POTENTIAL ADS−B/CDTI CAPABILITIES FOR NEAR−TERM DEPLOYMENT[1]

Anand Mundra, James J. Cieplak, David A. Domino,

Baltazar O. Olmos, Hans P. Stassen

The MITRE Corporation /Center for Advanced Aviation System Development

McLean, VA, USA

ABSTRACT

There is a considerable interest by airlines, general aviation, avionics and airframe manufacturers, and pilots in the U.S., in developing and deploying cockpit traffic display capabilities to provide near−term benefits in aviation. One important forum for this work has been RTCA Special Committee (SC)−186 which is charged with the generation of the Minimum Aviation System Performance Standards (MASPS) for Automatic Dependent Surveillance−Broadcast (ADS−B) and the Minimum Operational Performance Standards (MOPS) for a Cockpit Display of Traffic Information (CDTI). This committee has determined that there should be specific near−term and far−term components to the potential ADS−B/CDTI applications.

This paper documents a proposed evolution of near−term applications of CDTI, which may be deployed in terminal and oceanic regions. This evolution deliberately consists of small steps with specific consideration of potential implementation in the current system. These two domains, terminal and oceanic, are addressed because a preliminary benefits analysis shows considerable benefit in these two domains.

The RTCA group responsible for drafting the CDTI MOPS has determined that supporting the routine conduct of visual approaches and enhancement of their safety are two of the early steps to be taken in this evolution. Closed loop controller/pilot simulations are now under way to determine the efficacy of specific CDTI information facilitating such an application. These results are expected to be used as inputs to the CDTI MOPS. They would therefore also be used as part of the guidance to avionics manufacturers for potential updates to current TCAS traffic displays in the TCAS Change 7 time−frame. This paper documents some preliminary results of these simulations.

[1] The views and opinions presented in this paper are those of the authors, and do not reflect official views or policies of the U.S. Federal Aviation Administration or RTCA, Inc.

INTRODUCTION AND BACKGROUND

Sorenson, et al. (1991) document that the concept of cockpit display of traffic information has been studied since the 1940s, when ground radar information was first transmitted to aircraft via television.CDTI tests and studies continued over the years, with a focused effort in the 1970s at The Massachusetts Institute of Technology to study the potential uses of a cockpit display of traffic, integrated with map and weather information, in improving ATC services. These studies indicated that an airborne traffic situation display could be useful in a wide variety of ATC applications including conflict detection and resolution, sequencing, spacing and merging, monitoring runway occupancy, executing back up procedures in case of ATC failure, monitoring adjacent parallel approaches, and enhancing airport surface movements in reduced visibility. That work did not, however, consider the dynamics of multiple cockpits or pilot/controller interactions (Sorenson, et al., 1991). These latter factors were studied in considerable detail by the NASA Langley and Ames Research Centers in the 1980s primarily with respect to the tasks of in−trail following, self−spacing and merging in the approach control environment. (See, for example, Sorenson, 1983; Sorenson and Goka, 1983; Kelley, 1983; Kelley and Abbott, 1984; Abbott and Moen, 1981; and Abbott, et al., 1980). Through these studies, considerable insight into the performance of a CDTI−based operation was obtained with respect to the task of in−trail following.

An interesting aspect of the previous research on CDTI is that most of the pilots who flew as subjects had essentially no previous experience using a CDTI system to accomplish the experimental tasks. This situation changed radically after carriage of TCAS II (Traffic Alert and Collision Avoidance System) equipment was mandated in the U.S. for commercial aircraft with 30 or more passenger seats. By December 1993, the entire U.S. airline fleet as well as any international aircraft landing in the U.S. had been equipped with TCAS II, which includes a rudimentary traffic display. Most of these implementations on the more than 5,000 such airframes were on radar or EFIS (Electronic Flight Instrument System) displays. This has resulted in a significant pilot population gaining operational experience with a cockpit traffic display over the past 4 years.

Although the TCAS II traffic display was expressly designed to enhance collision avoidance through visual acquisition, it became apparent that pilots began unofficially using it for such purposes as judging separation from the previous aircraft during approaches to airports, to help determine their place in the landing sequence, and generally to enhance their awareness of the traffic situation around them. It was therefore natural to consider authorized uses of the TCAS II traffic display for the purposes of enhancing specific ATC operations. Sorenson, et al. (1991) identified five such potential applications, some requiring only minimal or no enhancements to the TCAS II traffic display, and others requiring more extensive capabilities. These applications included the enhancement of visual acquisition, reduced departure spacing, and station−keeping on final approach.

With the widespread availability of traffic information in the cockpit, another initiative was started by the FAA in 1993 to facilitate ATC applications of the TCAS II traffic display. This initiative explicitly recognized that deploying new operational concepts could only be done by taking simple, incremental steps. This recognition led to the concept, study, coordination and finally the authorization of an in−trail climb (ITC) procedure for the oceanic domain using the TCAS II traffic display. (Cieplak, 1994; Cieplak et al. 1994a; Cieplak et al., 1994b; Cieplak et al. 1995; Peppard & Cieplak, 1995; SAWG, 1995; Zeitlin et al., 1995; Zeitlin, 1995). In September 1994, United and Delta Airlines were authorized to request an in−trail climb in the Oakland and Anchorage Flight Information Regions (FIRs) at separations considerably less than those normally required in the oceanic airspace, by making use of their TCAS II traffic displays to determine the range in−trail. In 1996, these operational trials were expanded to include an in−trail descent (ITD) procedure, and were also expanded to include any airline that demonstrates compliance with appropriate requirements. Hawaiian and Cathay Pacific Airlines have now demonstrated such compliance, and several other airlines are in the process of doing the same. The ITC/ITD operational trials represent the first use of on−board traffic display information for routine air traffic control operations.

As indicated above, other uses of the TCAS II traffic display have been considered (see for example, Sorenson, et al., 1991 or Mundra and Buck, 1990). However, it became clear during the development of ITC that the limitations of the TCAS II traffic displays for ATC applications are indeed significant, and additional meaningful ATC applications may be difficult without some enhancements of the TCAS II type of display.

Recommendations of the RTCA Free Flight Task force (RTCA, 1995) led, in 1995, to the formation of RTCA SC−186. This committee has been charged with the dual responsibility for developing MASPS (Minimum Aviation System Performance Standards) for ADS−B and MOPS (Minimum Operational Performance Standards) for CDTI.

RTCA SC−186 has attracted active participation by airlines, general aviation, avionics and airframe manufacturers, pilots, and R&D organizations. Early in its deliberations, RTCA SC−186 determined that whereas Free Flight was an eventual goal of ADS−B and CDTI capabilities, its accomplishment must consist of many evolutionary steps, each facilitating specific benefits, and each providing full consideration to the realities of existing ATC operations and the numerous factors that must be considered in enhancing them. It developed a two−phase approach, clarifying and separating near−term and farther−term goals for both the ADS−B and the CDTI technology. In the CDTI domain, along with MOPS, guidance is also being developed for CDTI features for the near term.

For this near−term CDTI guidance, emphasis is being placed on developing requirements to facilitate enhancements to visual acquisition, enhanced operations in the oceanic domain, and enhancements to visual approaches in the terminal domain. Enhancement of visual acquisition is based on a demonstrated program by M.I.T. Lincoln Laboratory, resulting in MOPS for a Traffic Information Service (TIS)[2]. (Bussolari and Bernays, 1995; Chandra, 1997; RTCA, 1997) TIS and enhancement to visual acquisition will not be further discussed in this paper. The oceanic applications build on the success of the in−trail climb procedure. The enhancements to visual approaches build on the fact that pilots in the U.S. are already using the TCAS II traffic display, even with its limitations, in terminal operations[3].

[2] TIS provides pilots with a cockpit display of nearby traffic. It shows range, relative bearing and altitude of aircraft within 5 nmi and 1,200 ft altitude of own aircraft. Threat aircraft are highlighted; no resolution advisories are provided.

[3] The International Civil Aviation Organization (ICAO) SICASP working group has formulated the Airborne Separation Assurance System (ASAS) concept. Concepts being proposed here are intended to be compatible with these ICAO concepts.

Analyses and evaluations are under way to develop evolutionary concepts and requirements for these applications in the terminal and oceanic domains. The remainder of this paper describes this evolution and preliminary results of evaluations intended to provide inputs to the CDTI MOPS.

