00188.41–02

NAS2-98005 RTO-41

Technical Research in Advanced Air Transportation Technologies

Detailed Description for CE-11

Terminal Arrival: Self Spacing for Merging and In-trail Separation

John A. Sorensen

November 2000

Prepared For:

NASA Ames Research Center

Moffett Field, CA 94035-1000

and

NASA Langley Research Center

Hampton, VA 23681-2199

Prepared By: Seagull Technology, Inc.

Los Gatos, CA 95032-2547

TITAN SYSTEMS CORPORATION

SRC DIVISION

Preface

This report is the first version of a detailed description for the Distributed Air/Ground Traffic Management (DAG-TM) Concept Element (CE) 11, Terminal Arrival: Self Spacing for Merging and In-trail Separation. The ideas presented here are preliminary.

NASA is soliciting review of this report and welcomes comments. Comments should be sent to:

- Del Weathers, Manager, AATT ATM Concept Definition Sub-element, NASA Ames Research Center – dweathers@mail.arc.nasa.gov
- Richard Mogford, Manager, AATT Human Factors Sub-element, NASA Ames Research Center – rmogford@mail.arc.nasa.gov

Acknowledgement

This subtask of preparing this initial detailed description of the DAG TM Concept Element 11 (CE-11), Terminal Area Arrival: Self Spacing for Merging and In-Trail Separation, was performed by John Sorensen, of Seagull Technology, via subcontract to System Resources Corporation (SRC) under Research Task Order 41 of the Advanced Air Transportation Technologies (AATT) project's NASA Research Agreement Contract NAS2-98005 with SRC. Charlie Phillips served and overall contract manager, and he provided the overall outline from which this report is organized. He further made valuable suggestion for section layout and content level.

The author wishes to acknowledge Richard Mogford, of NASA Ames, and David Wing, of NASA Langley, who provided astute input and overall editing suggestions for revising the first draft of this document. Gary Lohr, Terry Abbott, and Sheila Conway, of NASA Langley, provided answers to detailed questions aimed at defining the technical and operational environment for CE-11. Anand Mundra and Oscar Olmos, of Mitre CAASD, gave a good summary of on-going research to support CE-11-related traffic display experiments being conducted by the FAA and Cargo Airline Association. In addition, Vernal Battiste, Walter Johnson, and Everett Palmer, of NASA Ames, summarized their past traffic display research and demonstrated their laboratory facilities for future investigation of CE-11 research issues.

Table of Contents

1. Introduction

Concept Element 11 (CE-11) is focused on bringing greater flight efficiency and runway throughput to busy terminal areas and runways through flight crew (FC) use of flight management system (FMS) and cockpit display of traffic information (CDTI) technology. The general idea is that by implementing a distributed control system via integrating FMS and CDTI avionics with the air traffic management (ATM) system would enable the flight crew (FC) to provide tighter control of the merging and spacing processes. The excess spacing buffers that exists between consecutive aircraft during approach could be reduced. This spacing buffer reduction could increase runway throughput. In addition, by enabling the aircraft to fly more direct or efficient routes within the terminal airspace, additional flight efficiencies could be realized.

This concept is based on the general hypothesis that by enabling distributed approach control conducted by the individual participating FCs would provide greater flight efficiency and other benefits and would be more cost effective than providing the air traffic service provider (ATSP) with more automation tools to pursue the same benefits. Future research experiments are to be conducted to prove or disprove this hypothesis.

This report is aimed at providing an initial detailed description of CE-11. It provides a resource for devising the CE-11 research plan. Because there are still unknown elements and details of the technology, operating procedures, scenarios and assumed operating environments that characterize the eventual mechanization of CE-11, this report should be considered a living document. As the research plan unfolds and further input is obtained from the NAS users, service providers, and other stake holders, this description will be updated to encompass these new inputs.

In this section, background material is first summarized concerning previous and on-going research on applications of CDTI and its perceived place within the distributed air-ground traffic management project (DAG TM) within NASA's AATT project. Then, the objectives of CE-11 are presented along with the scope of this document.

1.1 Background

1.1.1 Previous and On-going Related Research and Development

In pursuit of Concept Element 11, it is important to review the research, development, and testing that have previously been conducted relative to use of CDTI and related technology developments such as Threat Alert and Collision Avoidance System (TCAS) and Broadcast Automatic Dependent Surveillance (ADS-B). This is so that (a) previously well established technical results can be factored into defining the flight deck avionics requirements; and (b) documented previous research is not repeated; this saves both project development resources and time.

A review of this previous work is presented in Appendix B. The following summarizes the review findings.

1.1.1.1 Pre-1990 CDTI Research

The CTDI concept has been suggested and studied since sometime in the 1940's [3]. Airborne station-keeping equipment has been employed successfully by the military services for many years to maintain safe air-to-air separation in formation flying.

CDTI studies were pursued in the 1970's and 1980's by NASA to investigate potential applications that could increase airport capacity, reduce controller stress and workload, and enhance safety of flight. These studies used simulations of the TCAS, Mode S radar, and other data link systems to provide a prototype CDTI. Based on these studies, traffic displays were postulated and tested under simulated traffic conditions. In particular, strings of aircraft on approach to landing were set up with pilot instructions to establish and maintain specified spacing by using the CDTI for spacing cues. Pilots and controllers participated in these tests, and much was accomplished in understanding the relative vehicle dynamics, the human factors of traffic displays, and the potential of CDTI to provide throughput benefits. The studies also revealed potential problems such as increased pilot and controller workload and possibilities of traffic flow instability, secondary conflicts, and pilot distraction. [3-16]

Installation of TCAS II began about 1990 for the large air carriers. The requirement to carry and use a TCAS II was extended to cover all aircraft carrying more than 30 passengers. Later, aircraft carrying 10-30 passengers were required to carry the TCAS I. In all cases, installations have included some form of traffic display. Thus, via the TCAS program, the inclusion of a cockpit display of adjacent traffic became a reality.

