (196 000 n. mi.^{2}). Assuming that the average radio conversation takes place at a range of 37 km (20 n. mi.), this means a coverage area of roughly 708 000 km^2 (206 000 n. mi.^{2}) for the two aircraft combined.

The peak number of aircraft within this coverage area can now be estimated. To begin with, the North Atlantic track system occupies an area of approximately 10 000 000 km^2 (3 000 000 n. mi.^{2}). Thus, the VHF coverage area for a conflict in the middle of this track system would represent approximately 7% of the total area.

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Reference 1 states that the OASIS flight cost model projected a peak instantaneous airborne traffic count of 223 aircraft for the entire North Atlantic for the year 2005. We shall make the conservative assumption that all of this traffic lies within the track system. If this traffic were evenly distributed throughout the track system, then 7% of this number would mean an average of 16 aircraft within the VHF coverage area of two aircraft in conflict. Multiplying this number by a factor of 5 to account for uneven distribution, we arrive at a value of 80 for N_A.

In Section 8, maximum alert rates were estimated for same-direction and opposite-direction scenarios. Let us assume that the same-direction scenario applies 90% of the time and that the opposite-direction scenario applies 10% of the time (conservative for the North Atlantic). For separation minima of 30/5/2000 (reduced separation in both horizontal dimensions), this yields a maximum alert rate of 0.016 alerts per hour. This value will be used in equation (12) for R_A. A value of 45 seconds, or 0.0125 hours, will be used for t_c.

Substituting the above values into equation (12) yields a maximum probability of contention of 3.1% for the North Atlantic in the year 2005. Since the average alert rate per aircraft should be much less than the maximum, this result should be very conservative. It must also be remembered that same-direction encounters would tend to develop quite slowly. In many such encounters, it might be possible to wait for the voice channel to be clear, if necessary. Time would be much more critical for opposite-direction encounters.

If the vertical separation minimum is reduced, contention for the voice channel is more difficult to estimate. Although the

maximum alert rate would be much higher, voice communication should not be required for all of such alerts.

Oceanic Multipath Effects

In theory, TCAS interrogations and replies can reach an airborne receiver in two ways: a direct signal from the transmitter to the receiver, and an indirect signal reflected from the earth's surface. Since the path of the indirect signal is longer, it is delayed with respect to the direct signal. This can cause synchronous garble if the two signals overlap.

Over land areas, multipath should not be a serious problem for TCAS. This is because the reflected signal is typically both attenuated and scattered by the terrain. In oceanic areas, however, multipath is potentially a greater problem, as the ocean's surface forms a more nearly perfect reflector.

Figure 9 illustrates the geometry of the multipath problem. In this figure, A_1 and A_2 are the altitudes of two aircraft. R is the horizontal separation (range) of the two aircraft. The angle G is referred to as the grazing angle and is given by:

$$G = \arctan \frac{A_1 + A_2}{R} \qquad (13)$$

The delay of the reflected signal with respect to the direct signal is given approximately by:

$$t_D = R \ (\text{secant } (G) - 1)/c \qquad (14)$$

where t_D is the delay time in seconds and c is the speed of light.
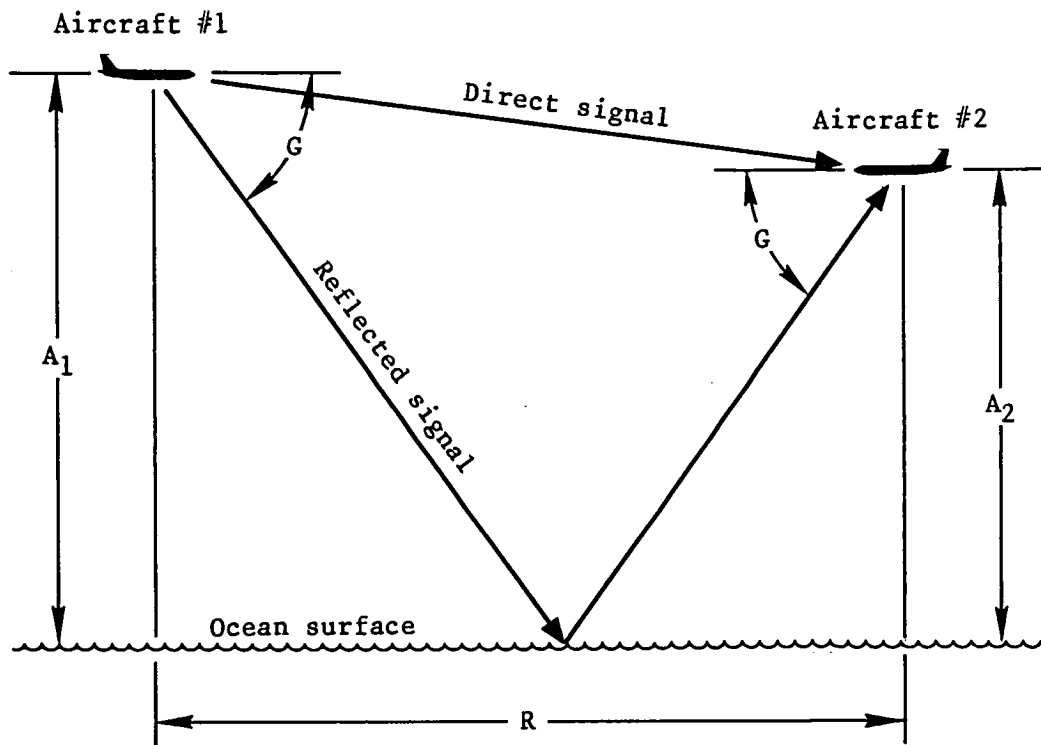
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Figure 9.--Multipath geometry.

Evaluation of these equations for altitudes and ranges which
would be typical for the oceanic CDTI system reveals that the
grazing angle can vary from 0.26 to 1.2 rad (15 – 70 deg) or more
and that the time delay would typically fall in the range of 10 – 50
microseconds. The significance of this time delay can be determined
by a comparison with the length of various transmissions. TCAS
interrogations are transmitted at a data rate of approximately 4
million bits per second. Short interrogations (normal surveillance,
56 bits) are approximately 18 microseconds in length, while long
interrogations (112 bits) are about 32 microseconds in length.
Replies are transmitted at a data rate of only 1 million bits per
second. Short and long replies are approximately 72 and 128
microseconds in length, respectively. It becomes clear, then, that
garble stemming from the overlapping of direct and multipath signals
could be a problem over most of the operating range of the oceanic
CDTI system.

Because of antenna shielding, it is expected that the multipath
problem would be the most severe for a bottom–antenna–to–
bottom–antenna link. The problem is exacerbated by the fact that
the short monopole antennas used at these frequencies tend to
produce maximum gain at about 0.35 rad (20 deg) from the
horizontal. This tends to amplify the reflected signal with respect
to the direct signal.

In 1977, M.I.T. Lincoln Laboratory conducted flight tests to
evaluate L–band multipath effects. The study report (Reference 9)
largely verifies the above analysis. Some of the findings of the
study were as follows:

(1) Multipath scattered from smooth surfaces, especially water
    surfaces, is a significant form of interference on the
    air–to–air channel.

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(2) Data collected over similar surfaces on different days
     exhibited striking consistency with regard to each
     multipath parameter.

(3) When compared with the direct signal, the echo in every
     case was delayed by an amount which agrees with the
     geometric formula (equation 14).

(4) The power of multipath echos varies greatly, with the span
     between the 10th and 90th percentiles being 10-15 dB. The
     smoother the surface, the less variation.

(5) Over oceanic surfaces, the power and signal distortion
     depend on the smoothness of the sea. On calm days, the
     surface acts more like a perfect reflector, with the
     greatest power and the least distortion.

(6) The median multipath-to-signal ratio can be as high as 0 dB
     over grazing angles ranging from approximately 0.26 to 0.70
     radians (15 to 40 degrees) for bottom-to-bottom signals.
     Individual reflected signals often exceed the direct signal
     power, with about 10% of the multipath echos exceeding the
     direct signal by 5 dB or more.

(7) These results are unaffected by altitude to any measurable
     degree.

(8) The use of a top-mounted antenna in the link results in
     significant reductions (15 dB or more) in received
     multipath at high grazing angles (0.17-1.3 radians, or
     10-75 degrees). The top-to-top antenna link reduces
     multipath levels still further for grazing angles above
     0.17 radians (10 degrees).

Figure 10, adapted from Reference 9, shows typical
multipath-to-signal ratios over a calm sea for various types of
links. Since TCAS II uses both top and bottom-mounted antennas, it
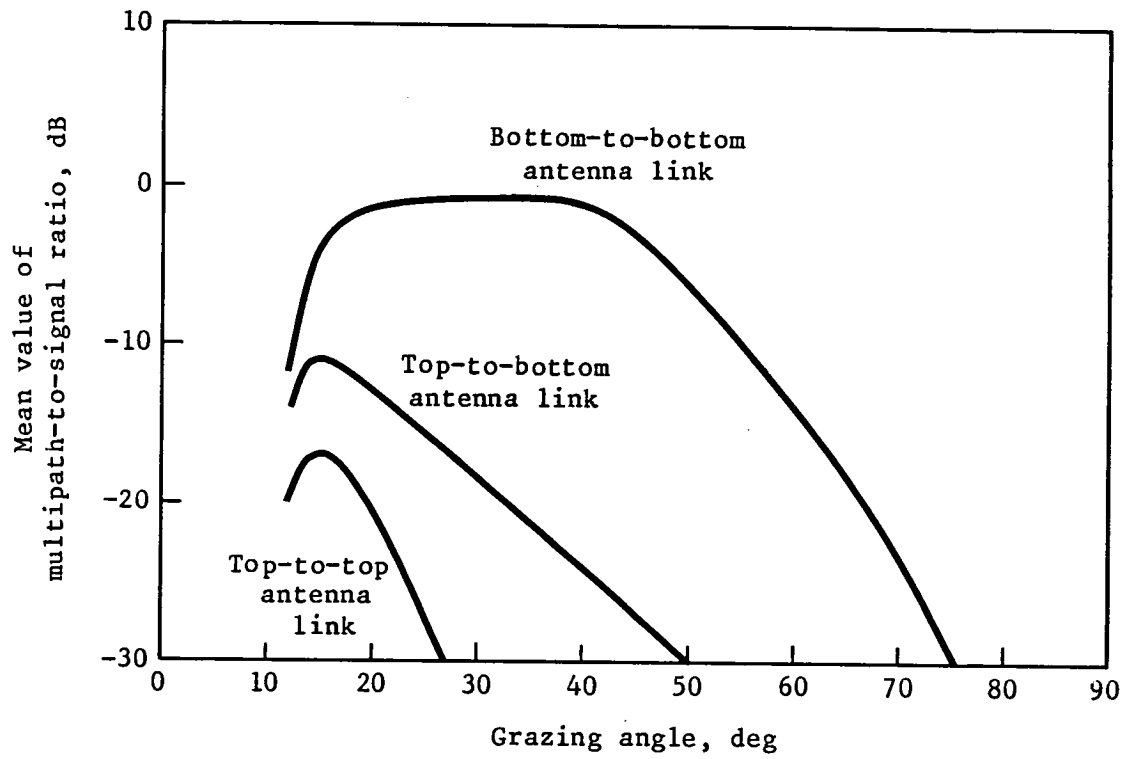becomes clear that the oceanic CDTI system would be resistant to

Figure 10.–Typical multipath-to-signal ratios over a calm sea.

multipath degradation, since TCAS places primary dependence on transmissions from the top-mounted antenna. The bottom-mounted antenna is used chiefly for fill-in during top antenna fades, especially at close ranges. In the baseline CDTI system, where all aircraft on CDTI-only tracks are equipped, the presence of diversity antennas at both ends of the link ensures that multipath effects would be minimal.