CDTI CONCEPTS FOR ENHANCING VISUAL APPROACHES

These concepts propose the use of an ADS−B based CDTI to enhance the conduct of visual approaches. Three types of CDTI enhancements are considered:

1. Enhancing the routine conduct of visual approaches
2. Enhancing the safety of visual approaches
3. Enhancing runway capacity through CDTI−aided visual approaches.

Visual approaches are the backbone of operations at major airports in the U.S. and are also used in certain other parts of the world such as Canada and some parts of Europe (e.g., The Netherlands). Although in their basic form, visual approaches simply imply the approach to a runway visually, i.e., without the aid of electronic navigational instruments, when other traffic is present, their conduct usually includes the use of visual separation between aircraft. Although this separation may be provided either by ATC (i.e., the tower) or by pilots, by and large, during visual approaches in busy conditions, it is the pilots that provide the separation. Traffic advisories are issued to pilots, and once they confirm acquisition of traffic, a visual approach clearance is issued. The pilot is then responsible for following the traffic to the runway or to a closely spaced parallel runway.

The process of issuing traffic advisories and waiting for confirmation of visual acquisition is considerably more workload intensive for controllers than when visual approaches are not conducted; however this increase in workload is accepted by ATC facilities because of the significant gains in runway capacity. When visual approaches can be conducted, the landing rate for a single runway is usually higher than when visual approaches can not be conducted, because during visual approaches aircraft typically land about 2 nmi in−trail compared to 2.5 or 3 nmi in−trail (and more in case of wake turbulence considerations) in IFR conditions (Lebron, 1987). This is always reflected in controllers spacing aircraft closer during the vectoring for final approach, e.g., spacing them 3 nmi on long final to get 2 nmi over the threshold, as against spacing them 4 nmi on long final to get 3 nmi over the threshold during IFR operations.

The most dramatic benefit of being able to conduct visual approaches is in multiple runway operations. Most busy U.S. airports utilize two or more independent arrival streams to their runways during visual approaches. When visual approaches cannot be conducted, then depending upon the runway geometry, one or more of these streams may be suspended, resulting in a significant loss in airport capacity. See Table 1. (Mundra, 1989; Mundra and Buck, 1990; Mundra, et al., 1993).

Table 1. Significance of Visual Approach Operations on Airport Capacity

Airport	Capacity during Visual Approach Operations	Capacity during Non−Visual Approach Operations
Atlanta Hartsfield	85	70 (Simultaneous ILSs)
Boston Logan	60	34 (Single runway)
Cleveland Hopkins	55	28 (Single runway)
Detroit Wayne	66	64 (Simultaneous ILSs)
Minneapolis St. Paul International	60	48 (Dependent parallel)
San Francisco International	52	33 (Single runway)

Enhancing the routine conduct of visual approaches

Even though visual approaches are conducted routinely in the U.S. for capacity benefits, they are by no means easy for the pilots.

Looking for the traffic for visual acquisition is workload intensive for pilots. Pilots may have difficulty in visually identifying aircraft, and may even mis−identify them (i.e., identify the wrong aircraft as the traffic of concern); they may later lose visual contact with their traffic in haze, sun light, or patchy clouds. Night operations are especially difficult because pilots may lose their traffic in background lights, especially while following the traffic to the runway.

Some traffic point−outs are of general interest for potential separation concern; however, as explained above, visual approaches generally also require the unambiguous (i.e., positive) identification of a particular aircraft that is or will become the “traffic to follow,” and from which the pilot will be required to maintain separation visually. This identification is based on the information provided by the controller on aircraft’s range, bearing, direction of travel, aircraft type, and sometimes other relevant information such as altitude, and airline company.

Controller’s issuance of the range and bearing of the traffic is based on their judgment in reading the radar traffic displays. This information is only approximate. Depending upon the winds and the resulting crab angle of the aircraft, the actual relative bearing of the targets from the perspective of the pilot may be quite different from what appears on a controller’s display. In addition, during maneuvering, the lag in the ground tracking systems can result in significant differences between the bearing to a target as perceived by a pilot compared to that issued by the controller.

With respect to range information, in a traffic point−out, it is difficult for pilots to make accurate visual judgments of range to another aircraft. Further, even if the initial range information were accurate, that range often changes continuously, and it is difficult for pilots to make visual judgments of changes in range. Regarding the company and aircraft type information in the traffic point−out, this information may not be visible except at short ranges.

If a pilot loses visual contact with his or her traffic while maintaining visual separation, he or she is required to advise the controller. This has significant consequences for both the pilot and the controller, because now the controller must provide another means of separation between that aircraft and the relevant traffic, and provide vectors for an instrument approach, affecting the traffic flow and controller workload. It may also result in breaking the aircraft out, and eventually suspending visual operations altogether. Such considerations may create situations where a pilot may lose the traffic temporarily and yet may not advise ATC in the hope of re−acquiring it. Because of these considerations, depending upon weather conditions, a pilot may not accept a visual approach clearance even though he may see the traffic, because he may not be confident of maintaining the traffic in sight all the way to the runway.

In certain situations the pilot may find it difficult if not impossible to adhere to a clearance to maintain visual separation. Pilots are sometimes surprised by unexpected slow−downs by the lead traffic, requiring them to rapidly adjust speed, reconfigure the aircraft, and in some cases request a break−out. Pilots have no way to recognize speed changes until separation has diminished. Pilots can also be startled by traffic on a closely spaced parallel approach that is supposed to maintain visual separation from them, and instead passes them.

Pilots may receive instructions to acquire traffic while on base leg, knowing fully well that after turn on, they may be right next to each other. In such a situation, it may be difficult for the pilots to judge the relative geometry visually, and determine what the intercept angle should be so that an adequate spatial relationship with the target is maintained (e.g., stay slightly behind traffic after turn−on to final approach).
ADS−B/CDTI provides the potential of helping with this complex set of pilot actions during the routine conduct of visual approaches in several ways:

- Improved visual traffic acquisition: Flight tests conducted by Andrews (1984, 1989, 1991) have shown that the average traffic acquisition time with the aid of a traffic advisory combined with a traffic display (i.e., alerted search) is considerably more effective than an unalerted search. One second of alerted search was shown to be as effective as eight seconds of unalerted search. Faster acquisition of traffic by pilots may reduce the time between issuance of advisories and confirmation of traffic acquisition and may result in reduced controller and pilot workload. ASRS reports by pilots also confirm that the traffic display helps in visual traffic acquisition[4].
- Aid to positive identification: The demands of the visual search environment can lead a pilot to mis−identify an aircraft of concern. Displaying the flight ID of the traffic will help unambiguously establish that a particular target on the display is the target of interest (if the call sign is transmitted) and further, will aid in the positive identification of the associated airplane visible through the windshield. The accurate correlation between the airplane seen visually, and its associated CDTI target is the mechanism which enables the confident use of the associated displayed information.
- Providing a capability to highlight or identify the traffic on the display may help maintain cognizance of that traffic during the high workload terminal operations. This will be especially true in simultaneous parallel runway operations, or any other time that multiple targets are being displayed. This capability also supports the continuous correlation of visual target to displayed target as discussed above.
- Providing ground speed, closure rate, and/or ground track information may help pilots judge closure and encounter geometries. Providing speed or closure information may help pilots confirm the selection of appropriate speeds on final, and may reduce the incidence of surprise due to unexpected slowdowns by providing a means of becoming aware of speed differences before the decrease in

range is apparent using visual cues alone. Providing ground track information may improve the pilot's situational awareness by providing the necessary clues to judge the phase of flight (e.g., downwind, base, or final). This information may also help the pilot judge closure geometry during merging onto final in single or dual stream approaches where the pilot would be required to space own aircraft properly during the merge, and then follow the aircraft on the opposite side visually.

- If a CDTI display can be certified and procedures approved for CDTI−separation, then it may be possible to rely on CDTI separations during a temporary loss of visual contact[5]. Such reliance on the display alone presupposes that the displayed target and the airplane seen visually have been identified and correlated as described above.

[4] It should be noted that in a full−mission night simulation of TCAS operation, it was concluded that the probability of visual acquisition of targets that triggered TCAS advisories was the same with or without traffic advisories (Chappell, et al.,1989). The result is plausible because aircraft lights at night are visible and conspicuous well beyond the threshold of TCAS traffic advisories (Sorenson et al. 1991). The pilots however rated the utility of the traffic display in visual acquisition to be very high. This may indicate other improvements in the visual acquisition task even at night.