Three elements of the TCAS or other traffic display design are of importance to the CDTI applications:

1. Surveillance – The accuracy, reliability, and volume of spatial coverage of the surveillance and the associated accuracy of the tracking algorithm govern to what extent TCAS/CDTI can be used for merging and spacing applications. The TCAS II surveillance system design was primarily the results of initial work performed at MIT Lincoln Laboratory.
2. Logic design – This is the conflict detection and resolution (CD&R) logic used to determine which aircraft to display or to indicate which aircraft may pose a threat. This must be interfaced with merging and spacing cues for other CDTI applications. The TCAS II threat detection and collision avoidance logic was primarily developed by the Mitre Corporation. Seven revisions of this software design have been released to the TCAS manufacturers..
3. Pilot interface – The human factors aspects of the display and other interface mechanisms used by the pilot are critical for adapting the system to merging and spacing. The TCAS II display design format and other aspects of the flight crew interface were investigated and perfected at both NASA Ames and Langley Research Centers.

During the 1980-1984 time period, NASA Ames and Langley Research Centers both sponsored analytical studies and conducted a series of cockpit simulator experiments to determine:

(a) What were the important elements that allowed pilots to use the CDTI for in-trail following?

(b) How could the CDTI be mechanized?

(c) What benefits might be realized from CDTI implementation?

At least six different cockpit simulator studies of multiple following aircraft in approach strings were made at NASA Langley and Ames to produce data to analyze in-trail dynamics to address these questions.

1.1.1.2 Post-1990 CDTI Developments

After TCAS was mandated for commercial air carriers, and TCAS I and TCAS II systems with their traffic displays became commonplace, pilots soon began to use these displays for other “unofficial” purposes than collision avoidance. The traffic display could help the pilot/flight crew with situational awareness of other traffic. Pilots started to use the display for in-trail following when cleared for unconstrained transcontinental routes. It became apparent that the TCAS/CDTI would provide many useful applications and that these applications should be identified, documented, and standardized so that operational use could be orderly. These applications have been pursued by the activity of the RTCA SC 186 and SAE G10 committees.

The first “official” use of the TCAS/CDTI for in-trail following control was for oceanic en route flight [17]. Currently, the United States has authorized the use of the TCAS II traffic display for in-trail climb (ITC) and in-trail descent (ITD) procedures when following other aircraft on oceanic routes. The constraints of this operation are that the trailing aircraft FC must see the Lead aircraft on the traffic display and there must be enough initial separation so that the ITC or ITD can be completed without violating acceptable separation as the trailing aircraft passes through the Lead’s altitude. In an enhanced ITC and ITD procedure, the CDTI would provide flight identification, speed, altitude, and range information directly to the FC thereby reducing or eliminating coordination with the Lead aircraft [18, 19].

1.1.1.3 On-going CDTI Research and Development

Two on-going technical developments are further enabling the use of CDTI:

(a) the broadcast of automatic dependent surveillance (ADS-B) where the aircraft broadcasts its precise state and intent based typically on GPS navigation data; and

(b) the broadcast of traffic information service (TIS-B) where the ground radar system determines states of aircraft and broadcasts these to those adjacent aircraft as a supplement to ADS-B or TCAS.

The minimum aviation system performance standards (MASPS) for ADS-B describe nearly 80 potential applications of CDTI based on ADS-B information [18]. These technologies have spurred activity by RTCA to define further acceptable applications, to develop requirements and operational procedures for these applications, and to develop and document minimum operating standards (MOPS) for the CDTI equipment [19].

Safe Flight 21 (SF21) is a current FAA sponsored cooperative government/industry effort to evaluate enhanced capabilities for Free Flight based on evolving communications, navigation, and surveillance (CNS) technologies [20]. SF21 will demonstrate the cockpit display of traffic, weather, and terrain information for FCs and will provide improved information for controllers. Under SF21, a cooperative government-industry team is conducting a series of operational evaluations (OpEvals) of various ADS-B applications in conjunction with the Cargo Airline Association plans to equip their fleets with advanced TCAS/CDTI based upon ADS-B. In 1999, enhanced visual approaches and see-and-avoid enhancements were the subject of the OpEval conducted by 24 participating aircraft in the Ohio River Valley (Airborne Express facility at Wilmington ILN). This was preceded by extensive cockpit simulation studies conducted to prepare for the OpEval by Mitre CAASD [21, 22]. In 2000, the OpEval was continued to examine approach spacing concepts using Constant Range and Constant Time Delay spacing cue criteria at the UPS facility at Louisville SDF airport. (See Appendix B for definition of the different spacing cues).

The goal of Capstone, a related project under SF21, is to implement and test traffic, terrain, and weather display technologies on general aviation aircraft flying out of Bethel, Alaska. This project is pertinent in that it is bringing the benefits of the cockpit display technology to the low end general aviation (GA) user.

Recent NASA and Mitre research has addressed the related use of ADS-B and CDTI to facilitate dual approaches to closely spaced parallel runways in instrument meteorological conditions (IMC) [24-28]. The objective is to maintain throughput and capacity as under visual conditions (VMC). Here the CDTI is used by the trailing aircraft to maintain a constrained longitudinal spacing relative to the Lead aircraft approaching the parallel runway. The concept is to provide adequate separation for both wake avoidance and blunder protection/collision avoidance purposes.