Multipath effects on the measurement of target bearing also need to be considered. TCAS manufacturers may use any of several methods of measuring target bearing. With some of these methods, the measurement accuracy could be degraded if a direct signal and a multipath signal were to be received at the time of the bearing measurement. This problem can be avoided, however, by using bearing measurements taken only on the early pulses in the Mode S or Mode C reply. Some of the early pulses in the direct signal will always be received free of multipath for all geometries appropriate to an oceanic track system.

Compatibility with TCAS II Resolution Advisories

What are the chances of a TCAS resolution advisory being issued which is incompatible with the pilot-negotiated resolution maneuvers? Assuming that the pilot-negotiated maneuvers are correct and timely, the chances are essentially zero. However, what happens if pilot-selected maneuvers are initiated late and the maneuvers selected are not the best choice? In order to answer these questions, an analysis was performed for vertical maneuvers.

For this compatibility analysis, the following assumptions were made:

(1) A conflict occurs involving two head-on, 310 m/s (600 knot) aircraft in level flight.

(2) Aircraft #1 is initially at a higher tracked altitude than aircraft #2, but the pilots choose for aircraft #1 to descend and for aircraft #2 to climb. (Perhaps this comes about because the aircraft were transposed in altitude as discussed in Appendix A.)

(3) Aircraft #1 accelerates vertically at 0.25 g to a 2.5 m/s (500 ft/min) descent rate, while aircraft #2 accelerates at 0.25 g to a 1.3 m/s (250 ft/min) climb rate.

(4) TCAS II issues vertical resolution advisories at 30 seconds to 1.9 km (1.0 n. mi.), or 33 seconds before closest approach.

Using these assumptions and the current TCAS II resolution logic, calculations were made to determine what initial altitude deficit would be required, as a function of pilot delay, to cause TCAS to issue vertical resolution advisories which reverse the pilot-selected maneuvers.

The results of this vertical compatibility analysis can be expressed by the following equation:

$$A_d = 125 - 3.81(t_D) \tag{15}$$

This equation gives the altitude deficit A_d, in meters, which must occur before a pilot delay of t_D seconds will result in a TCAS resolution advisory which reverses the sense of the pilot-selected maneuvers. For instance, a wrong-sense maneuver begun 50 seconds before closest approach (10 seconds late) can make up a deficit of about 87 meters (280 feet) in altitude without TCAS reversing the sense of the resolution maneuvers.

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In the horizontal plane, there is even less cause for concern about sense reversal. With a CDTI system based upon Minimum TCAS II, only vertical resolution advisories can be issued. Thus, if horizontal resolution is selected by the pilots, no incompatibility can result.

Impact on Pilot Workload

In the oceanic enroute environment, pilot workload is normally very light, a condition which is not expected to be greatly affected by the addition of a CDTI system. Reductions in lateral and/or longitudinal spacing should result in alert rates that are too low to significantly affect pilot workload (see Section 8). Reduction of the vertical separation minimum to 300 meters (1000 feet) on one-way tracks would have a more noticeable impact on pilot workload. As pointed out in Section 8, every time own aircraft passes an intruder on the same one-way track at an adjacent flight level, a CDTI alert is expected to result with this spacing. Only a small percentage of such alerts would require resolution maneuvers. However, the vertical situation would require more constant monitoring, and this could bring about a measurable increase in pilot workload during peak traffic conditions. Nevertheless, the total time required for monitoring and effecting resolution would still represent a small fraction of the pilot's workload capacity in normal conditions.

The one factor that would contribute to a significant workload increase when operating with reduced vertical separation is heavy turbulence. If a pilot, in overtaking another aircraft which was 300 m (1000 ft) above, were to pass directly underneath, he would experience a considerable workload because of the heavy turbulence, as described earlier. It is proposed that the two pilots agree to

maintain a lateral offset of at least 9 km (5 n. mi.) with the aid
of the CDTI display. This should relieve the pressure of trying to
maintain a precise flight level when flying in heavy turbulence and
should maintain the workload at a manageable level.

TCAS Interference Levels

The TCAS MOPS (Reference 2) requires that the interrogation rate
and/or power of TCAS II be controlled so as to minimize interference
effects. This requirement is principally aimed at preventing
interference with ground-based ATCRBS surveillance. In oceanic
areas the absence of ground-based sensors makes this concern almost
a non-issue. Nevertheless, this issue can be thoroughly laid to
rest with a simple analysis of the MOPS requirements vis-a-vis the
modified TCAS system.

The specific limitations of the TCAS MOPS are given in the form
of three inequalities which must be satisfied by each TCAS system.
One of these inequalities is aimed at preventing TCAS interrogations
from suppressing own aircraft's transponder for too large a portion
of time. This inequality is basically a limit on the total
interrogation rate, and presents no problems in the low-density
oceanic environment. Another inequality is aimed at limiting the
ATCRBS fruit rate caused by TCAS interrogations. This is not a
significant limitation for the oceanic CDTI system, since today's
traffic densities over the ocean are very low and the increase in
traffic levels over the next twenty years should be more than offset
by a gradual transition to Mode S transponders.

The remaining inequality is intended to limit the total
interference effect of all TCAS interrogations in a local area.

This inequality is the one which must be examined the most closely. The inequality can be expressed in the form:

$$\frac{I(P_a)(N_T)}{250 \text{ watts}} \leq 280 \tag{16}$$

Where I is the number of interrogations issued by own TCAS in one second, P_a is the average power per interrogation, and N_T is the approximate number of TCAS-equipped aircraft within the maximum surveillance range of own aircraft.

Approximations can be made as to how the variables in this inequality vary as a function of range. The variable N_T would be proportional to both traffic density and the square of the maximumn range (assuming uniform distribution). The variable I can be assumed, in the limiting case, to be roughly proportional to N_T. Therefore, I also would be proportional to traffic density and the square of maximum range. The variable P_a should be proportional to the maximum range squared. With these assumptions, then, equation (16) can be reduced to:

$$D^2 R_M^6 \leq K^2 \tag{17}$$

where D is traffic density, R_M is maximum range, and K is a constant. Solving for D, we see that the allowable traffic density is roughly inversely proportional to the cube of maximum range:

$$D \leq K/R_M^3 \tag{18}$$

We will now apply this finding to the CDTI system. To begin with, TCAS II is designed to be effective in a traffic density of up to 0.09 aircraft/km^2 (0.3 aircraft/ n. mi.^{2}). If the maximum range of TCAS is doubled for CDTI over the ocean, application of

equation (18) indicates that the system could operate effectively in a traffic density as high as 0.011 aircraft/km^2 (0.038 aircraft/n. mi.^{2}) while meeting the interference requirements.

The OASIS report (Reference 1) contains traffic projections which are useful in estimating future traffic densities over the ocean. Based upon separation minima of 30/5/2000, the OASIS flight cost model projected, for the year 2005, a peak of 70 aircraft in proximity over roughly a 15 400 km^2 (4500 n. mi.^{2}) portion of the North Atlantic. This number included aircraft both inside and outside of the track system. These numbers yield a peak traffic density of 0.0045 aircraft/km^2 (0.016 aircraft/n. mi.^{2}), easily meeting the upper limit derived above.

Finally, it should be remembered, as explained in Section 6, that it may not be necessary to double the maximum range of TCAS in order to double its reliable range over the ocean. That is, a reduced link margin might be acceptable in the high-altitude oceanic environment. This could ease any traffic density limitations even further. It should also be remembered, as pointed out previously, that if separation minima are reduced in such a way that the likelihood of head-on encounters is not increased, then the required range for TCAS in the oceanic mode might be considerably less than 74 km (40 n. mi.).

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SECTION 13

SYSTEM VARIATIONS AND EXTENSIONS

In this section, a number of variations and extensions of the CDTI concept are considered. First, a variation is described which would indefinitely allow both equipped and unequipped aircraft to use the oceanic track system. Next, possible adaptations are discussed which deal with the problem of non-track aircraft crossing the tracks. Finally, the possibility of extending the system to permit cruise climb is considered.

Variation to Include Unequipped Aircraft

A variation of the oceanic CDTI concept is possible to allow both equipped and unequipped aircraft to use the oceanic track system indefinitely. The basic ground rules for this variation are as follows:

(1) Separation minima are reduced for CDTI-equipped aircraft.

(2) CDTI-equipped aircraft enjoy the minimum restrictions on the selection of tracks, flight levels, and in-trail spacing.

(3) Unequipped aircraft are restricted to tracks, flight levels, and in-trail spacing distances which guarantee that the separation between pairs of unequipped aircraft is never reduced.

Both the separation minima and the resolution procedures would be modified with this variation.

Figure 11 presents an example of separation minima using the variation described above. In this example, CDTI-only tracks alternate with mixed-equipage tracks. Separation minima are reduced for CDTI-equipped aircraft to 56 km (30 n. mi.) laterally and to 5 minutes for in-trail spacing. Unequipped aircraft are restricted to mixed-equipage tracks and to 10 minutes for in-trail spacing.

With the mixed-equipage variation, air-to-air communication between equipped and unequipped aircraft might be possible if unequipped aircraft also monitored the designated CDTI voice frequency. However, as previously explained, the identification of unequipped aircraft for establishing communication would be a problem.