[5] Note, that even certifying CDTI separations in excess of standard radar separations may help, e.g., certifying to 5 nmi CDTI separations may help in visual approaches during marginal VFR conditions on downwind or base. Eventual reductions in CDTI separation standards to 3 nmi or lower would provide additional benefits on final approach. Various levels of certification may also be possible. For example, the certification requirements for equipment use during a temporary loss of visual contact on final approach, may differ from those where the display is used for separation indefinitely and in a high maneuvering environment due to the very different closure geometries in the two cases.

Safety enhancements of visual approaches

The difficulties described above in conducting visual approaches sometimes lead to safety related events. The Aviation Safety Reporting System (ASRS) administered by NASA (the U.S. National Aeronautics and Space Administration) contains reports from pilots and controllers about incidents that may have adversely affected the safety of flight. A search for reports relating to visual approaches was requested from ASRS. In the 64,440 total reports searched for the years 1992 through 1995, 150 were identified as being related to a perceived loss of safety during visual approaches[6].

[6] It should be noted that the ASRS receives reports only from those individuals who choose to report. Therefore, queries to the ASRS database may return only a subset of the total incidents that have occurred during visual approaches. Furthermore, ASRS reports represent the reporter's bias and may not include the facts as others perceive them.

Table 2 lists the causes for the safety events as categorized from the pilot reports[7].
An analysis of these reports shows that CDTI may be able to help reduce the incidence of many of these events. Some examples are discussed below. Of course, to what extent this information would be useful, and how it should be presented, needs to be determined through experiments.

Table 2. Number of ASRS Reports by Type of Incident

Reported Causal Factor	Number

		of Incidents Reported
1	Overshooting turn to final on parallel or nearly parallel approaches	33
2	Conflict in ATC procedure	24
3	Side−by−side approaches to closely spaced parallel runways	23
4	ATC error	16
5	Unnecessary TCAS alert causing go−around or other maneuver	11
6	Following the wrong aircraft	11
7	Failure to adhere to clearance, instruction or FAR	9
8	Incidents involving VFR aircraft not in communication with ATC	9
9	Late change in approach/procedure/clearance or instruction	6
10	Incident involving helicopters on published helicopter routes	5
11	Passing traffic to follow	5
12	Conflicting traffic being handled by another facility or sector	5
13	Inability of flight crew to communicate with ATC in a timely fashion	3
14	Identifying wrong conflicting aircraft	3
15	Flight crew not warned of conflicting aircraft departing	2
16	Returned incident report not relevant to visual approaches	2
17	Losing sight of traffic to follow	2
18	Conflict with traffic on runway	2
19	Incidents involving helicopters operating off published helicopter routes	1
20	Turning in front of traffic to follow	1

21	Visual clearance on an offset Localizer−LDA (interference with parallel runway)	1
22	Flight crew not aware/warned of another aircraft on approach	1
23	Approaching wrong runway after transition from IMC to VMC	1

[7] It should be noted that the sum total of the column providing counts of incidents related to causes exceeds 150, the total number of ASRS reports reviewed, because a single incident may be caused by multiple factors.

The most frequently reported problem (Item #1) involved overshooting the final on parallel approaches while flight crews were busy looking for the traffic to follow, or were trying to identify the correct runway. The distractions and confusion led to an overshoot of the intended final and caused a subsequent conflict with traffic on approach to a parallel runway. Overlaying traffic information on a navigation display with a graphical depiction of the final approach course or extended runway centerline may help such incidents. (A graphical depiction of the final approach course or the extended runway centerline is standard on EFIS displays). In general, the integration of traffic information with map−like displays should be an effective tool for the enhancement of situation awareness.

In a number of reports, pilots felt that the clearance provided by ATC was not ultimately realizable (Item 2). For example, instructions to follow an aircraft destined for a closely spaced parallel runway that is flying at significantly slower airspeeds may cause overtakes, making it impossible to maintain visual contact. Providing information about the target aircraft’s ground speed or closure rate may enable pilots to make a better assessment of the feasibility of following another aircraft on a closely spaced parallel approach, and in turn request a modified clearance or not accept an unrealizable one.

Items 6 and 14 relate to mis−identification of targets. Poor visibility and multiple, similar aircraft types in the field of view played a role in this. A Flight Id displayed next to the target on CDTI may help reduce the instances of such mis−identification. Items 11 and 20 relate to not being able to judge closure rates or geometries with the traffic, and may be helped by cues regarding closure rate. Item 17 relates to losing sight of traffic to follow, and may be helped by the improved situation awareness from a CDTI, and would be further helped if CDTI−based separation could be authorized. Finally, a CDTI may help pilots recognize ATC errors (Item 4) earlier, much the same way radar helps ATC recognize pilots’ errors.

Capacity enhancements of visual approaches

Most terminal facilities have specific established minima (e.g., 3,000 ft ceiling and 5 mi visibility) to which aircraft can be vectored for visual approaches; however, less than ideal environmental conditions such as haze, sun−in−the−eyes, or patchy clouds, may result in the suspension of visual approaches at ceiling and visibility values considerably higher than these minima. (Mundra and Buck, 1990). The CDTI may help improve such operations in several ways:

Reliably conducting visual operations to established minima: If the traffic display is proved to be reliable enough, then it may help keep traffic in (electronic) “view” during adverse visibility conditions such as scattered clouds or fog, sun−in−the−eyes, or city lights. This may help conduct visual operations reliably down to the established minima. This use would require the traffic display to be used in aiding visual acquisition and in monitoring separation as long as the actual aircraft separation exceeded radar separation standards.

Reducing the minima to which visual approaches may be conducted: The minimum ceiling authorized to vector for a visual approach is 500 ft above the minimum vectoring altitude (MVA). The 500 ft buffer is provided to enable aircraft sufficient area after clearing the cloud cover to acquire the traffic. If the traffic display helps pilots visually acquire the traffic faster and more consistently than an unaided search, the 500 ft buffer may be reduced. Most U.S. facilities also use a 5 mi visibility minimum in an effort to assure visual acquisition before the loss of radar separation. The improved acquisition ability provided by the traffic display may allow the reduction of the 5 mi visibility minimum to closer to 3 mi. If the traffic display is used in conjunction with point in space approaches, the minima may be reduced further. Flight management system (FMS) approaches are particularly promising in this regard, since they may permit trajectories to be flown without regard to the location of existing navigation aids.

Improving acceptance rates in marginal visual conditions: The ability to utilize a traffic display in aiding visual acquisition and in monitoring separation may help improve operational capacities of single stream approaches in marginal VMC since in the U.S. controllers may vector aircraft closer to radar separations if visual separations will be used at some point on final approach.

Table 3 shows potential capacity benefits and delay savings using CDTI enhanced operations at selected airports based on site specific operational weather conditions and arrival capacities. Through discussions with the individual airports (column 1), the typical weather and arrival capacity for current visual approach operations (column 2) and the potential weather and arrival capacity for CDTI enhanced operations (column 3) were estimated. (The CDTI based enhancement was assumed to enable the maintenance of visual approaches down to weather minima established by the facility for visual approaches.) The yearly percentage of time (column 4) that the ceiling and visibility conditions in column 3 exist was estimated based on four months of surface weather observations from each of these airports. Using these weather percentages and capacity numbers supplied by the airports, the annualized delay savings with the use of CDTI enhanced operations were estimated (column 5) with an airspace performance analysis capability developed by MITRE/CAASD.

Table 3 shows that SFO may realize significant delay savings with a CDTI based visual approach enhancement concept. It also indicates some benefit for other airports. These benefits would increase with the other potential CDTI enhancements listed above for reducing minima to which visual approaches may be conducted.