1.1.1.4 Initial Concept of CDTI within DAG TM

DAG TM is based upon the free flight premise that the pilot/FC can be more actively engaged in the problem of air traffic management which will provide cost-effective benefits that cannot be matched by implementing more sophisticated ground control. This inherently assumes that the FC has good situational awareness of the surrounding traffic and can use that information to conduct the processes of self separation with respect to interacting trajectories such as crossing paths, overtaking, merging, and station-keeping. This awareness is provided by the CDTI and the various cues presented to the FC on that display. Thus, the CDTI becomes a vital link between the FC, the FMS, digital data link, collaborative maneuvering with other aircraft, and collaborative decision making with the ATM controller/air traffic service provider (ATSP) and the airline operations control (AOC)/dispatcher.

Concept Element 11 addresses a practical first set of applications for the CDTI that will build off of the previous and on-going CDTI research summarized previously.

1.2 Objectives

This detailed Concept Element 11 description has the following objectives:

- It provides for technical transfer and sharing of information within the NASA research community concerning this concept. It is intended to capture the current thinking of NASA researchers concerning the future ATM environments and capabilities that may be created by this concept. It is intended to be a living document that is continually revised as the CE-11 project unfolds.
- It is a guide and resource for a planned program of research for CE-11 through 2004.
- It is consistent with and a subset of the AATT objectives as described in the AATT Air Traffic Management Operations Concept (ATM/OPSCON)[31].

1.3 Scope

This description of CE-11 is intended to provide enough detail to form a basis for further research into the concept. It is not, however, a research plan. The research plan is a separate document being developed by NASA [2] that describes how CE-11 presented here will be investigated, and how statements presented elsewhere as hypotheses will be tested.

The detailed description has a focus of operational and system requirements, and deliberately avoids design information to the extent possible. NASA Ames and Langley Research Centers are in the process of planning for and designing simulations and facilities to test the CE-11 premises, including the integration of the CDTI with the FMS and an “Autonomous Operations Planner” (AOP) which will function on board free maneuvering aircraft. This detailed description is consistent with, and provides additional guidance to these planning and design efforts.

Specifications for the mechanization of CE-11 concept are omitted from this document, since requirements for capabilities to support the CE-11 concept should evolve as a result of the research to be conducted. To avoid confusion with widely discussed tools and mechanisms such as flight information service (FIS) or Center-TRACON Automation System (CTAS) whose specifications are being developed elsewhere, this description typically uses general terms to describe the capabilities necessary to support this concept.

2. Problem Description

As stated in Ref. 1, the problem addressed by CE-11 is:

Excessive in-trail spacing buffers in arrival streams reduce runway throughput and airport capacity, especially in conditions of poor visibility and/or low ceilings.

In terminal area environments for which arrival demand approaches or exceeds capacity, aircraft landing rates are significantly lower under instrument meteorological conditions (IMC) than under visual meteorological conditions (VMC). In order to compensate for uncertainties in aircraft performance and position, the air traffic service provider (ATSP) applies in-trail spacing buffers to arrival streams under IMC in order to ensure that minimum separation requirements between successive aircraft are met. The resulting generous arrival spacing reduces runway throughput below its capacity to accept aircraft.

Thus, a primary problem that application of CE-11 services is directed at is the existence of excessive spacing buffers and spacing gaps between consecutive aircraft during the approach-to-landing phase of flight and how to reduce this excess using CDTI and FMS technology. Alternately, this problem can be stated as:

Determine how the use of FMS and CDTI avionics, associated procedures, and additional responsibilities by the flight crews of aircraft in the approach phase of flight can be used to reduce the amount of excess spacing buffer and inefficient spacing gaps between successive aircraft in order to improve the runway throughput.

A corollary problem is to determine how best to enhance the Decision Support Tool (DST)-generated clearances given by the ATSP to the approaching aircraft to facilitate improved runway throughput by taking advantage of the fact that the aircraft are CDTI equipped. For example, one DST - the CTAS Final Approach Spacing Tool (FAST) - determines best sequences and schedules to balance runway use and maximize throughput. Active FAST (aFAST) computes and displays to the controller cues of where to slow the aircraft down and where to turn the aircraft to achieve the best flow. It is then up to the controllers to issue clearances to the individual flight crews to realize the correct sequence and schedule to achieve these flows. Intuitively, it seems that if the flight crews could see these DST-generated clearances combined with traffic directly on the aircraft electronic navigation chart (i.e., CDTI) display, without needing verbal clearance by the controller, the flight crews could do a better (more timely and exact) job in executing the clearances. Combining DST-generated preferred approach trajectories with CDTI self spacing activity needs further investigation.

A related problem is the need to evolve away from using rigid, fixed routes within the Terminal Radar Approach Control (TRACON) airspace so that aircraft can fly more direct-operating-cost (DOC)-efficient paths from the entry boundary to the final approach fix (FAF). This freedom would also facilitate having flexibility to maneuver around storm cells while still using DST-generated information to provide efficient traffic flow. Here the issue is to determine how to use the CDTI for merging and separation while simultaneously each aircraft is using its FMS in conjunction with the DST information to determine individual optimum paths to the FAF.

This problem description includes a number of inherent assumptions that need to be verified by experimental research. These assumptions include:

1. After applying ATSP DSTs to controlling the terminal area approach traffic, there remains

significant excess spacing buffers between consecutive aircraft that warrant investigation into methods of further reduction – including FC participation in spacing reduction via enhanced flight deck technology.

2. Within the TRACON airspace, the common route segments used by approaching aircraft are of sufficient lengths to allow the FC's to capture and maintain specified spacing at a net reduction in overall ATSP and FC workload.
3. ATSP and FC personnel will accept the CE-11 concept as operationally viable and aircraft operators will accept the concept as economically beneficial, given that (a) responsibility for longitudinal spacing between consecutive aircraft will be turned over to the FC's, and (b) this concept is shown to be technically feasible.