If voice contact were possible between CDTI-equipped aircraft and unequipped aircraft, then resolution procedures would have to be only slightly modified. In equipped-unequipped conflicts, resolution maneuvers would become the primary responsibility of the pilot of the equipped aircraft. Voice contact would be used primarily for the pilot of the equipped aircraft to obtain the heading of the unequipped aircraft and to ensure that the pilot of the unequipped aircraft was apprised of the situation and did not make an uncooperative maneuver. It would not be desirable, in general, for the pilot of the equipped aircraft to recommend a maneuver for the unequipped aircraft, since the CDTI might not show all other traffic in the vicinity of the unequipped aircraft. However, in cases involving deviation from assigned flight level by the unequipped aircraft, it would be reasonable for the pilot of the equipped aircraft to suggest a return to assigned flight level for the unequipped aircraft. The pilot of the unequipped aircraft could confirm the reasonableness of this maneuver on the basis of
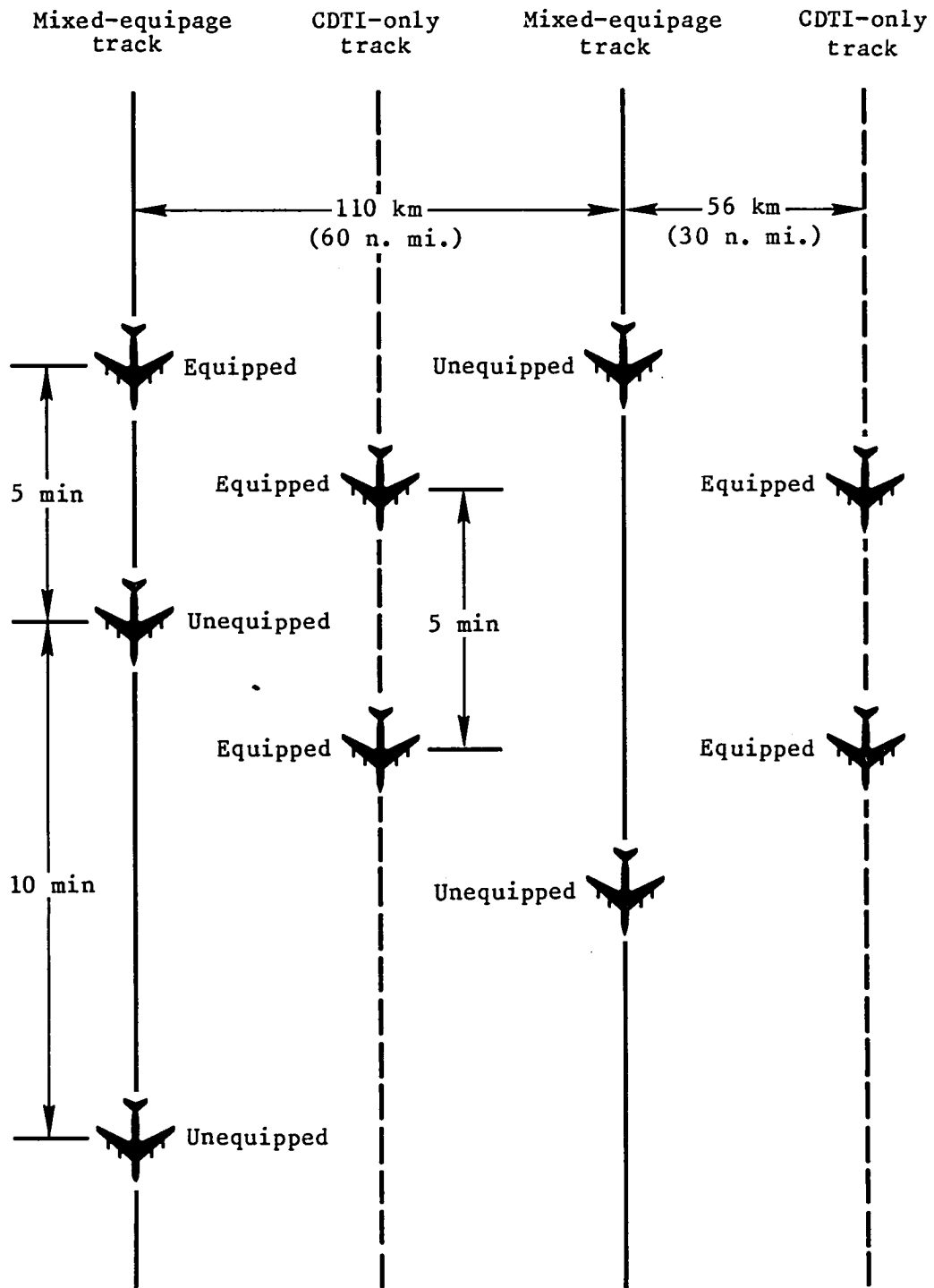
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Figure 11.–Sample separation minima for the
mixed-equipage variation.

exchanged, assigned and actual flight levels, without the need to observe a CDTI display.

If voice contact were not possible for equipped-unequipped conflicts, no guarantee would exist that the unequipped aircraft would not make an uncooperative maneuver. However, since no time would be required for a conversation, the pilot of the equipped aircraft would have more time (perhaps 45 more seconds) to execute a resolution maneuver. This extra time would in most cases allow nearly as much separation to be achieved as would be possible if both aircraft performed cooperative maneuvers. Without voice contact, the heading of an unequipped intruder would not be known with extreme accuracy (assuming the CDTI system is based upon Minimum TCAS II). Thus, the vertical dimension would have to be relied upon more heavily for resolution. For same-direction encounters, the oceanic control system often would have to be contacted for final resolution.

The mixed-equipage variation described above would have the following advantages:

(1) Reduced spacing would give equipped aircraft a greater selection of routes and/or reduced waiting time for entry into the track system.

(2) Unequipped aircraft would not be penalized.

(3) The incidence of conflicts between unequipped aircraft would not be increased.

(4) The first aircraft to equip with CDTI could obtain immediate positive benefits.

(5) The system could eventually transition, if desired, to an all-CDTI system; a greater variety of transition strategies would be possible.

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However, the mixed-equipage variation would have the following disadvantages:

(1) Resolution by one aircraft would be less reliable.
(2) Without the natural redundancy of having both conflict aircraft equipped, the variation would be more susceptible to equipment failures; this would mean either less system reliability or a higher cost for CDTI equipment.
(3) In an equipped-unequipped conflict, the data link might not be as reliable, since ATCRBS transponders generally use only a single, bottom-mounted antenna; thus, the link would be somewhat more susceptible to signal fades and multipath effects.

For a given set of separation minima, maximum alert rates (at capacity loading) for this system variation would actually be the same as those computed for the baseline CDTI system. However, actual alert rates would depend on the mix of equipped and unequipped aircraft, as well as their distribution within the track system.

It is to be expected that the introduction of the oceanic CDTI concept would initially be accompanied by skepticism and distrust on the part of some of the persons and organizations involved. The basic concept, which applies reduced separations only between equipped aircraft, is able to instill a higher level of confidence than the mixed-equipage approach described here because of the equipment redundancy, the cross-checking possible through the action of two sets of crews, the ease of establishing voice contact, and the confirmation possible of each pilot's intentions. Primarily for this reason, it is recommended that the CDTI concept be implemented

initially by applying reduced separation minima only between equipped aircraft. Once experience has been acquired with this type of operation, the use of reduced separations between equipped and unequipped aircraft could be considered.

Adaptations for Non-Track Aircraft Crossing the Tracks

The occurrence of non-track aircraft crossing the tracks of today's oceanic track systems is becoming increasingly common. In this situation, the non-track aircraft is usually forced to fly above or below the track system. In order for a non-track aircraft to actually fly through the track system, air traffic controllers must create, at the appropriate flight level, a moving "window" in the stream of traffic on each track which is to be crossed. For typical oceanic control systems, controllers do not have a situation display, and position reports are received on an infrequent basis (only about once an hour from each aircraft). Therefore, the controller's ability to mentally project a non-track aircraft ahead is limited, and such "windows" must be very large in size. This can produce delays and can lower traffic capacity on the tracks.

Under the oceanic CDTI concept, if the non-track aircraft is CDTI-equipped, then the size of the windows on CDTI-only tracks can be somewhat reduced, resulting in less delay on these tracks. This is illustrated in Figure 12. The amount of such reductions would depend on the statistical distribution representing a controller's ability to accurately project the non-track aircraft across the tracks.

In general, specific tracks are not permanently established for crossing aircraft. Consequently, the pilot of an aircraft in the oceanic track system cannot visualize the intended separation
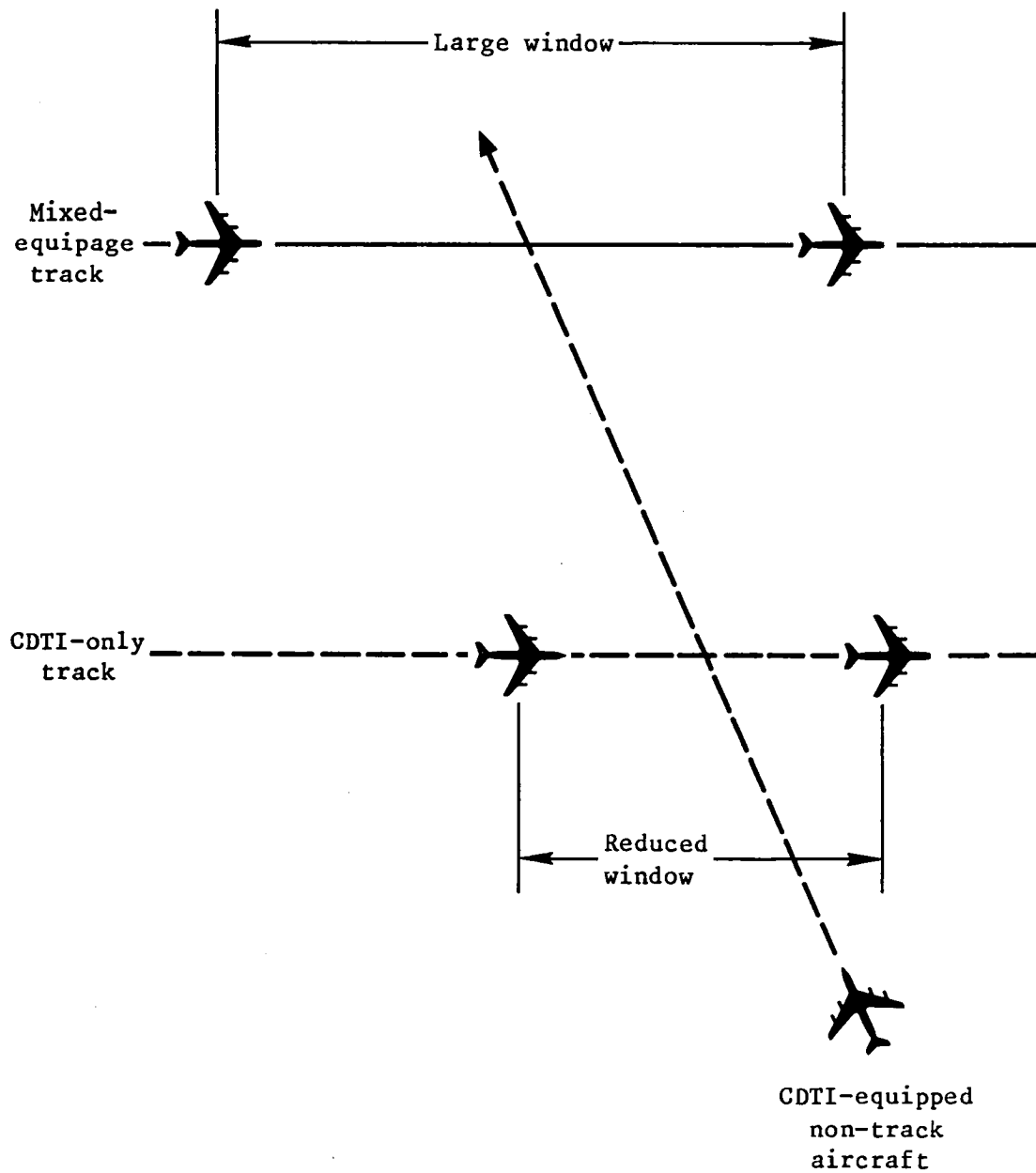
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Figure 12.–Adaptation to permit a non-track aircraft to cross the tracks.