Table 3. Potential Benefits from Enhanced Visual Approach Procedures

with CDTI

Airport	Typical Weather and Arrival Capacity for Visual Approach Operations (ceiling−ft & vis−sm)	Potential Weather and Arrival Capacity for CDTI Enhanced Operations (ceiling −ft & vis−sm)	Time in CDTI Enhanced Weather (yearly %)	CDTI Delay Savings (hrs/yr)
Dallas−Fort Worth	>2100 & 7	< 2100 & 7 and	4.37 %	168.3

(DFW)	92 arrivals	>2100 & 3 92 arrivals (normally 79)		
New York Kennedy (JFK)	>3500 & 5 74 arrivals	< 3500 & 5 and >2500 & 5 74 arrivals (normally 55)	2.27 %	357.8
Seattle−Tacoma (SEA)	>5000 & 7 60 arrivals	< 5000 & 7 and >3500 & 5 60 arrivals (normally 44)	6.31 %	133.4
San Francisco (SFO)	>2600 & 7 52 arrivals	< 2600 & 7 and >2300 & 5 52 arrivals (normally 35)	6.74 %	1680.6
St. Louis (STL)	>4000 & 5 76 arrivals	< 4000 & 5 and > 2500 & 5 76 arrivals (normally 64)	2.65%	90.5

Table 4. A Potential Evolution of CDTI Applications for Enhancing Visual Apporaches

Application	Name	Comments	
I	Enhancement of the safety and the routine conduct of visual approaches	Use of CDTI features by pilots is optional; no change in procedures	CDTI as used as a procedural enhancement; No reliance on CDTI for separation
II	Enhanced identification of traffic Controllers to issue call signs of traffic in visual approach clearances	Controllers to issue call signs of traffic in visual approach clearances	
III	a. Contingent approaches using distinct glide slope intercept altitudes	New airspace and approach procedures; requires break out if target is not acquired by designated point on approach	
	b. Contingent approaches using an offset intermediate approach segment		

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	c. Contingent approaches using an offset final approach path		
IV	CDTI−based vertical separation before visual acquisition	Potentially lower ceiling and visibility requirements based on lower vertical separation minima (e.g., 500 ft) for CDTI separation	CDTI as a required procedural component; reliance on CDTI for separation in specific ways
V	CDTI−based horizontal separation before visual acquisition	Potentially lower ceiling and visibility requirements based on contingent geometries and CDTI separation	
VI	Continued approach during temporary loss of visual acquisition	Use of CDTI separation to established separation standards > or = radar separation standards	
VII	wake vortex separations lower than standard radar separations during temporary loss of visual acquisition	Use of CDTI separation to separations lower than standard radar wake vortex separations	

Introducing ADS−B/CDTI capabilities for enhancing visual approaches is a complex endeavor, and will require several phases. Table 4 shows one possible evolution for introducing such capabilities. For more detail on the potential evolution, see Stassen (1997).

Potential CDTI Features for Enhancing Visual Approaches

The following features have been proposed by the enhanced approaches subgroup of RTCA SC−186 WG3 as worthy of being evaluated for their utility in enhancing the routine conduct and safety of visual approaches. Evaluations are being conducted to assess the utility of these features for visual approach enhancements.

Table 5. List of Candidate CDTI Features for Enhancing Visual Approaches

Target Range
Target Bearing
Target Vertical Speed
Target Closure Rate
Target Ground speed
Target Heading
Target Flight ID

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Target Highlighting
Relative Track Vectors
Moveable Datablocks
Center Map View [8]
Ground Track Vectors
Predicted Altitude Function [9]
Range Reference

CDTI EVALUATIONS FOR ENHANCEMENTS OF VISUAL APPROACH OPERATIONS

Two studies are reported that explore the potential utility of various CDTI features, as overlays to the TCAS traffic display, for enhancing visual approach operations with respect to their routine conduct and safety. Evaluations to explore capacity enhancements of visual approaches are planned in the future.

In a preliminary evaluation (Evaluation 1), eight line pilots were trained in the operation of several CDTI features. Pilots then flew six single stream visual approach scenarios with all features available for their use. After completing the scenarios, pilots were asked to rank the relative utility of the various CDTI augmentations. Results from this ranking identified a core feature set as being potentially useful during the visual approach to landing. A follow−on study (Evaluation 2), evaluated this feature set in greater detail. Results from the preliminary evaluation and an overview of Evaluation 2 are provided below.

Simulation Environment

The simulation test bed, located at The MITRE Corporation, consisted of a generic mid−fidelity transport cockpit with an out−the−window view (120 degrees laterally X 50 degrees vertically), a controller station (composed of a combined TRACON and Tower position), and simulated traffic representing terminal area operations at the Seattle−Tacoma International Airport. Approach operations were modeled to closely match that of the Seattle TRACON employing a southern flow operation. Pilots controlled the lateral and vertical axes of the aircraft via a combination of auto−pilot and auto−throttle controls. Subject pilots always operated as pilot flying and a confederate experimenter performed the duties of pilot−not−flying (e.g., communications, checklists, call−outs, etc.). In evaluation 1, a single controller provided vectors for the subject cockpit only (i.e., communications with other aircraft were not modeled). In evaluation 2, pilots were provided with a voice party line using simulated pseudo−pilots of other aircraft. Table 6 provides an overview of the two studies.

[8] Although the center map view is available in some EFIS installations today, it is included in this list in order to determine if it may be required for some CDTI applications.

[9] This is intended to be a visualization capability to enable a pilot to determine if his projected path will be above or below the current position of the aircraft in front, and is intended to aid in situations where wake vortex may be a concern.

The CDTI platform consisted of an integrated EFIS display modeled after a 747−400 “glass cockpit” navigation display. All CDTI enhancements, along with standard TCAS symbology, were overlaid onto the navigation display (Figure 1). Only TCAS traffic and proximate traffic symbology were available during the simulation. TCAS alerts (i.e., TA’s, RA’s) were not simulated. Targets appearing on the traffic display were correlated with visible traffic in the out−the−window view. That is, pilots could verify “traffic in sight” using the simulated visual scene and follow that traffic to a landing or a parallel runway.

Although Figure 1 shows CDTI features on an EFIS navigation display, they need not appear on such displays. In fact, for the current fleet, these features, if implemented in the near term, are just as likely to appear on many other display types such as weather radar or standalone displays.

Preliminary Evaluation

As a result of the extensive features list originally identified by SC−186 WG3 as being potentially useful during a visual approach to landing (Table 5), a primary objective for the preliminary evaluation was in establishing a core feature set, which would then be further examined in Evaluation 2.

Two ranking procedures were used to gather pilot feedback on feature utility. Pilots were first asked to rank order the seven items of alphanumeric information that were available for only a single target based on their perceived usefulness during the visual approach to landing. Results from this ranking are provided in Table 7. Alphanumeric depiction of Flight ID and closure rate are seen to be ranked high in this Table. Alphanumeric depiction of range and bearing were ranked low. Note that range and bearing were also available to pilots in graphical form through the standard TCAS II traffic display. The results thus indicate that alphanumeric values for range and bearing may have minimal additional value for enhancing visual approaches. It should be noted that ground track heading was also available graphically, through a heading vector.

Table 6. Overview of Preliminary Evaluation and Evaluation 2

	Preliminary Evaluation (Evaluation 1)	Evaluation 2
Scenarios	Six Routine Approaches	5 Routine Approaches + 3 Safety Scenarios
Traffic Flow	Single Stream only	Single and Dual Stream (closely spaced parallels)
Traffic Density	Low to Medium	High Density
ATC Communications	No Party−Line	Party−Line Available
Auto−pilot	All scenarios flown on auto−pilot	Auto−pilot disengaged once visual approach clearance is provided
Number of Subject Pilots	8	16