CE-11 addresses these and many related problems, assumptions, and issues regarding the mechanization of and human factors associated with using the CDTI, FMS, and related avionics during the approach phase of flight.

3. Approach

In this section, a FC-directed free maneuvering, merging and spacing concept is first summarized to set the context for the more detailed description. This is followed by a summary of the three modes of flight being addressed. In all cases, the objective is to determine how enhanced flight deck technology and FC procedures working in conjunction with the ATSP can be used to facilitate safe, orderly, and more expeditious traffic in the terminal area.

3.1 Concept Overview

In VMC, aircraft are often able to maintain closer spacing during the terminal approach phase of flight, thereby increasing the capacity of the terminal area and the runway acceptance rate. In the current system, the FC's are often requested to accept responsibility for visual self-separation once they acknowledge they can see the immediately leading aircraft. In this situation, the FC is responsible for determining and then maintaining a safe separation from the immediate Lead aircraft, and is therefore not subject to the ATSP's minimum separation requirements. CE-11 addresses providing similar spacing during IMC via use of the CDTI.

Figure 1 is a bubble chart of the different aspects of CE-11. It shows the conceptual sequential roles of the ATSP and FC (that is, properly Equipped Aircraft) in using both ground system and flight deck technology to improve the approach phase of flight, beginning outside of the TRACON and ending at the FAF. Note that the ATSP continues to have extensive involvement in this concept in defining and managing the traffic approach scenario and in conducting the ATSP procedures that enable this concept to work. The roles and responsibilities of ATSP and FC are discussed further in Section 8.

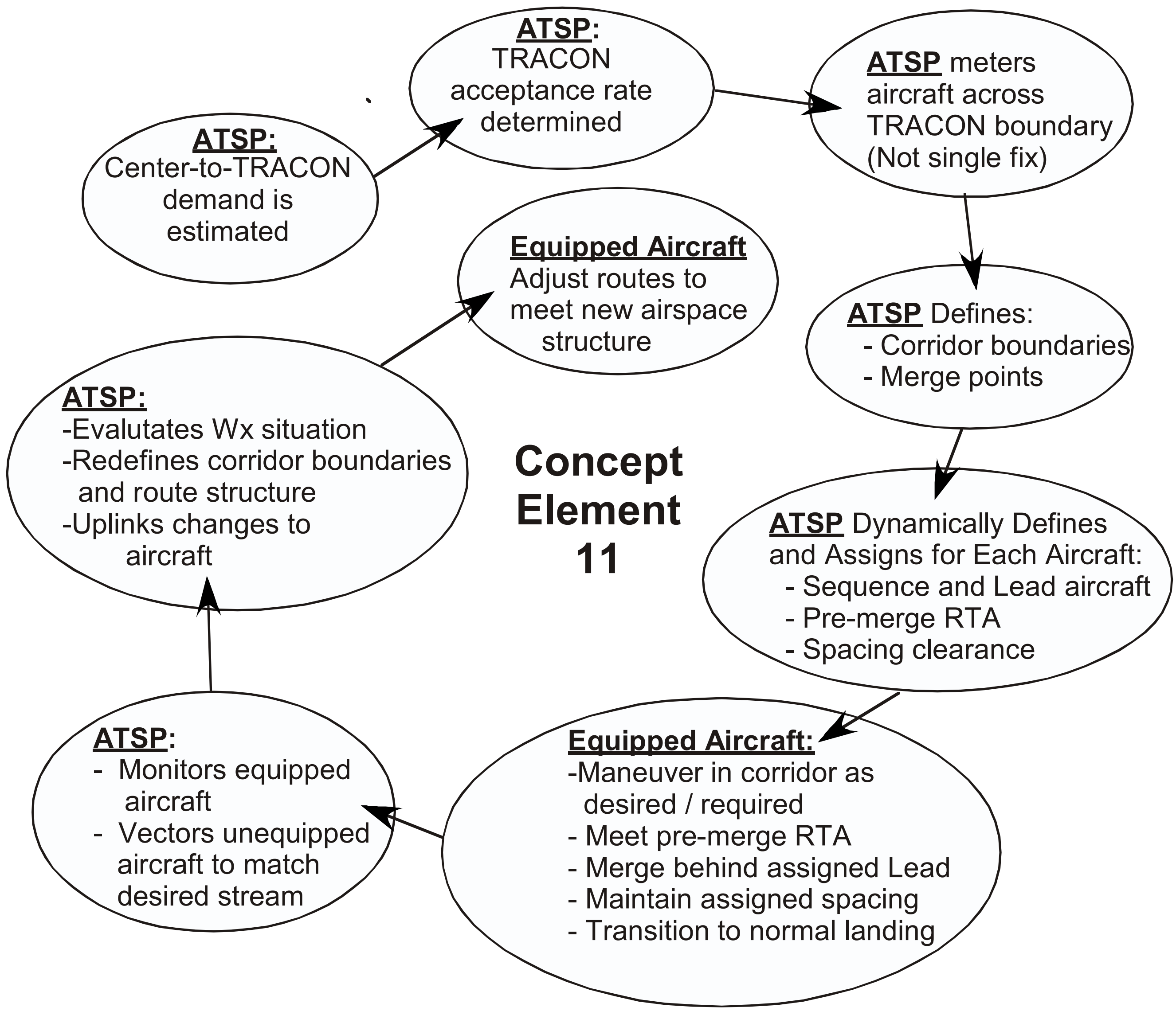

Figure 1. Sequential stages of the CE-11 processes.