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geometry merely by knowing the two assigned track identifiers. The pilots of two aircraft in conflict must devise a resolution strategy based only on the actual geometry at that moment. Even so, the pilots should be able to develop acceptable resolutions, and this capability should permit the "window" for separating a crossing aircraft from a track aircraft to be reduced when both are equipped.

The reduced separations may not produce as much advantage as at first expected, however, because only some of the tracks would be those reserved for CDTI-equipped aircraft. The additional complexity for the oceanic controllers in determining the clearances for a CDTI-equipped aircraft's crossing path when some tracks require one separation and others another may more than offset the limited benefits. On the other hand, if reduced separations were permitted between equipped and unequipped aircraft, it would be convenient and beneficial to apply reduced separations for a CDTI-equipped crossing aircraft.

The oceanic CDTI system would be much less helpful in the case of an unequipped aircraft crossing the tracks. In this case, the size of the windows on CDTI-only tracks probably could not be reduced significantly if safety were to be maintained. The resolution of a crossing encounter would be much more difficult for one pilot than for two. Air-to-air communication between the pilots might help to some extent, but, as previously explained, proper radio identification becomes a problem in establishing contact with an unequipped aircraft.

It seems likely that as CDTI were introduced to a track system, the strategy for dealing with non-track aircraft crossing the tracks would evolve with time. Early reports from CDTI-equipped aircraft on crossing traffic could give a much better idea of what separation

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distances were required. Reductions in the sizes of the track
windows would become much more feasible once confidence in the CDTI
system had been established and a high level of CDTI equipage had
been attained.

Extension to Permit Cruise Climb

The concept of cruise climb simply means that an aircraft is
allowed to perform free-form flight in the vertical dimension. This
would enable a pilot to fly constantly at his aircraft's most
fuel-efficient altitude. For most aircraft, the optimum altitude
increases slightly as fuel is burned off and the aircraft gross
weight decreases. Studies have shown that controllers find it
extremely difficult to project multiple cruise climb trajectories in
three dimensions. Therefore, in order to permit cruise climb, the
altitude spectrum of an oceanic track system would have to be
divided into one or more layers, or ranges of altitudes. Each
altitude clearance would be issued as a range; a pilot could fly at
any altitude within the range and would only need a new clearance if
it became necessary to transition to another altitude layer. With a
system of this sort, heavy reliance would be placed upon the
horizontal dimension for the safe separation of aircraft.

The benefits of cruise climb are significant. The UK delegation
of the international Aviation Review Committee (ARC) estimated the
potential savings in flight costs at 66 million dollars over 11
years (1995-2005) for the North Atlantic fleet (Reference 1). This
estimate was based upon the assumption of a single-layer system with
15/2 horizontal separation minima.

In order to rely more on the horizontal dimension for aircraft
separation without loss of traffic capacity, it would be necessary

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to reduce lateral and longitudinal separation minima to the greatest degree possible. Therefore, in order to support the cruise climb concept, the oceanic CDTI system would have to allow sufficient reductions in horizontal separation minima both to offset the loss of vertical flight levels and to provide sufficient capacity for reasonable traffic growth.

In the North Atlantic track system, four flight levels with 610 m (2000 ft) spacing are currently used. If the oceanic CDTI system were employed to reduce lateral and longitudinal spacing each by a factor of two, then a single-layer cruise climb system would have approximately the same traffic capacity as before. As noted previously, ARC projections are for about an 80% traffic increase for the North Atlantic by the year 2005. A vertical expansion of the North Atlantic track system, enabling a two-layer system, might therefore be necessary to provide adequate capacity for future growth. Thus, the potential of an oceanic CDTI system based upon Minimum TCAS II for supporting the cruise climb concept is marginal. A CDTI system based upon Enhanced TCAS II, possibly combined with improvements in lateral navigational performance, might allow a reduction to 28 km (15 n. mi.) track separation. This would provide better support for the cruise climb concept, but at additional capital costs for users.

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SECTION 14

CONCLUSIONS

The purpose of this study was to document a concept for reducing oceanic separation minima through the use of a TCAS-derived CDTI and to provide initial understanding about the feasibility of this concept. The limited depth of the study in many areas is recognized. On the basis of the study to date, the following conclusions have been drawn:

(1) The oceanic CDTI concept as described in this document appears feasible and offers promise of achieving reduced separation minima in an oceanic track system. The system has limitations and uncertainties, enumerated below, but none of these appears to represent an insurmountable hurdle.

(2) Separation minima in an oceanic track system could be reduced in four principal ways. From the study to date, they would be preferred in the following order:

- Vertical separation minimum reduced from 610 m (2000 ft) to 300 m (1000 ft), in conjunction with using only one-way tracks.
- Lateral separation minimum reduced from 110 km (60 n. mi.) to 56 km (30 n. mi.) at the same time that the longitudinal separation minimum is reduced from 10 minutes to 5 minutes.
- Lateral separation minimum reduced from 110 km (60 n. mi.) to 56 km (30 n. mi.).
- Longitudinal separation minimum reduced from 10 minutes to 5 minutes.

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(3) The following modifications to the Minimum TCAS II
     equipment would be required to support this oceanic CDTI
     concept:

     -    Increased TCAS transmitter power and receiver
          sensitivity to increase the maximum surveillance
          range. The maximum range required depends upon
          how the separation minima are reduced.
     -    A device for manually entering the aircraft's ATC
          call sign.
     -    One new set of air-to-air data link formats and
          protocols for read-out of the ATC call sign.
     -    A switch that permits the pilot to select either
          the oceanic mode or the normal mode of operation
          of his TCAS.
     -    A test switch which the pilot can activate while
          airborne to receive a display of all targets
          being tracked by his TCAS unit.
     -    A new display scale capable of displaying greater
          ranges than the current TCAS II system.
     -    The ability to display the ATC call sign with
          each target.

(4) The following modifications to the logic of the Minimum
     TCAS II would be required:

     -    Enlarge the range boundaries to provide a CDTI
          alert whenever the target can come within 9.3 km
          (5 n. mi.) within 105 seconds.
     -    Set the vertical boundaries to provide an alert
          whenever the target is within 370 m (1200 ft) in
          altitude or there is closing in altitude such

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that the target can be at own altitude within 45 seconds.

- Enlarge the proximity advisory boundaries.

(5) The oceanic CDTI concept should be implemented in such a way that reduced separations are applied only between aircraft which are CDTI-equipped. In this way, there is redundancy to protect against any human errors or equipment malfunctions.

(6) The voice coordination achieved through use of a common VHF frequency is extremely important to the effectiveness of this concept. It permits the exchange of additional data which can clarify a situation and assist in selection of resolution actions, and it permits the pilots to declare their intentions.

(7) The procedures for responding to a CDTI alert are natural and intuitive. Specific resolution rules for particular situations should not be prescribed.

(8) Data does not exist for making sound estimates of typical CDTI alert rates in an oceanic track system. Estimates which are thought to represent upper bounds for each of the four reduced separation alternatives are:

Reduced Vertical Spacing
with One-Way Tracks   − 4 Alerts per Flight

Reduced Lateral and
Reduced Longitudinal Spacing   − 1.7 Flights per Alert

Reduced Lateral Spacing   — 3.5 Flights per Alert

Reduced Lateral Spacing   — 20 Flights per Alert

(9) Based on data from the OASIS study, the following cost
savings in millions of discounted 1979 U.S. dollars could
be realized in the North Atlantic for the years 1986-2005,
if all aircraft were CDTI-equipped:

Reduced Vertical Spacing
With One-Way Tracks   —   437

Reduced Lateral and
Reduced Longitudinal Spacing   —   216

Reduced Lateral Spacing   —   136

Reduced Longitudinal Spacing   —   98

(10) Radio Frequency interference between TCAS units over the
ocean would not be a problem.

(11) Multipath signals reflected from the ocean's surface do not
appear to represent a problem because the TCAS top antenna
can generally receive a direct signal that is significantly
stronger than the multipath signal.

(12) Contention for the voice channel appears to be no problem.
A single VHF frequency can be used for the entire oceanic
track system.

(13) The pilot workload represented by this CDTI concept is
modest, except possibly for encounters occurring when

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one aircraft is slowly overtaking another in the reduced vertical separation scenario.

(14) The introduction of reduced separation minima should be done only by converting whole tracks to CDTI-only use. That is, reduced separation should not be used on mixed-equipage tracks.

(15) The CDTI concept proposed here provides for easy transition to CDTI equipage. Early aircraft to equip can receive immediate benefits; the whole oceanic fleet need not be equipped.

(16) The significant uncertainties of the concept are:

- What maximum surveillance range is achievable at reasonable cost?
- What will be the actual cost increment for the CDTI modifications to the TCAS unit?
- What will actual aircraft densities be in oceanic airspace?
- Is the bearing accuracy attainable with Minimum TCAS II adequate to support horizontal resolution?
- Can the production TCAS system be built with enough reliability to support this concept?
- Can altimetry accuracies and controls for detecting altimetry errors suitable for this concept be obtained?
- Do pilots have the ability to make sound judgments in the variety of situations which they might experience?

(17) No judgment can be made at this time about whether it is
     feasible to reduce separation minima between equipped and
     unequipped aircraft. It is recommended that this not be
     attempted until operational experience has been gained in
     the use of reduced separation between equipped aircraft.

(18) The use of reduced separation minima between an aircraft
     crossing the oceanic track system and aircraft flying
     within the track system does not appear to be immediately
     feasible.

(19) The feasibility of using the proposed CDTI concept to
     support cruise climb procedures is doubtful.

SECTION 15

RECOMMENDATIONS FOR FURTHER STUDY

In this section, a number of recommendations are made for further studies which might be conducted to verify more fully the feasibility of the oceanic CDTI concept. Included are recommendations for data collection efforts and cockpit simulation experiments.

Data Collection Efforts

In order to more accurately determine the effectiveness of the oceanic CDTI system, more accurate data is needed on the navigational performance of today's transoceanic aircraft in both the vertical and longitudinal dimensions. The FAA Technical Center is currently conducting a large data collection effort aimed at determining the heightkeeping accuracy of aircraft at high altitudes. This data, when it becomes available, should help support the analysis of vertical spacing reductions with the CDTI system. For longitudinal analysis, a data collection effort is recommended for the North Atlantic track system similar to the one conducted for the Central East Pacific track system in 1973 – 1974 (Reference 8). Such a study would compare entry and exit times for pairs of aircraft on the same track and flight level. Such data could help estimate the probability of overtake for various longitudinal spacings.