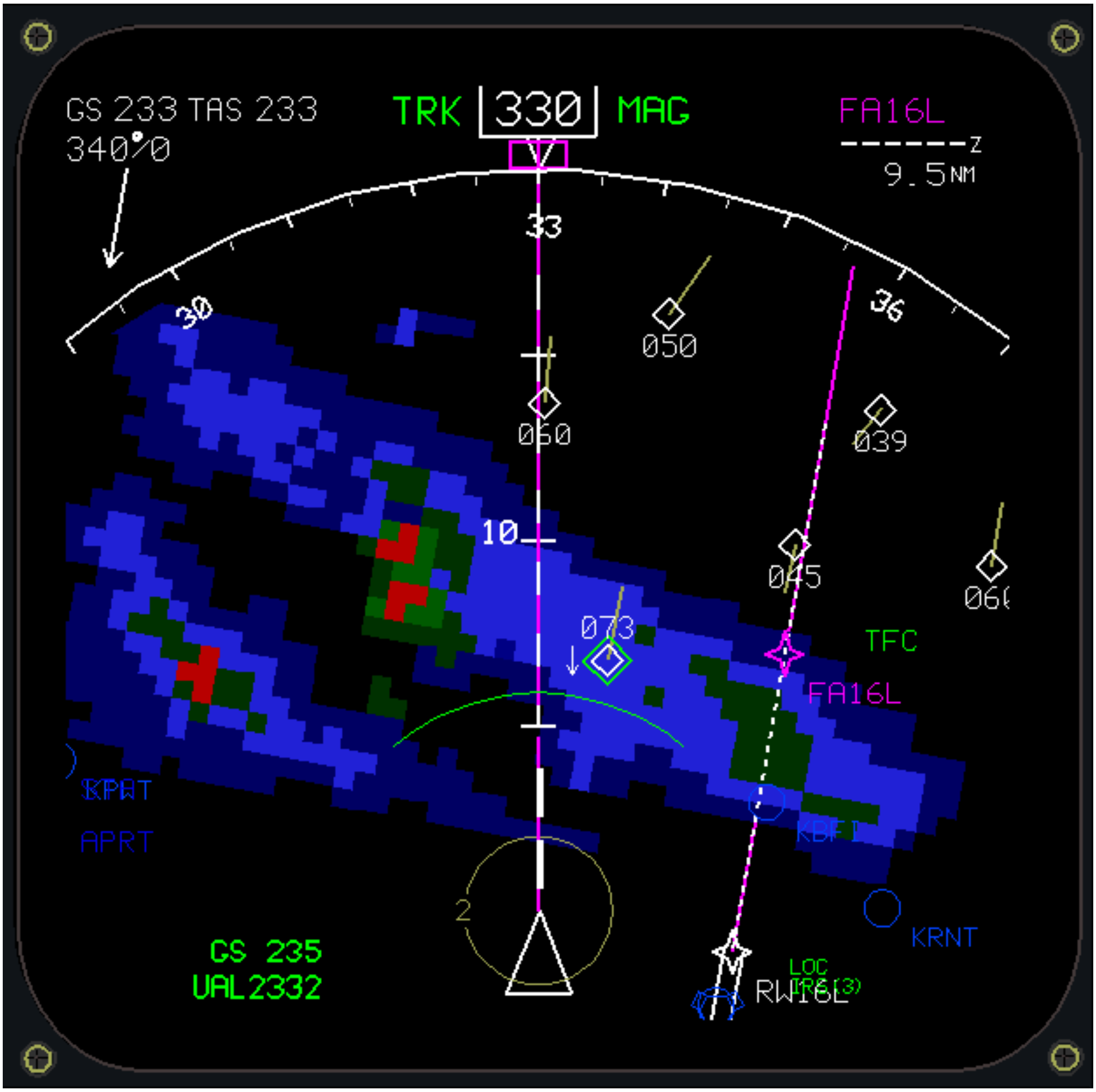

Figure 1. TCAS Navigation Display with Overlay of CDTI Enhancements

Traffic at the 1 o'clock position is highlighted with a diamond which outlines the TCAS symbol. Ground speed in knots (235) and Flight ID (UAL2332) for the highlighted target is displayed in the lower left−hand corner. If Closure Rate is available, it would be displayed in place of Ground speed (e.g., CR 32). Ground track vectors are depicted emanating from each target.

Table 7. Average Rank Order of Target Alphanumeric Information

from 1 (Most Useful) to 7 (Least Useful)

Flight ID	2.63
Closure Rate	2.88

Ground speed	3.25
Range	3.38
Heading	4.50
Vertical Speed	5.25
Bearing	6.13

Pilots were then asked to rank all features based on their perceived impact on the safety of visual approach operations. Results from the second ranking are provided in Table 8.

Table 8. Ranking of All Features from 1 (Feature is Essential for Enhancing the Safety of Visual Approaches) to 5 (Feature is Distracting and May Degrade the Safety of Visual Approaches)

Target Highlighting	1.63	Full Map View	2.63
Closure Rate	1.75	Moveable Datablocks	2.63
Ground speed	2.00	Heading	2.88
Range Ring	2.13	Relative Track Vectors	2.88
Flight ID	2.19	Predicted Altitude Function	3.13
Ground Track Vectors	2.44	Vertical Speed	3.19
Range	2.50	Bearing	3.25

In addition to the ranking results above, all sessions were videotaped and later reviewed to gather feature usage data. Based on the results, it was determined that the following core feature set may prove useful in enhancing routine visual approaches.
Evaluation 2

The purpose of Evaluation 2 was to determine the relative utility of the six core features listed in Table 9.

Table 9. Core Feature Set Being Evaluated in Evaluation 2

Flight ID
Target Selection and Highlighting
Target Closure Rate
Target Ground speed
Ground Track Vectors
Range Ring

<u>Experimental Design</u>

Evaluation 2 was carried out using a 4 X 2 mixed factors design (Table 10). The two variables included:

1. Target Speed Cue (within−subjects): Three speed cues were compared against one another and against a standard TCAS display (baseline condition).
2. Ground Track Vectors (between−subjects): Comparisons were made between a CDTI display with track vectors available and a second display with no track vectors available.

Table 10. Experimental Design for Evaluation 2

Baseline		Closure Rate (Alphanumeric)	Ground speed (Alphanumeric)	Graphical Display of Closure Rate
2 Scenarios	Ground Track Vectors	2 Scenarios	2 Scenarios	2 Scenarios
2 Scenarios	No Ground Track Vectors	2 Scenarios	2 Scenarios	2 Scenarios

All conditions included a two−mile range ring surrounding ownship. In addition, target selection and highlighting along with Flight ID were available for all conditions with the exception of the baseline condition (standard TCAS display). The two scenarios within each cell included a single and a dual stream scenario for a total of eight scenarios with each subject. Of these eight scenarios, three were “safety scenarios” designed to determine the impact of the various features on the safety of visual approaches. The safety scenarios were composed of the following:

1) Traffic to follow slows early during the approach to landing (Single Stream)
2) Traffic on parallel runway overshoots the turn to final (Dual Stream)
3) Traffic on parallel runway slows early making it difficult for the subject to adhere to the clearance to maintain visual separation (Dual Stream)

Procedure

Pilots were tasked to conduct a visual approach as they normally would within a dense terminal environment. Subjects were briefed that the CDTI information was available as an enhancement to the TCAS traffic display. As such, they were not required to make use of the features but rather, were encouraged to use the CDTI information as a potential enhancement to their conduct of the visual approach. This paradigm is a substantial departure from earlier work for which subjects were tasked to maintain a specific in−trail distance from traffic displayed on the CDTI (Sorenson, 1983; Kelly, 1983). Specifically, for the visual approach application, pilots assume responsibility for separation through visual acquisition and, as such, spacing is at their discretion during the approach.

Performance Data

The following data were collected during the visual approach scenarios:

1) Communication Content. Communications with ATC were recorded and reviewed to determine specific instances for which the CDTI played a role during the visual approach to landing (i.e., a request for Flight ID).

2) Subjective Feature Preference. Pilots were asked to rank the relative utility of the various CDTI features available to them during the visual approach to landing.

3) Subject Interaction with CDTI. All sessions were videotaped and reviewed to determine pilots interaction with the CDTI.

4) Speed Profile. Assessments were made of when subjects began slowing during the visual approach to landing.

5) Spacing on traffic to follow and on traffic on the parallel runway. Mean spacing between the subject cockpit and traffic to follow was recorded.

6) Inter−arrival time. The difference in arrival time between the traffic to follow and the subject aircraft was recorded.

7) Lateral RMS Error. Tracking error along the extended centerline was recorded to determine overshoots by the subject pilot during the visual approach.

CDTI Interfaces for Evaluation 2

These evaluations were intended to identify the relative utility of the CDTI information being presented for the routine conduct of visual approaches and for enhancing their safety. Specific formats being used were merely one potential depiction of that information. This is also true of the pilot interface for the CDTI. As such, there was no intention to evaluate or recommend a specific interface. However, because of the significant limitations on cockpit panel space, there was considerable discussion within SC−186 on minimizing and simplifying the number of CDTI pilot inputs. As a result, a three button panel was developed as an illustration of a simple pilot interface for the selection and removal of CDTI features as follows. (Note: a two button panel would suffice and is explained below).

1) Forward Selection. An initial press displays Flight Ids (i.e., call signs) for all aircraft displayed on the traffic display. A subsequent press begins the target selection process in the order of the target range (Figure 1). The closest target to ownship will be selected (i.e., first highlighted), followed by the next closest target, etc.
2) Backward Selection. Enables the pilot to cycle through the targets in reverse order, mainly to recover from “selection overshoots” of the desired target.
3) Reset. Removes CDTI features (this button could be eliminated by allowing the reset function to occur when the forward selection and backward selection button are pressed simultaneously). The results of Evaluation 2 will be available in July 1997.