Self separation will enable the FC's of equipped aircraft to merge autonomously with another arrival stream and/or maintain in-trail separation relative to a designated Lead aircraft under IMC as they would under VMC, thus potentially increasing arrival throughput. In this investigation, self merging and spacing applies to aircraft that are subject to spacing requirements during arrival, extending from the terminal area feeder fix (FF) or TRACON boundary to the FAF.

Anticipated procedures for self merging and spacing involve the ATSP transferring responsibility for in-trail separation to FCs of properly equipped aircraft, while retaining responsibility for separating these aircraft from crossing and non-equipped traffic. Once the FC receives clearance to merge and maintain spacing relative to a designated Lead aircraft, the FC establishes and maintains a relative position of their aircraft with frequent monitoring and speed/course adjustments.

Under some conditions, information such as required time of arrival (RTA) at the FAF may be provided by an appropriate ATSP-based DST, thereby enabling accurate inter-arrival spacing that accounts for differing final approach speeds or wake vortex avoidance. Similarly, RTAs may be used at each traffic stream merge point so that aircraft FMS guidance generates trajectories that are smoothly merged by meeting the associated RTAs.

Self merging and spacing will make use of data link capabilities to provide traffic position information. The CDTI and/or advanced flight director/heads up display (HUD) will provide guidance technology as the source of spatial and temporal situation awareness to the FC. Cues within the traffic display will provide information to the FC to enable either manual merging followed by station-keeping or monitoring of automatic 4D trajectory management by the FMS.

3.2 Summary of the CE-11 Operational Modes

For the purposes of addressing the phases of flight being considered within CE-11, the flight approach process is divided into three operational modes. Each of these modes has different operational complexity, technical capability, and potential benefits:

1. FREE MANEUVERING Mode: The self guidance and separation of each equipped aircraft within unstructured arrival corridors, or zones. Here, the aircraft FC is cleared to design their own direct path within a defined approach corridor during the initial arrival phase of flight. During this process, the FC or FMS defines its own route leading to the future merge point. (Some aircraft will remain on fixed routes within this corridor.) This mode of operation precedes the process of MERGING onto a common route. In the MANEUVERING mode, the FC responsibility for self-separation is longitudinal only. The hypothesis is that ATSP precludes lateral separation issues by 1) metering aircraft in the stream across an arrival boundary ("pre-organizing" the stream to have the right sequence and to not have lateral conflicts), 2) assigning spacing or RTA clearances that match the sequence coming into the TRACON such that aircraft will not be passing each other with inadequate separation, 3) keeping streams adequately separated from other streams, and 4) being responsible for over-flight separation from the streams.
2. MERGING Mode: The MERGING of multiple routes, or streams of aircraft. Each aircraft FC is responsible for adjusting in-trail position consistent with proper MERGING and then SPACING behind the designated Lead aircraft approaching from another stream (and arrival zone).
3. SPACING Mode: The in-trail temporal SPACING mode of flight along either a flexible or a specific structured arrival route. Here, aircraft are in a common stream, or flying along a common path (e.g., post MERGING) that crosses the FAF and leads to the designated runway for that string. Each equipped aircraft FC is responsible for maintaining a specified temporal separation from a designated Lead aircraft in the same string or stream.

Note that the SPACING mode can occur anywhere throughout the arrival process, not just after the final merge. However, the MANEUVERING and MERGING modes are currently envisioned to be segregated. Each of the three modes is now discussed further.

3.2.1 In-trail temporal SPACING mode

The spacing mode is directed to in- trail spacing control of multiple aircraft that either form a string along a fixed route or form a stream within an approach zone. Such a string is depicted in

Figure 2 that shows traffic approaching an airport under a south flow configuration. In Figure 2, Aircraft B is tracking Lead Aircraft A on the extended final approach to Runway 18R.

In this mode of flight, the FC is given the authority to implement reduced spacing between their aircraft and the preceding Lead aircraft while in a single arrival string or stream ending at a stabilized approach point (e.g., FAF). Optimal arrival spacing is defined not in the spatial sense such as a fixed distance between aircraft, but rather in the temporal sense, whereby geometric spacing is continually tightened as the aircraft reduce speed. This results in the achievement of a tighter desired separation time between aircraft once the trailing aircraft reaches the stabilized approach point. In this way, all participating aircraft are able to maintain the higher speed profiles that support maximum flow across the runway threshold. The target separation is based on an accurate ETA for the preceding Lead aircraft at the runway threshold that is derived from knowledge of the final approach threshold crossing speeds of both aircraft.

In order to implement this spacing management, the trailing aircraft would require certain information. First, the target separation time between it and the designated Lead aircraft would be calculated by the ATSP and transmitted via addressed datalink or voice to the trailing aircraft FC. This target separation time calculation could be based on either

1. wake vortex behavior predictions taking into account the Lead aircraft type and configuration and current local weather conditions (a la AVOSS [29]);
2. runway occupancy time estimate; or
3. regulatory separation requirements between the particular aircraft types.

Additionally, the target separation time between the two preceding aircraft (Lead and Lead + 1) may be required for more accurate prediction of the speed profile of the immediately preceding aircraft. Regular frequent updates of the Lead aircraft state and trajectory information through broadcast datalink may be required to generate the dynamic temporal-spacing guidance cues.

The spacing guidance cues could be provided to the FC on the CDTI for manual control, or the guidance requirements could be provided to the autopilot/autothrottle system through the FMS for hands-off active automatic control. In the absence of broadcast trajectory information for the Lead aircraft (e.g., non-ADS-B equipage such as for Aircraft C in Fig. 2), an alternate trajectory prediction would be required, possibly supplied by an ATSP DST.