Another data collection effort which might be both convenient and highly useful would be to install an experimental TCAS system, modified to support the oceanic CDTI concept, on an aircraft flying regularly in the North Atlantic track system. Provisions

would be made to record the surveillance data on any aircraft that come within range. Such data, if combined with data on own aircraft's position, could provide useful information on:

(1) the frequency of large lateral navigation errors,
(2) the distribution of vertical flight technical errors over the ocean,
(3) the distribution of longitudinal spacing (determined by studying data for adjacent flight levels),
(4) the effects of multipath in actual conditions,
(5) the feasibility of increasing the TCAS surveillance range,
(6) CDTI alert rates to be expected, and
(7) expected costs in a production version of the CDTI modifications.

Cockpit Simulation Experiments

Perhaps the best available means for further evaluating the oceanic CDTI concept is cockpit simulation. The simulation of one-on-one encounters could help to resolve many of the unanswered questions related to such a system. The following would be required: two cockpits with flight controls providing inputs to a common computer flight model, motion simulation capability able to simulate heavy turbulence, a simulated CDTI display in each cockpit, and a common voice channel. Instrument flight simulation would be perfectly adequate, and no visual effects would be necessary. Simulation experiments could be designed to:

(1) Determine the exact alert time requirements for effective resolution with routine maneuvers in various geometries.

(2) Asses the ability of pilots to initiate and conduct the necessary coordination and to select appropriate resolution strategies.

(3) Evaluate the adequacy of the TCAS-derived bearing data to support pilot selection of horizontal resolution maneuvers.

(4) Assess the ability of pilots to accomodate 300 m (1000 ft) vertical spacing in the presence of heavy turbulence.

(5) Determine the most efficient and understandable phraseology for air-to-air communication.

APPENDIX A

PROPOSED PILOT PROCEDURES
FOR SPECIFIC ENCOUNTER GEOMETRIES

In this appendix, detailed pilot procedures are described for specific encounter geometries. In general, there are four basic situations that are likely to give rise to a CDTI alert with the reduced separation schemes considered in this study . They are:

(1) The aircraft are flying in the same direction on the same track and have been assigned to adjacent flight levels. One or both aircraft have drifted off the assigned flight level toward the other aircraft.

(2) The aircraft are flying in opposite directions on adjacent tracks and have been assigned the same flight level. One or both aircraft have drifted laterally from the nominal track centerlines toward the other aircraft.

(3) The aircraft are flying in the same direction on adjacent tracks and have been assigned the same flight level. One or both aircraft have drifted laterally from the nominal track centerlines toward the other aircraft.

(4) The aircraft are flying in the same direction on the same track at the same flight level. They entered the track with near-minimum longitudinal separation and the trailing aircraft has closed on the leading aircraft.

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Of course, composite situations which combine more than one of the situations listed above are also possible. For example, an aircraft assigned to an adjacent track at an adjacent flight level could deviate laterally toward own aircraft and could also drop below its assigned flight level. Such a situation could be handled either as a lateral deviation or a vertical deviation. Because no special procedures are required for the composite situations, they are not discussed separately.

For the four well-defined situations listed above, the resolution actions to be preferred are those actions which will cause the aircraft to return to their assigned track centerlines, flight levels, and Mach numbers. Where it cannot be determined which aircraft is in error (as might be the case for situation number 2 or number 3 when the navigation systems in both aircraft show the aircraft on centerline), then actions to return to centerline would be taken assuming that both aircraft share the navigation error equally. That is, both aircraft would be assumed to have a navigation error of the same magnitude but opposite sign. By exchanging information about assigned tracks, flight levels, or Mach numbers as appropriate, it is quite easy to visualize the desirable resolution. This is true provided that the navigation errors are not so great as to cause the aircraft positions to be transposed (the actual flight level of the aircraft with the higher assigned flight level is lower than that of the other aircraft; the aircraft with the northerly assigned track is actually to the south; or the trailing aircraft is actually ahead).

The preceding situations come about from normal navigational variations which are quite normal in kind but may be unusually large in degree. Other situations can occur due to blunders, equipment malfunctions, or other effects, possibly in conjunction with

aircraft changing flight levels or in-flight emergencies. These situations can be so varied that specific procedures cannot be recommended for them. They are, however, treated in a generalized way after the procedures for the four specific situations are presented.

Procedures For The Same Direction, Same Track, Adjacent Flight Levels Situation

If, at the time of the CDTI alert, the target is at fairly close range (say within 19 km, or 10 n. mi.), has a very low closing rate, and has less than the minimum vertical separation, the pilot may suppose that the target aircraft is assigned to fly the same track in the same direction at the adjacent flight level. If the situation is not critical, the pilot would attempt to contact the pilot of the target aircraft on the designated VHF frequency. He would then determine whether his own aircraft was flying at the assigned flight level. If not, he would immediately begin to return to his assigned flight level (assuming that this increases the vertical separation from the target).

He would tell the pilot of the target aircraft his intentions and would ask for the assigned flight level of the target aircraft. He would confirm that the assigned flight levels reflected the allowable minimum vertical separation and that both aircraft were at or near those flight levels.

If own aircraft is at or very near the assigned flight level, but the target is not near an adjacent flight level, the first step should be to determine the assigned flight level for the target. If this is an adjacent flight level, the pilot of own aircraft should notify the pilot of the target aircraft that his flight level is

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observed to be different than the assigned value. If the other pilot recognizes this and agrees to return to the assigned flight level, own pilot should monitor his CDTI display to confirm that corrective action is being taken. If the other pilot indicates that he is at the assigned altitude, then the possibility of correspondence error within one of the aircraft should be considered. Altimeter settings in both cockpits should be rechecked, and the readings from the cockpit altimeters should be exchanged by voice. If there is a difference between the cockpit altimeter reading and the flight level being reported by the transponder for one of the aircraft, the pilot of that aircraft should try to identify the cause of the difference. He might compare the indications from the dual altimetry system on his own aircraft. If there is a correspondence error, it may be difficult to determine the source of the error and there may be little confidence in the altimetry system for that aircraft. In this event, the pilots may agree to maintain at least 9 km (5 n. mi.) lateral separation with the aid of their CDTI displays. They might have to deviate from the course centerlines indicated by their navigation systems to achieve this, but the required lateral deviation should not be more than 4 to 6 km (2 or 3 n. mi.), and this should be of no consequence to the oceanic control system. Therefore, the control system would not have to be notified.

The actions selected by the pilots in response to the CDTI alert for the situation being discussed here should ensure that the separation between aircraft, as indicated by TCAS, at all times exceeds 9 km (5 n. mi.) lateral or 240 m (800 ft) vertical separation. In some cases, the higher aircraft may have drifted significantly below the assigned altitude. Or it may be that the higher aircraft has received a higher assigned flight level en route and is climbing to the higher flight level. In both cases, it is

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possible that the higher aircraft will be limited in climb capability. If this is so, the pilot of the lower aircraft may wish to descend slightly in order to achieve the 240 m (800 ft) minimum vertical separation. The pilot should not depart from his assigned flight level by more than 90 m (300 ft) in this situation unless a critical situation exists. If he does deviate, he should return to his assigned flight level as soon as possible.

Procedures For The Opposite Direction, Adjacent Track, Same Flight Level Situation

The pilot would suspect this situation if he were to observe the target converging rapidly, at a long range, and offset noticeably from the nose. The target would likely be at nearly the same flight level. Such a situation might arise due to lateral flight technical error or navigation position error on the part of one or both aircraft.

The first step in this situation would be to make voice contact with the target aircraft. Provided that the situation did not demand immediate action, the pilot would first exchange assigned track identifiers.

By taking account of the assigned tracks and by observing the geometry on the CDTI display, the pilot would determine whether or not the aircraft are in a transposed geometry. The geometry is a transposed geometry if the target aircraft, on the basis of the TCAS data, is predicted to pass off the right wing of own aircraft, but on the basis of assigned track numbers ought to pass off the left wing. Figure A-1 shows an example of one geometry that is transposed and one that is not. If the geometry is not transposed, then the pilot would suggest that each aircraft be turned in the
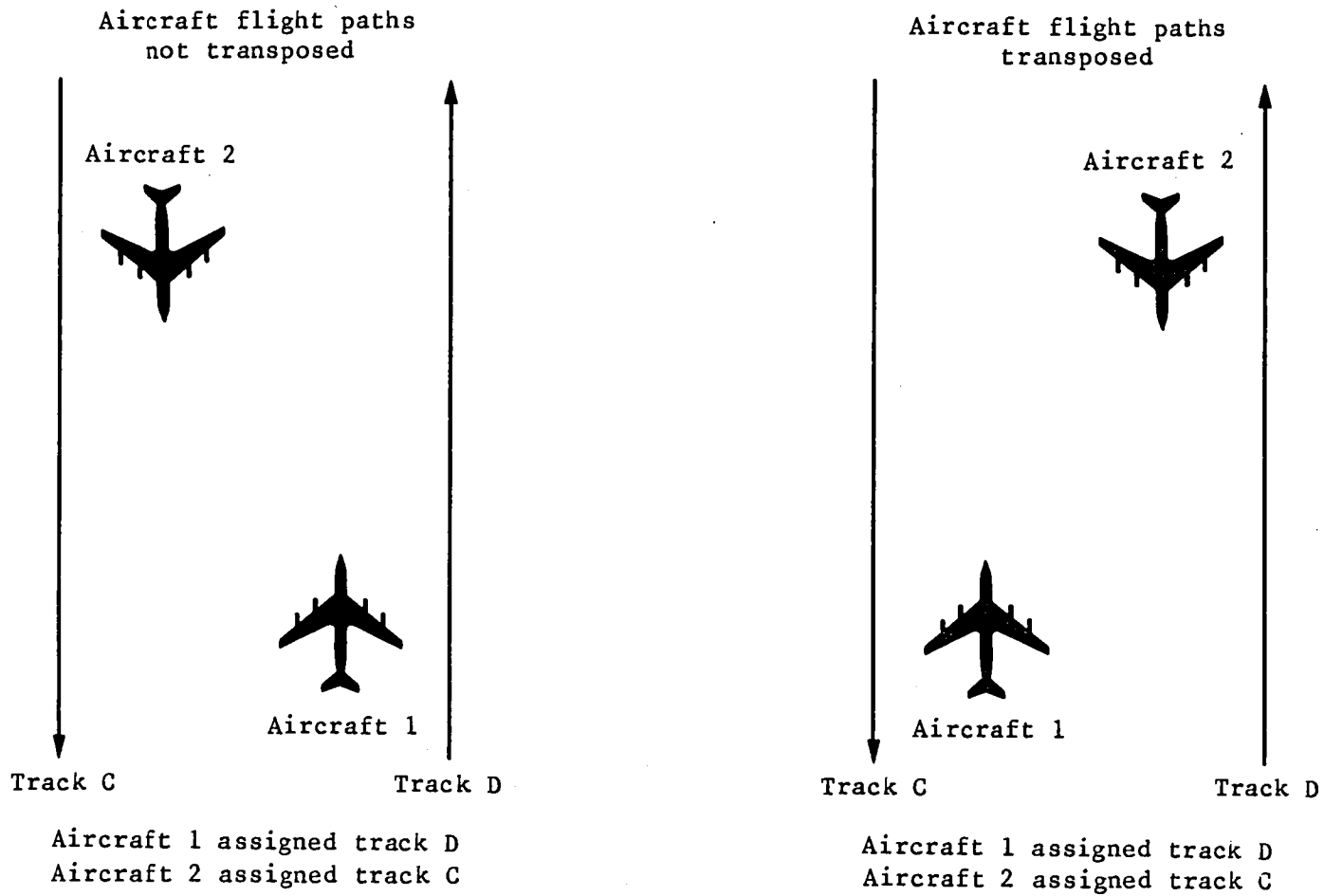
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Aircraft flight paths
not transposed

Aircraft 2

Aircraft 1

Track C   Track D

Aircraft 1 assigned track D
Aircraft 2 assigned track C

Aircraft flight paths
transposed

Aircraft 2

Aircraft 1

Track C   Track D

Aircraft 1 assigned track D
Aircraft 2 assigned track C

Figure A-1.–Definition of a transposed encounter geometry.

direction to increase the miss distance. In the geometry that is
not transposed in Figure A-1, each aircraft would have to turn right
to increase the miss distance.