Evaluations are also being planned to determine CDTI information useful in the capacity enhancement of visual approaches. In addition to the features listed in Table 2, these may consider a graphical depiction of own aircraft future position in relation to the glide path of the lead aircraft. In addition, warnings for range, range rate, and vertical separation may also be considered.

CDTI CONCEPTS FOR OCEANIC ENHANCEMENTS

Using CDTI for enhancing ATM operations is often assumed to involve self separation by pilots. However, Table 11 proposes an evolution in the oceanic domain where, in the first four phases, the pilot would not be required to assume separation responsibility. Changing separation responsibilities is a major challenge in ATC procedures. One of the most significant contributions of the ITC procedure is establishing that useful cockpit display based procedures are possible without changing separation responsibilities. Concepts V–IX do involve active use of the CDTI display by flight crews to monitor and maintain their own separation from other aircraft.

Table 11. Proposed Oceanic CDTI Concepts

Concept #	Name	
I	Enhanced ITC/ITD	Procedural Enhancements
II	Lead Climbs/Lead Descents	(No Change to Current
III	Limited Duration Longitudinal Separation based on CDTI Distance Measurement	Separation Responsibility)
IV	Longitudinal Separation based on Periodic CDTI Distance Measurements	
V	Initial Cockpit Based Self Separation (Reduced Separation ITC/ITD/LC/LD)	Pilot Responsible for Separation
VI	Limited Duration Station−Keeping	
VII	Lateral passing	
VIII	Crossing/Merging	
IX	Extended Self Separation (Time, Quantity, and Situation)	

The following paragraphs review the technical basis for such a design.

Existing ICAO standards for Oceanic separations

International Civil Aviation Organization Procedures for Air Navigation Services—Rules of the Air and Air Traffic Services (PANS RAC Doc. 4444) [1] part III, paragraph 8.2.2.1 requires aircraft climbing or descending on the same track to be separated by 15 min when passing through the level of another aircraft (10 min if navigational aids permit frequent determination of position and speed). Paragraph 8.3.1.2 authorizes this separation to be reduced to 10 nmi (19 km) distance at the time the level is crossed (Figure 1), provided the following apply:

- Each aircraft utilizes “on track” distance measuring equipment (DME) stations.
- One aircraft maintains a level while vertical separation does not exist.
- Separation is established by obtaining simultaneous DME readings from the aircraft. This distance−based separation rule, the similar FAA Order 7110.65H [2] DME distance−based rule (paragraph 6−31.c.1), as well as other co−altitude longitudinal distance−based rules cannot be applied in most oceanic airspace due to the lack of DME stations. It should be noted that the intent of these procedures is to obtain an accurate measurement of relative distance between aircraft.

PANS RAC Doc. 4444 part III, paragraphs 9., 9.1, and 9.2 authorizes the reduction in separation minima when special electronic or other aids enable the pilot−in−command of an aircraft to determine accurately the aircraft’s position and when adequate communication facilities exist for that position to be transmitted without delay to the appropriate ATC unit. However, the communication between pilots and the appropriate ATC unit need not necessarily be without delay, if the aircraft is able to closely adhere to their current flight plan and the air traffic situation is such that an adequate level of safety can be maintained.

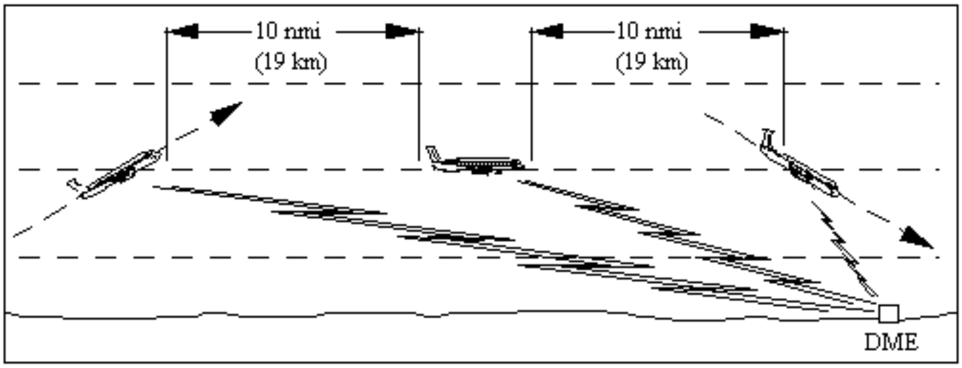

Figure 2. ICAO Requirements for Aircraft Climbing or Descending on Same Track Utilizing DME

The cockpit display of traffic information is an electronic means of determining aircraft relative position information. ADS−B/CDTI has the ability to sense the presence of and compute the relative position of nearby equipped aircraft.

The ITC procedure took advantage of the range determination capability of the TCAS II display by having flight crews determine the relative distance to a lead aircraft and relay that information to ATC for application of procedural non−radar separation minima. The first four operational concepts in Table 11 would function similarly. In these procedures, flight crews would determine the relative distance between aircraft on the CDTI and relay that information to ATC. Air traffic controllers would then apply non−radar separation minima to enable trailing aircraft to climb through the altitude of another aircraft or to allow an aircraft to climb to co−altitude with another aircraft and then ensure longitudinal separation. There would be no change of responsibility for pilots and controllers.

Near−term procedures maintaining current separation responsibilities

Enhanced In−Trail Climb/In−Trail Descents (procedure I in Table 11)

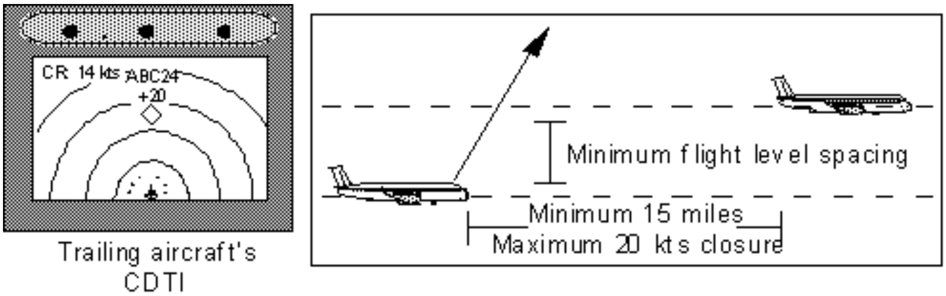

Figure 3. In−Trail Climb

The TCAS II display had numerous limitations with respect to its use in the ITC/ITD procedure. In addition to determining range, the procedure requires the trailing aircraft to positively identify the lead aircraft and to determine the closure rate. These requirements are currently accomplished in the ITC procedure in a cumbersome manner through voice communications and the use of transponder squawk−standby procedures. ADS−B could significantly enhance these procedures by providing this information (the identity of the traffic and the closure rate) on the CDTI (Figure 3). Longer reception ranges of up to 120 nmi would provide increasing benefit by proportionately increasing the likelihood of the applicability of the procedure. The ITC procedure incorporates certain distance safety buffers due partly to the inadequate availability characteristics of the current traffic display. An ADS−B based CDTI that has demonstrated adequate reliability and availability characteristics may enable a reduction in the current 15 nmi minimum separation requirement.

Lead Climbs/Lead Descents (Procedure II in Table 11)

Lead climbs (LC) and lead descents (LD) are a direct extension of ITCs and ITDs and could be conducted with an ADS−B based CDTI due to ADS−B's ability to "see" aircraft in the aft quadrants. The procedures would be similar to the ITC and ITD, except that the climbing or descending aircraft would be in the lead.

Longitudinal Separation based on CDTI Distance Measurement (Procedures III and IV)

A conservative step in establishing oceanic co−altitude distance−based longitudinal separation using ADS−B/CDTI would be to initially limit the period of time the aircraft could be at the same altitude. A precedent for this procedure, where direct pilot/controller communications do not exist, is a procedure that Anchorage Air Route Traffic Control Center is currently authorized to use based on DME/area navigation (RNAV) reports. The current Anchorage procedure reduces longitudinal separation to 30 miles between aircraft if distance is verified by DME reports or radar observation, or to at least 40 miles for aircraft reporting RNAV positions. Application of DME/RNAV separation is authorized for up to 75 minutes without maintaining direct pilot/controller communications in two designated control areas for aircraft established on or transitioning to the North Pacific Composite Route System (NOPAC). Aircraft involved are also assigned mach numbers in accordance with FAA Order 7110.65, Paragraph 8−3−3, Mach Number Technique. It should be noted, that the most common completion of this procedure is a request for (and granting of) a higher altitude by one of the aircraft involved.