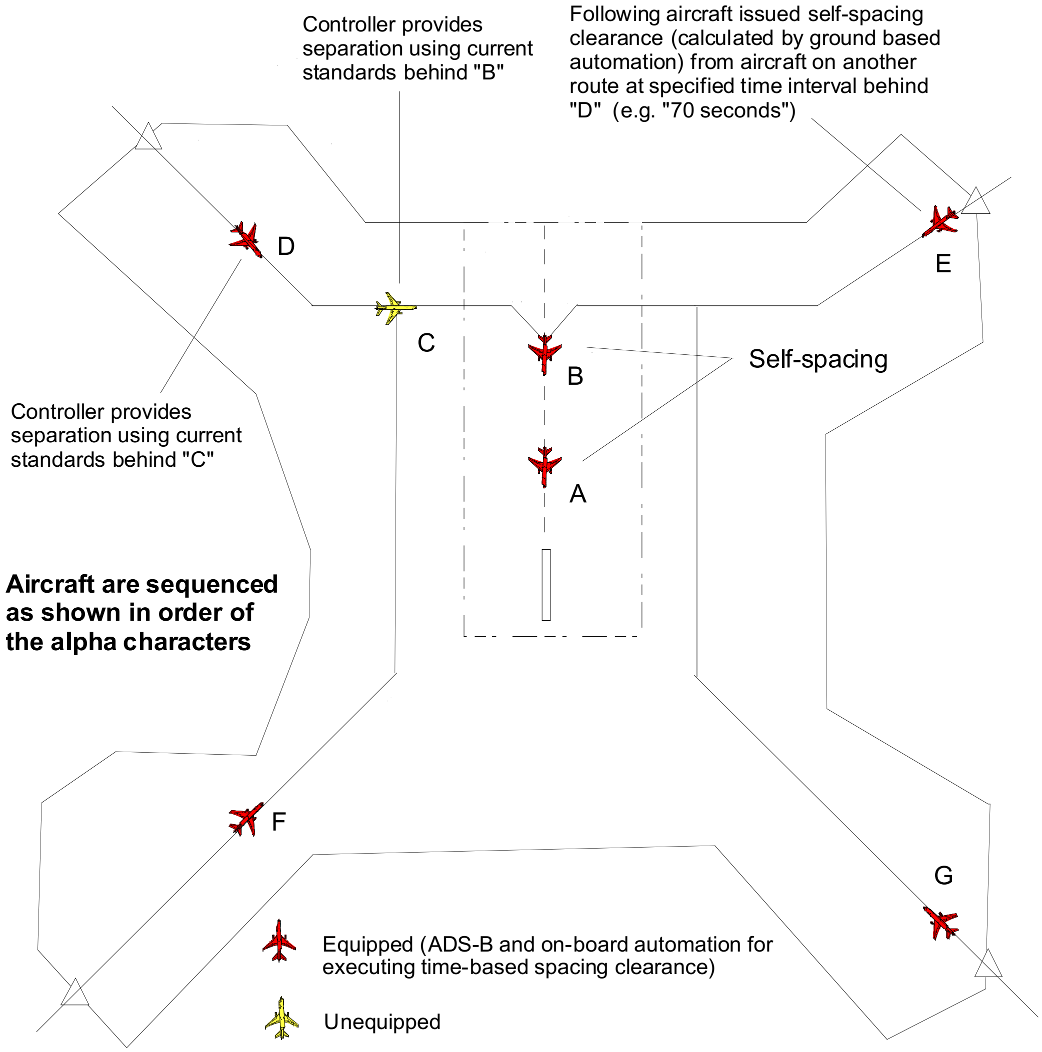

Figure 2. Depiction of approaching aircraft on common route segments. Aircraft B is self spacing relative to Aircraft A. (Diagram courtesy of Gary Lohr of NASA Langley Research Center.)

3.2.2 MERGING onto a common arrival route mode

The concept of merging aircraft from several streams, or routes, onto a common route is also depicted in Figure 2. Here, Own Aircraft E on the northeast diagonal leg is to merge behind Lead Aircraft D which is approaching from the northwest to the extended base leg. The merge will take place when Aircraft E turns from its base leg onto the extended final approach leg behind D which has previously turned onto this leg.

During this mode of operation, the processes of merging aircraft onto a common arrival route and time-spacing management along such routes are implemented simultaneously. Before or upon entering the terminal area, participating aircraft on both free maneuvering and structured arrival routes are provided sequence assignment instructions that may include time spacing behind another aircraft on a separate arrival route. The multiple routes later merge onto a common approach route. Each aircraft would follow its route but adjust speed and vertical profile while merging with another arrival stream to position itself in terms of meeting minimum geometric separation requirements while following temporal-spacing guidance cues to fall in behind the assigned Lead aircraft. Additionally, the aircraft may undergo multiple stream merges in this way before ending up in the final arrival stream prior to landing.

There are two ways each equipped aircraft may be guided before it merges behind the assigned Lead aircraft:

1. It may be given a “ghost” image of the Lead aircraft as computed and projected on its own route before the merge point; or
2. It may be given an RTA at the merge point that is computed based upon the Lead aircraft crossing that point at the appropriate time separation before the RTA.

3.2.3. Free MANEUVERING in unstructured arrival corridors

The concept of aircraft flying in flexible, free maneuvering, arrival zones is depicted in Figure 3, again for a generic TRACON. The flexible zones are shown in green. Aircraft G which is to merge behind Lead Aircraft F is on a different route than F, but it maintains proper spacing relative to F as both aircraft head toward a point where they will be on a common structured route.

In this mode, structured arrival routes are replaced with or conceptually broadened into arrival regions or zones. Instead of entering the terminal area via an arrival fix and following fixed structured routes thereafter, participating aircraft cross an “arrival zone boundary” and are provided authority to maneuver laterally within designated arrival zones that are segregated from departure corridors. The sizes of the arrival and departure zones could be static or could be dynamic to optimize terminal operations for inbound and outbound pushes or for weather considerations. Aircraft would be responsible for separation assurance, for remaining inside the arrival zones, and for merging into close-in arrival streams based on sequence assignments provided by the ATSP.