If the geometry is very nearly head-on, the pilot would assume
that both aircraft were midway between their two assigned tracks,
and would suggest that each aircraft be turned in the direction that
would take it back towards its assigned track.

If the geometry is transposed, the pilot would suggest that one
aircraft climb and that the other descend. The implication here is
that there exists a significant navigation error. Turning to
increase the existing miss distance would only increase this
navigation error. Turning the aircraft in the direction which
initially reduces the miss distance, even if such turns would
ultimately lead to increased separation, would not be advisable.
Because of the high closing rate and the indications of significant
navigation errors, vertical resolution is considered as more
positive and is preferred in this case.

In the opposite direction, adjacent track situation, the
suggested resolutions do not require determining which aircraft has
deviated from its assigned track, as was suggested in the preceding
sections. This is because a significant contributor to the
navigation error causing the TCAS notification may be measurement
error. The instruments in both cockpits may indicate that the
aircraft are exactly on course, yet the two TCAS units could show
miss distances substantially less than the separation distance
between tracks. When this is the case, it is difficult to determine
which aircraft is in error. Furthermore, in this high closing rate
situation, there is not a great deal of time to do extensive voice

coordination. Thus, the strategy is to involve both aircraft equally.

The pilots should maneuver their aircraft so that they will have at least 19 km (10 n. mi.) lateral separation or 240 m (800 ft) vertical separation at their closest approach.

Procedures For The Same Direction, Adjacent Track, Same Flight Level Situation

The pilot should be able to recognize this situation by the fact that the target would be relatively close (9-19 km, or 5-10 n. mi. lateral separation) at the time of the CDTI alert and would have a very slow closing rate. The target would appear in roughly the three o'clock or nine o'clock direction and would be at nearly the same flight level. It is possible that the pilot would have observed the target well before the CDTI alert occurs because it would have been displayed as a proximate target. In this situation, there would generally not be a great time pressure, and there would be time for discussion about a course of action.

The pilot should first make voice contact with the pilot of the target aircraft, and they should exchange assigned track identifiers. If the situation is critical, the pilot should suggest immediate action to resolve the situation or at least to stabilize the situation. The situation could be stabilized by having the pilots fly headings that diverge by 10 or 20 degrees. This would provide time to work out a permanent resolution that allows both aircraft to get back on their assigned tracks. Whether the encounter was critical or not, in this situation a permanent resolution must be devised because otherwise the aircraft would be in close proximity for a very long time. It may require several

verbal exchanges of data of several types for the pilots to be able
to deduce the cause of the CDTI alert and to determine appropriate
resolution that will put them back on the correct tracks.

The pilots should first exchange present latitude and longitude
coordinates. These coordinates when visualized on the chart
depicting the tracks will tell immediately if one of the aircraft
has a significant flight technical error. If flight technical error
is the source of the problem, a suitable resolution can then be
worked out.

If, however, the coordinates of both aircraft lie close to the
assigned tracks, the range between aircraft as measured by both TCAS
units should be compared. If both read the same, then one or both
of the aircraft have a navigation error. In this case, the pilot in
each aircraft should check his primary navigation system against his
backup system(s). The pilots should verbally exchange the results
of this cross-check. If both navigation systems for one aircraft
agree, but they disagree for the other aircraft, then the second
aircraft's primary navigation system should be suspected, and that
aircraft should turn so as to return to its true assigned track.
Assuming that that aircraft's secondary navigation system indicates
a position more consistent with the observed TCAS range between
aircraft, that aircraft should continue its flight using the
secondary navigation system.

If the aircraft were in transposed positions at the time of the
CDTI alert, it is still desirable that they resolve the encounter in
a way that puts both aircraft back on their true assigned tracks.
This may require that the aircraft achieve vertical or longitudinal
separation before exchanging lateral positions. They should
maintain at least 9 km (5 n. mi.) horizontal or 240 m (800 ft)
vertical separation throughout this resolution.

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If the other pilot is first to make voice contact, the procedures are basically the same as just described. In almost all cases, the target would already be present on the display in own aircraft, at least as a proximate target. In these cases, own pilot would be able to confirm and monitor the resolution independently. If the TCAS on own aircraft does not acquire the target, own pilot should check his navigation position and agree with the other pilot to whatever actions seem warranted by the situation.

Procedures For The Same Direction, Same Track, Same Flight Level Situation

At the time a CDTI alert occurs in this situation, the target would be approximately five miles ahead of or behind own aircraft with a very small closing rate. The flight levels would be nearly the same. It is highly likely that own pilot would have noticed the presence of the target well in advance of the CDTI alert, because the target would have been displayed as a proximate target for a long time prior to the alert.

If the pilot becomes aware of the presence of the target aircraft in this situation, he should take action without waiting for a CDTI alert from his TCAS. He should attempt to keep a longitudinal spacing of at least 19 km (10 n. mi.) between aircraft. To do this he should first make voice contact with the other pilot and exchange assigned and current Mach numbers and assigned track identifiers with him. If one aircraft has deviated from its assigned Mach number, it should return to that Mach number after a longitudinal separation of at least 19 km (10 n. mi.) has been achieved.

If both pilots feel they are, and have been, flying at the assigned Mach number, then the trailing aircraft will have the

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responsibility for adjusting its Mach number so as to maintain at
least 19 km (10 n. mi.) longitudinal separation. If this results in
an unacceptable cruise speed, then the pilot of the trailing
aircraft may request clearance to a different flight level or a
different track from the oceanic control system. The pilot should
not depart from his assigned flight level or track without clearance
from the oceanic control system.

If own pilot does not have the target on his display at the time
the other pilot initiates voice contact, he should respond to the
questions and recheck his current Mach number against his assigned
Mach number. If the other pilot indicates that his aircraft is the
trailing aircraft, then own pilot needs to take no action other than
checking his Mach number. If, however, own aircraft is the trailing
aircraft and own TCAS has not yet displayed the target, own pilot
should exchange latitude and longitude coordinates with the other
pilot. If these coordinates indicate that own aircraft has closed
to within 28 km (15 n. mi.) of the target, own pilot should
immediately slow to a Mach number that is at least 0.02 less than
the Mach number of the target. Own pilot should then ask for a new
assigned flight level or track from the oceanic control system.

Procedures For All Other Situations

There are many other situations in which a CDTI alert could be
given. They could come about from a variety of causes such as an
in-flight emergency which forces an aircraft to make an immediate
descent, waypoint insertion errors which lead to large navigation
errors, or navigation errors on the part of an aircraft flying
through the airspace of the oceanic track system on an approved
flight plan that intersects the established tracks. It is not
possible to categorize these types of situations and to provide

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guidance for specific cases. In most of these cases, there has been a significant departure from the assigned flight path of at least one of the aircraft. Thus, reference to the assigned tracks, flight levels or Mach numbers is not likely to provide help in the resolution of these situations.

At the time a CDTI alert occurs, the pilot should check the CDTI display and make voice contact with the target. If, after a brief verbal interchange with the other pilot and a brief analysis of the CDTI display, the pilot cannot identify the situation as one of the four listed previously, he should consider the situation as an abnormal situation. He should disregard the assigned flight path information and should attempt to generate a resolution only on the basis of current position and velocity information as derived from the CDTI display or from conversation with the other pilot.

The pilots should first develop and carry out actions that will resolve any immediate threat of collision. This should be done without regard for assigned flight paths. The actions should, however, account for any additional aircraft in the vicinity. When the situation is under control, the pilots can then diagnose the problem and determine how to return to their assigned flight paths.

In selecting the resolution action, the pilot would generally maneuver to increase the separation at closest approach. For example, if it appeared that the other aircraft would be at about the same flight level at closest approach but that the aircraft would pass right-wing-tip-to-right-wing-tip with about 19-28 km (10-15 n. mi.) lateral separation, then it would be reasonable for both pilots to turn left. Likewise, if it appeared that the aircraft were headed toward each other horizontally but would have 180 m (600 ft) of vertical separation at closest approach, vertical resolution would be appropriate.

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Pilots should be cautioned against trying to use turn maneuvers when the correct maneuver is not immediately obvious. Pilots would not have a great deal of experience at resolving conflicts in the horizontal dimension. Given the bearing measurement error of the TCAS unit, especially at great distances where link margins may be small, it may be difficult to predict what the horizontal situation at closest approach will be, based on the displayed data. Furthermore, bearing measurement errors can be influenced by aircraft structure and can be significantly different at different bearings. For these reasons, when the best horizontal resolution maneuver is not immediately obvious vertical resolution is preferred.

If one pilot does not have the other aircraft on his CDTI display at the time that the other pilot initiates voice contact, then the resolution should be done with vertical maneuvers. By exchanging flight level information, the two pilots can agree on a course of action even if one does not have the target displayed. It would be very difficult for a pilot to agree to a horizontal maneuver when he could not see the target on his display.

After one pilot has suggested a resolution, the two pilots should negotiate, come to a final agreement, and then carry it out. They can then proceed to diagnose the situation and determine how to return to their assigned flight paths.