A CDTI based limited duration longitudinal separation concept would be an extension of the Anchorage procedure, but with the substitution of a CDTI distance measurement reported to ATC instead of having ATC obtain DME/RNAV reports from both the in−trail and lead aircraft.

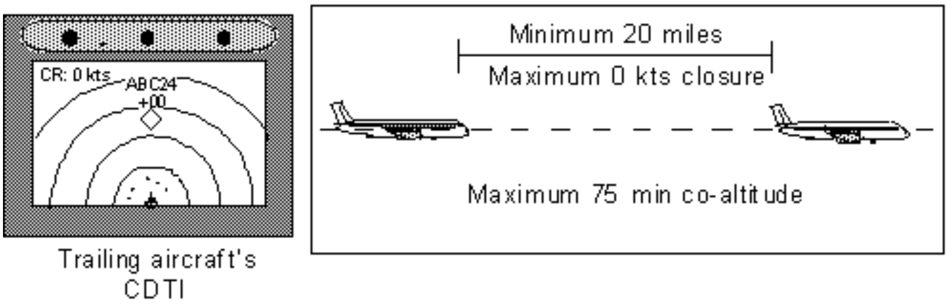

Figure 4. Limited Duration Longitudinal Separation Concept

Since the separation is based on the initial distance measurement and mach number assignments, no continuous monitoring tasks by the pilots would be required. The procedure could however require that the pilot reconfirm the initial parameters of the procedure when reaching co−altitude. These initial parameters would include call−sign, bearing, distance, and ground speed closure with the lead aircraft. Acceptable limits for each of these variables would need to be defined to assure safe separation.

The standard completion of this procedure may be the request for and granting of a higher or lower altitude to one of the aircraft, or the transition into a radar covered area.

In application IV, the procedure is applied repeatedly as new distance reports are received from the pilots. Evolving to it would primarily be a function of having demonstrated adequate availability and reliability of the surveillance system.

Early Oceanic Self−Separation Concepts

The oceanic domain is an ideal venue for initial applications of cockpit self separation. Certain oceanic areas involve one way, parallel traffic associated with structured tracks where there are few intersections at co−altitudes, the aircraft separations are large, the closing speeds are very small, and decision times are correspondingly large. They also correspond to situations when pilot workload is relatively low.

It is proposed that initial application involve only pair−wise application for two aircraft equipped with ADS−B/CDTI, with ATC assuring separation of the pair from other traffic. It is envisioned that in addition to the increased surveillance capability of the ADS−B system, these initial applications will need certain additional features of the CDTI such as flight ID, closure rate information, and alerts to facilitate structured situation where self separation would be authorized for limited periods between the designated pair of aircraft. These applications begin with simple steps such as enhancing the ITC/ITD/LC/LD procedures that last a very limited time, and evolve to a longitudinal distance standard of (say) 30 nmi for a pair on certain specified tracks.

In application V in Table 11, enhancements to the ITC/ITD/LC/LD procedures are envisioned with self separation responsibilities. A pilot who sees on his CDTI a potential to perform an ITC, ITD, LC or LD, would coordinate via air to air voice link with the other aircraft involved to assure a near−term strategic understanding of that aircraft’s plans, and would then request clearance from ATC, possibly via direct controller pilot communications, to execute a self−separation procedure. The request would identify the other aircraft involved, current relative position information, and the planned maneuver, including final relative position information. ATC will assess the situation, and, if appropriate (i.e., if strategic traffic, weather, FIR boundary, and other conditions are acceptable, and the final position of the aircraft can be managed for separation by the ground after the maneuver), grant the request with notification to the other aircraft involved. At that time, ATC would only be responsible for separation between the pair of aircraft involved and other aircraft. ATC would be expected to annotate flight strips in some appropriate manner. If a neighboring sector will become involved, coordination between the two controllers will be required.

The pilot will notify the other aircraft via air to air voice of his intentions and execute the maneuver, maintaining separation based on the CDTI display. Separations perhaps as low as 5 nmi may be possible based on use of the CDTI. Once the procedure is complete, ATC would reassume separation responsibility and apply standard separations.

The Limited Duration Station Keeping procedure (procedure VI) would work similar to the previous procedure except the controlling aircraft would only climb one altitude step and then station keep for a limited time against the other aircraft. To assist in station keeping, it may be found that the pilot would need to initiate a CDTI−based graphical warning area (e.g., circle, square, or oval.) The algorithms in the CDTI will continuously compare the target aircraft to this area, and notify the pilot aurally and visually if the target aircraft crosses the boundary of the area. The area will be set (possibly by the pilot) so that he is alerted well before the required separation minimum is reached. The notification will simply indicate to the pilot that relative separation has changed by the pilot defined amount and he should assess the situation. Often the pilot may simply reset the graphical warning area, e.g., if the relative distance between the two aircraft is either increasing, or else decreasing at an acceptably slow rate. If the situation calls for action, the controlling pilot may have to slow down or speed up or request an altitude change or return to ATC control. If the situation is a true contingency event, the pilot will have to decide how best to respond, and keep ATC notified of such contingency events.

Again, as in procedure III, the standard completion of this procedure may be entry into a radar covered airspace, or the request and granting of a change in altitude by one of the aircraft.

Steps VII and VIII envision that as experience is gained with this procedure, it may be extended to shallow crossings and extended station keeping, similar to step IV earlier.

Table 12 tabulates the potential CDTI featured being considered to support these procedures. Evaluations will be conducted in July 1997 in medium fidelity simulations, and then subsequently in high fidelity simulations to determine what features are necessary. The outputs of these evaluations are expected to be provided for incorporation into the CDTI MOPS.

Table 12. Potential CDTI Information for Oceanic CDTI Concepts

Raw Data on Target

- Flight Id
- Range
- Bearing
- Speed
- Ground track
- Altitude
- Vertical Speed

Alerts
- Closure rate alert
- Range alert
- Altitude or vertical separation alert

CONCLUSIONS

- The significant operational experience gained by pilots in the use of the current TCAS II traffic display in the commercial airline fleet prompts the possibility of fruitfully introducing CDTI capabilities in the air traffic system.
- CDTI feature requirements depend upon the intended function or application.
- Use of CDTI in air traffic applications do not necessarily require a transfer of separation responsibility to the cockpit. Several applications with meaningful benefits are possible in the oceanic and terminal domains that build on existing procedures or uses, and that maintain current separation responsibilities.
- Preliminary results from laboratory evaluations indicate that a set of simple core features may be able to facilitate some of these applications.
- It may be possible to deploy these applications in the near term because of their incremental nature.

REFERENCES

Abbot, Terrence S., Gene C. Moen, Lee H. Person, Gerald R. Keyser, Kenneth R. Yennie, and John F. Garren, 1980, Flight Investigation of Cockpit Displayed Traffic Information Utilizing Coded Symbology in an Advanced Operational Environment. NASA Technical Paper 1684, Langley, VA.

Abbot, Terrence S., and Gene C. Moen, 1981, Effect of Display Size on Utilization of Traffic Situation Display for Self−Spacing task. NASA Technical Paper 1885. Langley, VA.

Abbott, Terrence S., 1985, A Compensatory Algorithm for the Slow−Down Effect on Constant−Time−Separation Approaches. NASA Technical Paper 2386, Langley, VA.

Andrews, J. W., 1984, Air−to−Air Visual Acquisition Performance with TCAS II, Project Report ATC−130, Lincoln Laboratory, Massachusetts Institute of Technology, DOT/FAA/PM−84/17, Lexington, MA.

Andrews, J. W., 1989, “Modeling of air to air visual acquisition,” The Lincoln Laboratory Journal, Vol. 2 #3, Lexington, MA.

Andrews, J. W., 1991, Unalerted Air−to−Air Visual Acquisition, Project Report ATC−152, Lincoln Laboratory, Massachusetts Institute of Technology, DOT/FAA/PM−87/34, Lexington, MA.

Bussolari, S. R., and D. J. Bernays, “Mode S data link applications for general aviation,” in Proceedings of the 14th Digital Avionics Systems Conference, American Institute of Aeronautics and Astronautics/Institute of Electrical and Electronics Engineers, Cambridge, MA, pp. 199–206.