In this mode of flight, aircraft would have the authority to maneuver tactically for weather avoidance, separation, spacing, or descent profile management without clearance from the ATSP. Non-participating (e.g., non-equipped) aircraft, such as Aircraft E in Fig. 3, would remain on structured arrival routes (or vectored paths) and receive all clearances from the ATSP. Although CE-11 does not specifically address the management of departures, the arrival operations would be designed in such a way as to not unduly impact departure operations.

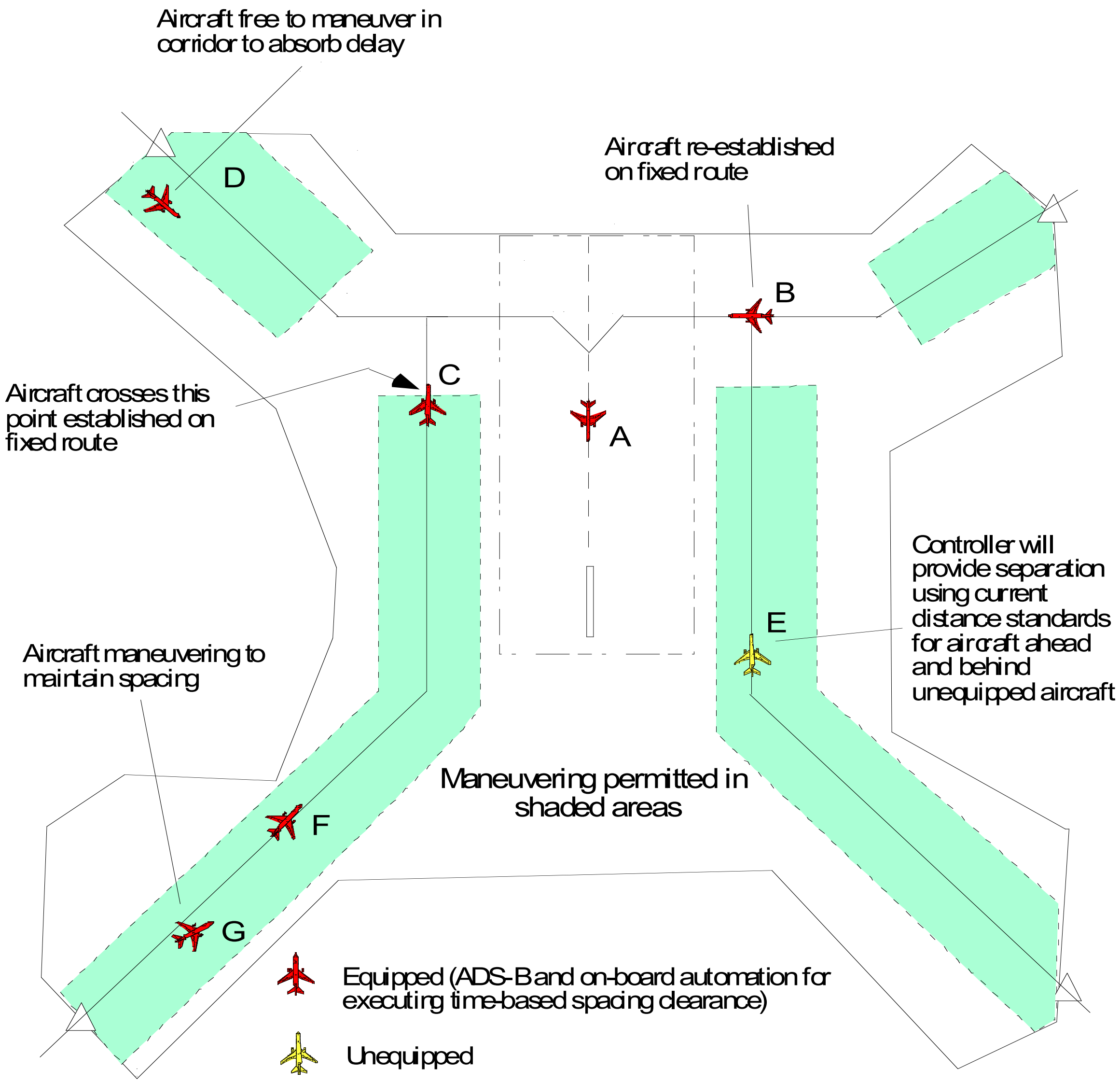

Figure 3. Sketch of Free Maneuvering Zones and Aircraft (D, F, G) in free maneuvering mode on approach (Courtesy of Gary Lohr, NASA Langley Research Center).

4. Operational Requirements

This section refers to a description of the Operational Needs Statements (ONS) which apply to CE-11. These ONS have been created to support the development and on-going revision of the AATT ATM/OPSCON.

See Appendix A for the operational requirements, presented as a table. CE-11, Self Spacing for Merging and In-Trail Separation, applies to the Traffic Management – Synchronization service area as defined in the AATT ATM/OPSCON.

5. Operational Environment

This section describes the assumed operational conditions under which CE-11 will be applied. The operational environment includes the airspace structure, routes within this structure, and their constraints; the mix of aircraft types, their equipment, and performance limits; the weather and visibility conditions; the CNS infrastructure within the airspace that enable connecting the FC with ATSP; and the ATM capabilities of the environment. Each of these elements is discussed from the point of view of representing the range of environments that need to be considered.