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APPENDIX B

DETERMINING CROSS-TRACK ALERT PARAMETERS

To determine the y-dimension of the box enclosing the aircraft used by the alert rate model, the following scenario has been developed. A pair of aircraft traveling on adjacent coaltitude parallel routes each head at a blunder angle, Beta, towards the other route. At a given time the orientation of the pair of aircraft is as shown in Figure B-1 for same-direction traffic, and Figure B-2 for opposite-direction traffic. Opposite-direction aircraft are assumed to be traveling at 310 m/s (600 knots), while for same-direction traffic, an aircraft at 260 m/s (500 knots) is overtaking an aircraft on the parallel route traveling at 240 m/s (460 knots). Given any specific orientation of the aircraft, as represented by Theta, the maximum cross-track distance at which an alert can occur can be computed from the TCAS tau criterion:

$$\text{Th} \geq \frac{R - D}{V_R} \qquad (B-1)$$

With the orientation as shown,

$$R = y/\sin(\text{Theta}) \qquad (B-2)$$

while

$$R = -[V_1 \cos(\text{Theta-Beta}) - V_2 \cos(\text{Theta+Beta})] \qquad (B-3)$$

for the same-direction case, and

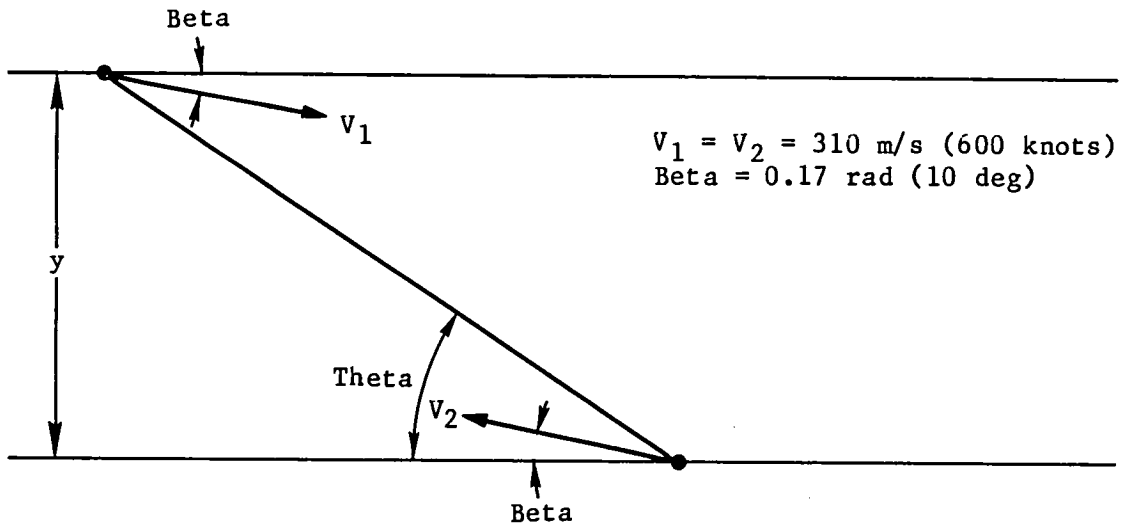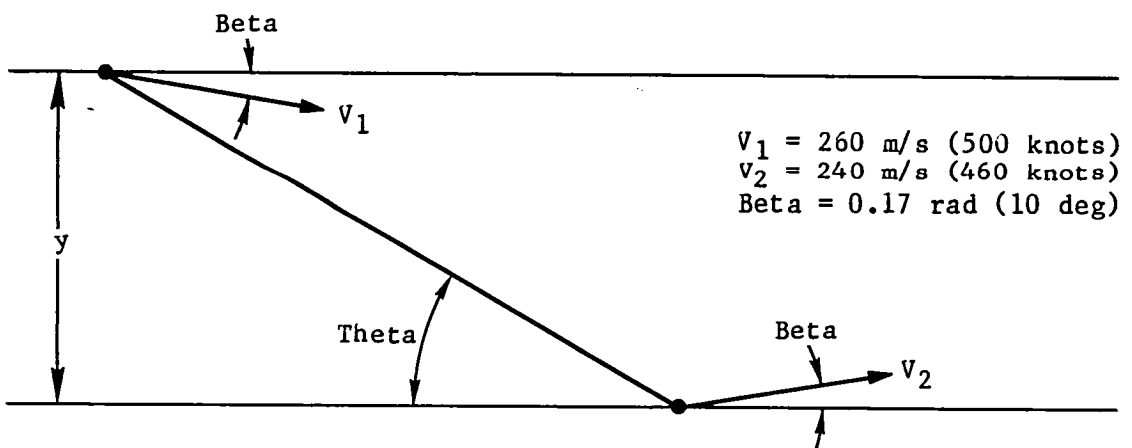**Figure B-1.—Opposite-direction cross-track scenario.**

$V_1 = V_2 = 310$ m/s (600 knots)
Beta = 0.17 rad (10 deg)

Figure B-2.—Same-direction cross-track scenario.

$V_1 = 260$ m/s (500 knots)
$V_2 = 240$ m/s (460 knots)
Beta = 0.17 rad (10 deg)

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$$\dot{R} = -(V_1 + V_2) \cos (\text{Theta-Beta}) \qquad\qquad \text{(B-4)}$$

for the opposite-direction case, where V_1 and V_2 are the
velocities of the two aircraft.

The angle Beta, assumed to be 0.17 rad (10 degrees), is chosen
to represent the cross-track angle that would result if an error of
one degree latitude were entered into the airborne navigation unit
for the next ten-degree longitude reporting position. It has been
suggested that this would be a likely cause for the occurrence of
large errors (e.g., 110 km (60 n. mi.)). Such an occurrence is
actually very rare, as procedures have been developed to guard
against waypoint insertion errors. Obviously, the simultaneous
occurrence of two such blunders is even less likely.

Given these parameters, and with D = 9.3 km (5 n. mi.) and
T_h = 105 sec, Figures B-3 and B-4 show the resultant maximum
cross-track distance as a function of Theta for same-direction and
opposite-direction aircraft pairs. The worst-case same-direction
encounter occurs when the aircraft are nearly opposite each other,
while the worst-case opposite-direction encounter occurs when the
aircraft are between 0.8 and 1.0 rad (45 and 60 deg) apart. Tau-dot
logic has the effect of decreasing false alerts resulting from
encounters that have large miss distances. That is, the logic will
suppress alerts that equation (B-1) would signal if the actual miss
distance were greater than M in equation (C-17) of Appendix C. This
equation is a bounding equation which includes the effects resulting
from errors in range measurement.

The result of including tau-dot logic in the opposite-direction
encounter can also be seen in Figure B-4, as the value for M and the
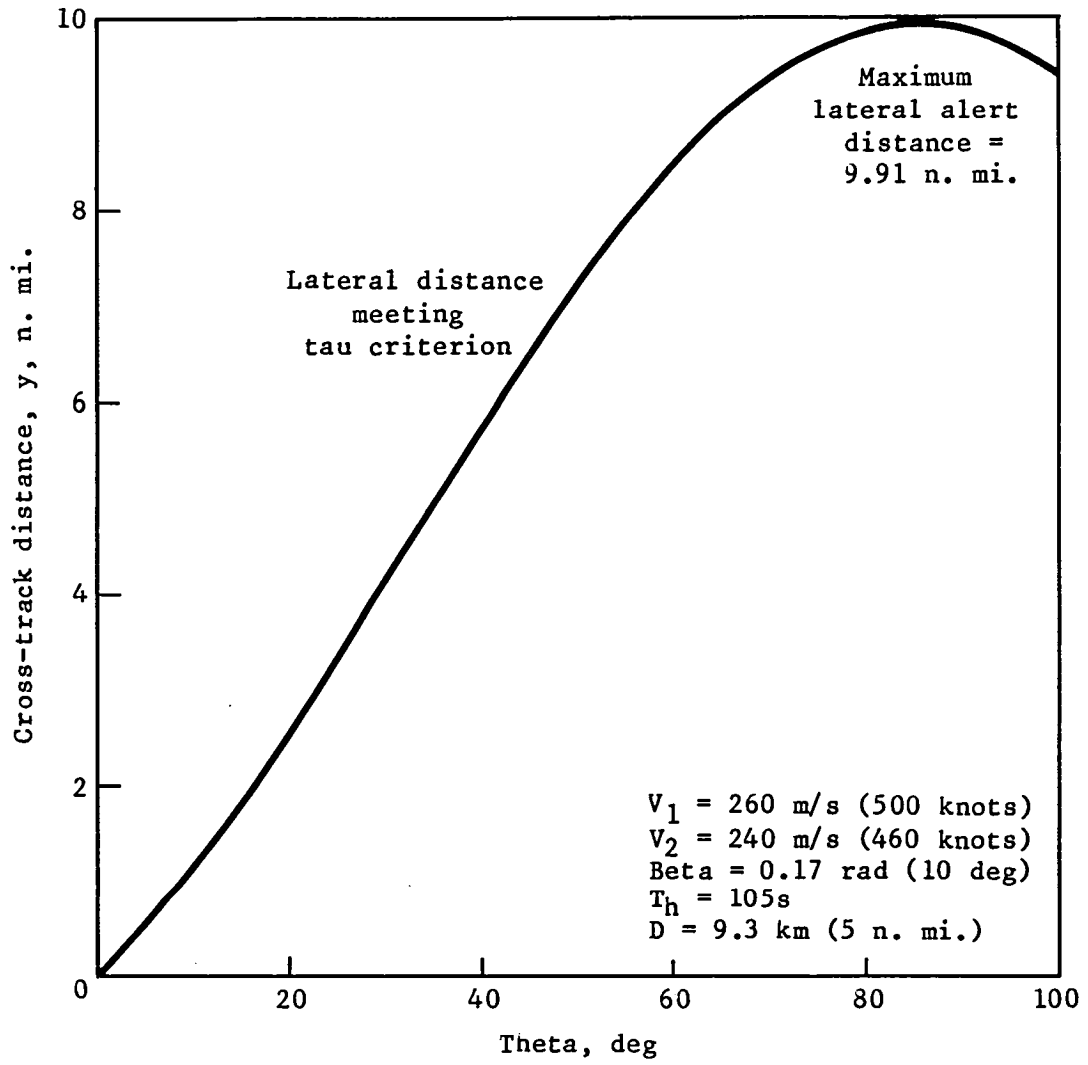actual miss distance as a function of Theta are also plotted. In