Chandra, D., 1997, “Pilot Evaluation of Data Link Services for general Aviation,” in R. E. Jensen (Ed.), Proceedings of the Ninth International Symposium on Aviation Psychology, Ohio State University, Columbus, OH.

Chappel l, S. L., et al., 1989, “Pilots’ use of a Traffic Alert and Collision Avoidance System (TCAS II) in a simulated air carrier operations,” NASA TM−10094, NASA Ames Research Center, Moffett Field, CA.

Cieplak, J. J., Mundra, A., Peppard, K. W., Sweeney, F., 1994, "Extension of Distance−Based Non−Radar Separation Rules to an Oceanic In−Trail Climb Procedure," Proceedings of the 9th Annual International Oceanic Airspace Conference, Fall.

Cieplak, J. J., Peppard, K. W., Sweeney, F., Stone, R. P., Briggs, E., F., 1994, "Oceanic In−Trail Climb Using TCAS II," Proceedings of the Air Traffic Control Association Annual Meeting, Fall.

Cieplak, J. J., 1994, "TCAS Assisted In−Trail Climb in Oceanic Airspace," The MITRE Corporation Corporation/Center for Advanced Aviation System Development, McLean, Va, MP−94W0000034 − video tape, March.

Cieplak, J. J., Mundra, A. D., Peppard, K. W., 1995, "Operational Trials of the In−Trail Climb Procedure: Interim Results," MTR−95W0000121, The MITRE Corporation/Center for Advanced Aviation System Development, McLean, Va, September

Cieplak, J. J., and Swensson, R., 1997,“Oceanic ADS−B/CDTI Operational Concepts Summary”, The MITRE Corporation, To be published September.

Connelly, M. E., May 1977, Simulation Studies of Airborne Traffic Situation Display Applications, Final Report, The Massachusetts Institute of Technology, ESL−R−751, Cambridge, MA.

Endsley, Mica R., 1995, Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors. 37(1) 32−64.

Fracker, Martin L., 1988, A Theory of Situation Assessment: Implications for Measuring Situation Awareness. In Proceedings of the Human Factors Society 32nd Annual Meeting, Human Factors Society, Santa Monica, CA, pp. 102–106.

Hart, Sandra G., and Les L. Loomis, 1980, Evaluation of the Potential Format and Content of a Cockpit Display of Traffic Information, Human Factors. 22(5) 591−604.

Harwood, K., B. Barnett, and C. D. Wickens, April 1988, Situational Awareness: a Conceptual and Methodological Framework, Proceedings of the 11th Symposium of Psychology in the Department of Defense.

Kelly, James R., 1983, Effect of Lead Aircraft Ground−Speed Quantization on Self−Spacing Performance Using a Cockpit Display of Traffic Information, NASA Technical Paper 2194. Langley, VA.

Kelly, James R. and Terrence S. Abbott, 1984, In−trail Spacing Dynamics of Multiple CDTI−equipped Aircraft Queues, NASA Technical Memorandum 85699, Langley, VA.

Lebron, J., 1987, “Estimates of Potential Increases in Airport Capacity through ATC System Improvements in the Airport and Terminal Areas,” FAA−DL5−87−1, Department of Transportation, Federal Aviation Administration, Washington, D.C.

Marshak, William P., Gilbert Kuperman, Eric G. Ramsey, and Denise Wilson, 1987, Situational Awareness in Map Displays, Proceedings of the Human Factors Society 31st Annual Meeting. (533−535). Human Factors Society, Santa Monica, CA.

Mundra, A. D., (1989),“A Description of Air Traffic Control in the Current Terminal Airspace Environment,” The MITRE Corporation Corporation/Center for Advanced Aviation System Development, McLean, Va, MTR−88W00167, March.

Mundra, A. D., and Buck, W. W., (1990), "The Need for Multiple VFR Approach Concepts," The Journal of Air Traffic Control. January−March.

Mundra, A. D., Cieplak, J. J., Domino, D. D., (1993) "Enhancing Visual Approaches with the TCAS Traffic Display," Proceedings of the Air Traffic Control Association Annual Meeting, Fall.

Orasanu, J., 1995, Situation Awareness: Its Role in Flight Crew Decision Making, Proceedings of the 8th International Symposium on Aviation Psychology, Ohio State University, Columbus, OH.

Palmer, E. A., S. J. Jago, D. L. Baty, and S. L. O’Connor, 1980, Perception of Horizontal Aircraft Separation on a Cockpit Display of Traffic Separation, Human Factors. 22(5),
605−620.

Peppard, K. W., and Cieplak, J. J., 1995, "Flying to New Heights with the Oceanic In−Trail Climb," The Journal of Air Traffic Control, January−March.

RTCA, Incorporated, 1995, Report of the RTCA Board of Directors’ Select Committee on Free Flight, Washington, D.C.

RTCA, Incorporated, 1997, Minimum Operating Performance Standards for Traffic Information Service Data Link Communications, DO−239, Washington, D.C.

Sarter, Nadine, and David D. Woods, 1991, Situation Awareness: A Critical But Ill−Defined Phenomenon, The International Journal of Aviation Psychology. 1(1), 45−58.

SAE International, 1990, Human Interface Design Methodology for Integrated Display Symbology. SAE ARP 4155.

SAWG, 1995 (Separation Assistance Working Group Oceanic In−Trail Climb Subgroup, Cieplak, J. J., Ed), “Oceanic In−Trail Climb Using TCAS II − Issues Summary,” The MITRE Corporation Corporation/Center for Advanced Aviation System Development, McLean, Va, MP−95W0000242, September.

Sorensen, John A., and Tsuyoshi Goka, 1983, “Analysis of In−Trail Following Dynamics of CDTI−Equipped Aircraft,” Journal of Guidance and Control. 6(3).162−169.

Sorenson, J. A., July 1983, System Modeling to Predict Pilot Performance during An In−Trail Following Experiment, AMA Report #83−16, NASA Ames Research Center, Moffett Field, CA.

Sorensen, John A., Walter Hollister, Malcolm Burgess, and Dean Davis, 1991, Traffic Alert and Collision Avoidance System (TCAS) − Cockpit Display of Traffic Information (CDTI) Investigation. Phase I −− Feasibility Study. DOT/FAA/RD−91−8, DoT/Federal Aviation Administration, Washington, D.C.

Stassen, Hans Peter, 1997, Enhancing the Safety and Efficiency of Runway Approaches Using a Cockpit Display of Traffic Information, The MITRE. Corporation/Center for Advanced Aviation System Development, McLean VA., to be published September

Weiner, Earl L., 1993, Life in the Second Decade of the Glass Cockpit. In R. S. Jensen and D. Neumeister (Eds.) Proceedings of the Seventh International Symposium on Aviation Psychology, (pp. 1–11). Department of Aviation, Ohio State University, Columbus, OH.

Wickens, C. D., 1984, Engineering Psychology and Human Performance, Charles E. Merrill, Columbus, OH.

Williams, D. H., 1983, Time based Self Spacing Techniques Using Cockpit Display of Traffic Information during Approach to Landing in a Terminal Area Vectoring Environment, NASA TM 84601, NASA Langley Research Center, Hampton, VA.

Williams, David H., and Douglas C. Wells, 1986, Jet Transport Flight Operations Using Cockpit Display of Traffic Information During Instrument Meteorological Conditions., NASA Technical Paper 2567, Washington D.C.

Zeitlin, A. D., Love, W. D., Cieplak, J. J., 1995, "Enhancements to the Next Generation Collision Avoidance System: Opportunities for Greater Safety and Efficiency," AIAA Digital Avionics Systems Conference, Fall.

Zeitlin, A. D., 1995, "TCAS Oceanic In−Trail Climb Procedure Safety Analysis," MTR 95−W0000096, The MITRE Corporation Corporation/Center for Advanced Aviation System Development, McLean, Va, August.

ABBREVIATIONS

ADS−B Automatic Dependent Surveillance−Broadcast
ASRS Aviation Safety Reporting System

CAASD Center for Advanced Aviation System Development
CDTI Cockpit Display of Traffic Information

FAR Federal Aviation Regulations
FIR Flight Information Region

ITC In−Trail Climb
ITD In Trail Descent

LC Lead Climb
LD Lead descent

MASPS Minimum Aviation System Performance Standards
MOPS Minimum Operating Performance Standards

TCAS Traffic Alert and Collision Avoidance System
TIS Traffic Information Service