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Figure B-3.–Cross-track alert parameters for same-direction track pair.
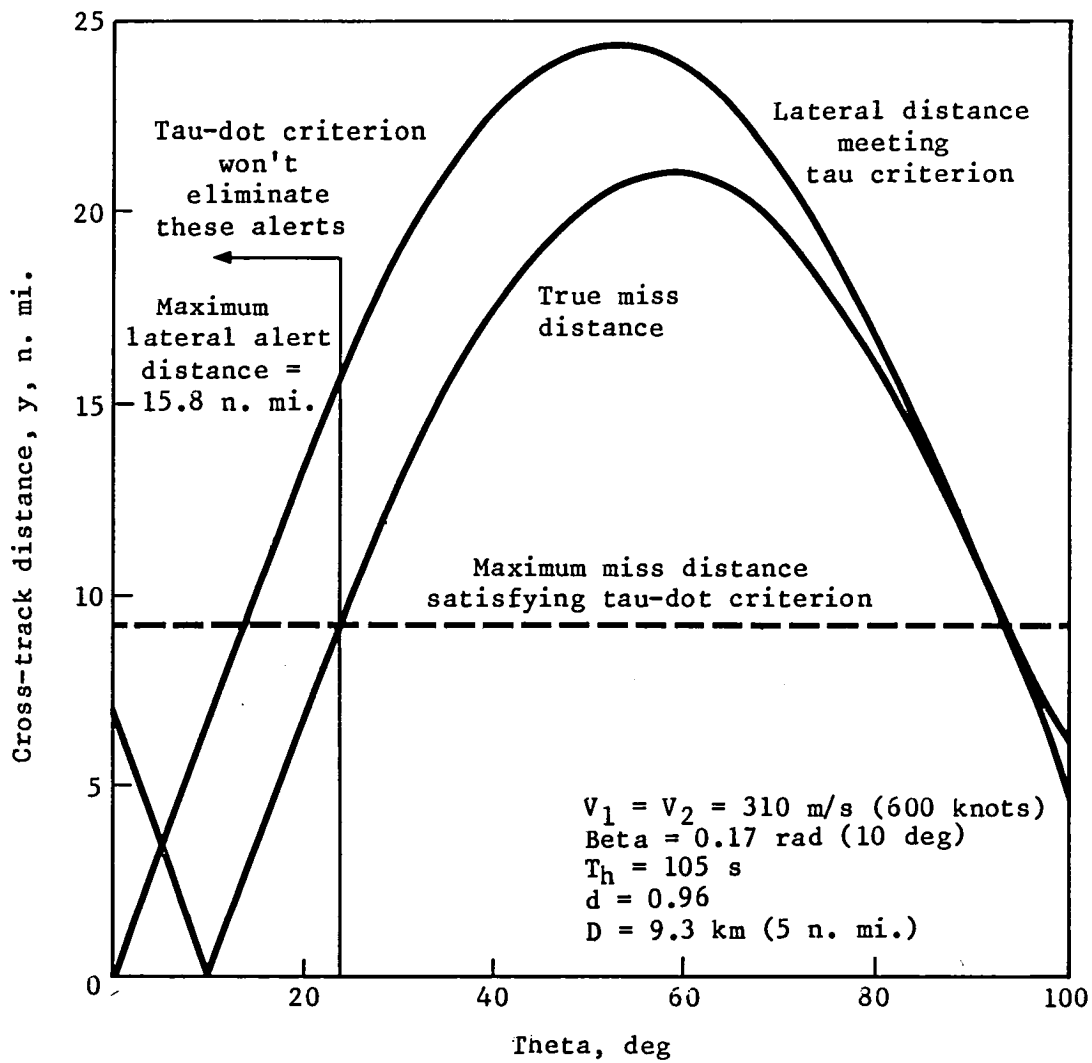
Figure B-4.–Cross-track alert parameters for opposite-direction track pair.

this case, false alerts resulting from encounters where Theta is
greater than approximately 0.44 rad (25 deg) will be suppressed.
The maximum cross-track distance pertaining to values of Theta less
than 0.44 rad is approximately 28 km (15 n. mi.); i.e. the
y-dimension of the box is reduced by 19 km (10 n. mi.). This
results in a substantial reduction of false alerts, particularly
when a lateral route separation minimum of 56 km (30 n. mi.) is
considered.

For the same-direction case, the tau-dot logic does not improve
the false alert rate, as the actual miss distance (see Figure B-3)
is less than M for values of Theta between approximately 0.7 rad (40
degrees) and 1.5 rad (85 degrees), which includes the orientation
resulting in maximum cross-distance at which an alert can occur.
However, this distance of approximately 13 km (7 n. mi.) is still
less than the tau-dot-aided opposite-direction case.

APPENDIX C

EFFECT OF TAU-DOT LOGIC FOR LARGE
HORIZONTAL MISS DISTANCES

In this appendix, a formula will be derived which places an
upper bound on the average horizontal miss distance for which the
tau-dot logic will totally prevent a CDTI alert.

In the Minimum TCAS II system, the time until horizontal closest
approach is estimated by dividing the tracked range by the negative
of the range rate. This quantity is called tau. For a collision
course encounter in which the aircraft are flying linear paths, the
value of tau decreases by exactly one second for each second of
elapsed time. In contrast, for a linear encounter with a large
horizontal miss distance, tau decreases less than one second for
each second of elapsed time. Tau-dot logic takes advantage of this
fact by computing the time rate of change of tau and looking for a
value significantly less than unity. In this way, it is possible to
eliminate some unnecessary alerts.

For two converging aircraft in straight flight, tau can be
expressed as:

$$\text{Tau} = t[1 + (M/Vt)^2] \qquad\qquad\text{(C-1)}$$

where t is the true time to closest approach, M is horizontal miss
distance, and V is the magnitude of the relative velocity vector.
Taking the first derivative with respect to t gives the following
formula for tau-dot:

$$\text{Tau-dot} = 1 - (M/Vt)^2 \qquad\qquad\text{(C-2)}$$

Because of uncertainty in the measured value of range, tau-dot must
be treated as a random variable whose mean value is given by
equation (C-2). This means that the tau-dot test can be written as:

$$\text{Tau-dot} = 1 - (M/Vt)^2 + e > d \qquad\qquad (C-3)$$

where e is the sample error and d is the tau-dot threshold.

For an encounter involving a large miss distance, once the
horizontal criterion for a CDTI alert is satisfied, the tau-dot test
will be made approximately once per second until either the test is
passed (and an alert is declared) or the point of closest approach
is reached without an alert. The horizontal criterion for a CDTI
alert can be expressed as:

$$\text{Tau (modified)} = \text{Tau} - \frac{D(\text{Tau}/t)^{1/2}}{V} \leq T_h \qquad\qquad (C-4)$$

where D is a distance modifier, T_h is a modified tau threshold,
and Tau is given by equation (C-1). It can be shown from equations
(C-1) and (C-4) that the maximum value of t during the time that an
alert is possible is given by:

$$t_{max} = T_h + D/V_{min} \qquad\qquad (C-5)$$

which occurs when M = 0. V_{min} is the minimum expected value for V.

Operationally, the value of tau-dot can be computed by the
formula:

$$\text{Tau-dot} = \frac{\text{Tau (Previous)} - \text{Tau (Current)}}{\text{Time between measurements}} \qquad\qquad (C-6)$$

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However, in the version of the tau-dot logic tested for Minimum TCAS II, the value of tau-dot was smoothed by calculating a weighted average value for the past five processing cycles, with the most recently computed value being weighted the most heavily. It can be shown that the jitter in this smoothed value of tau-dot is approximately given by the formula:

$$S_{tau\text{-}dot} = \frac{(2/15)^{1/2} S_R}{|V_R| \times 1s} \qquad (C\text{-}7)$$

where $S_{tau\text{-}dot}$ is the standard deviation of error in the calculated value of tau-dot, S_R is the standard deviation of error in range, and V_R is the range rate. The tau-dot jitter is also a weak function of the jitter in range rate, but it is estimated that the contribution of range rate error is not a first-order effect.

We now wish to estimate the expected value of the largest positive error in the computed value of tau-dot during a straight encounter. Let this value be e_{max}. Let P_1 be the probability of the tau-dot error being greater than e_{max} on a single trial. Then the probability of the maximum error on N trials being greater than e_{max} is given by:

$$P_N = 1 - (1 - P_1)^N \qquad (C\text{-}8)$$

If P_1 is very small (much less than N^{-1}), then a binomial expansion can be used to give the following approximation:

$$P_N = N(P_1) \qquad (C\text{-}9)$$

In order to derive the expected value for e_{max}, we must let:

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$$P_N = 50\% \tag{C-10}$$

Since one test of the tau-dot logic is made each second, the maximum number of trials N is equal to the maximum value of the time to closest approach, t_{max}, in seconds. This was given by equation (C-5). Thus, equations (C-9) and (C-10) become:

$$P_N = \frac{(T_h + D/V_{min}) \, P_1}{1s} = 0.5 \tag{C-11}$$

Solving for P_1,

$$P_1 = \frac{0.5s}{T_h + D/V_{min}} \tag{C-12}$$

For opposite-direction encounters using the oceanic CDTI system, this equation will be evaluated with the following values:

$$V_{min} = 370 \text{ m/s (720 knots)}$$
$$T_h = 105 \text{ s}$$
$$D = 9.3 \text{ km (5 n. mi.)}$$

Substituting these values into equation (C-12) yields the result:

$$P_1 = 0.0039 \tag{C-13}$$

From data collected by the FAA Technical Center, it has been determined that the TCAS measurement error for range has approximately a Gaussian distribution with a standard deviation of about 12 meters (40 feet). The error in tau-dot can therefore also be assumed to have a Gaussian distribution. From tables for

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Gaussian distributions, it can be determined that a probability of 0.0039 corresponds to 2.7 standard deviations. Therefore, for CDTI alerts for opposite-direction encounters,

$$e_{max} = 2.7 \ (S_{tau-dot}) \qquad\qquad (C-14)$$

The absolute value of range rate can be given by:

$$|V_R| = \frac{V}{[1 + (M/Vt)^2]^{1/2}} \qquad\qquad (C-15)$$

Thus, equations (C-7), (C-14), and (C-15) can be combined to give:

$$e_{max} = \frac{0.97 \ (S_R)}{V \times 1s} \ [1 + (M/Vt)^2]^{1/2} \qquad\qquad (C-16)$$

The above expression for e_{max} can be substituted for e in equation (C-3). It is clear from the result that the largest expected value of tau-dot occurs when the time to closest approach, t, is the greatest. This occurs when the horizontal criterion for a CDTI alert (i.e., equation C-4) is first satisfied. In other words, the probability of the tau-dot test being passed is the greatest on its first trial. Thus, equations (C-1), (C-3), (C-4), and (C-16) can be solved simultaneously to eliminate the variable t and give the following result for M:

$$M \geq \frac{VT_h + D(1 + Q^2)^{1/2}}{Q + (1/Q)} \qquad\qquad (C-17)$$

where Q is given approximately by:

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$$Q = [1 - d + (V_j/V)(2 - d)^{1/2}]^{1/2} \qquad \text{(C-18)}$$

V_j has the dimensions of velocity and can be thought of as an effective jitter velocity. The value of V_j is given by:

$$V_j = 0.97 \ (S_R)/1s \qquad \text{(C-19)}$$

Equation (C-17) defines an upper bound on the average horizontal miss distance for which the tau-dot logic will totally prevent a CDTI alert for an opposite-direction encounter. The maximum value of the variable V should be used in evaluating this equation.

Evaluating the above equations with S_R = 12 m (40 ft), V = 620 m/s (1200 knots), d = 0.96, T_h = 105 s, and D = 9.3 km (5 n. mi.) gives the following results:

$$V_j = 12 \text{ m/s (23 knots)}$$
$$Q = 0.24$$
$$M \geq 17 \text{ km (9.3 n. mi.)}$$

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