5.1 Airspace Structure and Route Constraints

The CE-11 operating airspace environment consists of the approach sectors, areas, or "zones" within the TRACON ranging from the entry feeder fixes at the TRACON boundary, and the boundary itself, to the final approach fixes (FAF) and possibly to the runway thresholds. During the in-trail spacing mode, flight will be constrained to be along fixed routes within these zones starting from specific entry point feeder fixes. These routes would be part of the normal aircraft flight plan and be specified by the Standard Approach Route (STAR) and runway approach plates for the given airport. During the free maneuvering mode, the aircraft can fly along any non-conflicting path from entry to exit point within its approach zone. For this mode, the entry point can be anywhere along the boundary between the zone and the adjacent Center airspace; it is not restricted to specific entry points.

For in-trail spacing, the aircraft are initialized in a single string along a fixed route where no further merging is required before reaching the FAF. Therefore, a long route beginning at zone entry point and having down wind, base, and final approach legs represents a suitable baseline test case. Such routes are depicted in Figure 2. An example would be a corner post entry approach to Runway 18L from the BYP feeder fix at Dallas-Ft Worth (DFW) TRACON. A variation would be a long non-corner post route such as the path from Big Sur feeder fix in the Bay Area TRACON from the Oakland Center and Southern California into San Francisco (SFO) Runway 28L. Initially, the typical four-cornerpost TRACON with flow to a single runway would be the nominal case for defining the route structure and surrounding airspace. This nominal case can be chosen by survey of several terminal areas to determine where CE-11 promises the most benefit.

For the merging mode, the aircraft are initialized into two or more strings that merge at waypoints before reaching the FAF. This mode extends the in-trail spacing mode in that it includes the process of merging two or more strings of aircraft. Means must be provided for showing spacing cues on the CDTI to account for aircraft that will become the designated Lead after the merge takes place. That is, each equipped aircraft is guided such that it will successfully merge behind and self space with a Lead aircraft that is initially on a different approach route. This is illustrated in Figure 2 where Aircraft E is on the northeast diagonal leg and will merge behind Aircraft D which is on the northwest diagonal leg. The merge occurs as Aircraft E turns onto the final leg behind Aircraft D.

In the free maneuvering mode, each of the aircraft can use the airspace within a defined corridor for the initial segment of their approach. In this phase of flight, the aircraft FMS or FC computes the desired approach route within the zone before the aircraft enters the zone. This route may be picked to (a) minimize direct operating cost (DOC); (b) minimize fuel while achieving a required or assigned time of arrival (RTA) at the FAF or other waypoints; or (c) weave through a series of storm cells representing inclement convective weather that are blocking the zone. In each case, the intended route may be linked to the ATSP to aid the ATSP in monitoring the in- trail spacing process.

Each aircraft that enters the approach zone may have unique entry points and unique approach routes thereafter. They may not merge until close to the FAF. However, they will merge eventually, and the CDTI is used to give each FC the merging and spacing cues along the specific route so that the future spacing after the merge is as desired for safety and throughput maximization.

One way the free maneuvering self separation process can be visualized and mechanized is to project each of the various approaching routes onto a common route passing through the zone and to compute the spacing cues to facilitate spacing control along that route. This process would allow two different flexible routes to be merged at any range to the FAF.

An alternate way is to constrain in-trail spacing to only after the common merge point and to compute the RTA for each aircraft at the merge point so that proper spacing occurs thereafter. This allows each aircraft to follow a more flexible speed profile along their specific route leading up to the common merge point. It requires that the FMS have RTA capability.

Some of the airspace and route geometry issues that need to be investigated to define the CE-11 operational environment, especially during the free maneuvering mode, are the following:

1. Definition of the approach zone geometry:

   a. How are the lateral and vertical dimensions and boundaries of the approach zone defined and communicated to the FMS/FC before the aircraft reaches the TRACON?

   b. What are the lateral and vertical spacing constraints relative to the zone boundaries?

   c. How are the common merge points and FAF defined?

2. Definition of approach zone weather and its effect on approach route computation – By definition, CE-11 is directed at control of flight in IMC under instrument flight rules (IFR). The goal is to achieve or exceed the same flight efficiencies as seen under VMC. The base case is that the approach zones are free of storm cells. The additional weather cases have increasingly dense weather cells that restrict more and more of the approach airspace. Issues are:

   a. How many different weather cell situations need to be examined?

   b. How do the free maneuvering mode approach routes and associated trajectory computation process change as the available airspace becomes more restricted with weather cells?

   c. At what point does the approach through the zone become closed due to weather?

3. Route structure (or absence thereof) – A variation of the free maneuvering mode is the case where some of the aircraft have the equipment to allow computation and use of flexible routes within the approach zone and others have older equipment that only allows flight along fixed routes. This mixed equipment environment may require that fixed route aircraft be segregated from those capable of more flexibility if the approach that an RTA at the merge point is used to guide the aircraft on the flexible path.
4. Dynamic re-sectorization – This is a longer term case where the definition of the approach zone airspace and its boundaries are changed from time to time to accommodate variations in traffic flow and direction or changing weather conditions. The issues are:
   a. How do the new zone boundaries get computed by the ATSP and linked to the incoming aircraft?
   b. What information is needed to make these computations?
   c. How soon before the aircraft reaches the TRACON boundary does the up link of new zone boundaries need to occur?

Within the design of the airspace for CE-11, other assumptions are made regarding the nature of the structure:

1. There may be separate routes and entry points for slower aircraft, such as turboprops. These routes would be merged with those of the faster aircraft at waypoints close to the FAF.
2. The effects of weather cells affect all three modes of flight and will be brought into the scenarios tested as appropriate.
3. Each approach zone is defined by a centerline that may represent the structured route that would be followed by unequipped aircraft.
4. Special Use Airspace is not considered as part of the airspace constraints for CE-11.
5. Runway closure and re-configuration because of wind shifts are off-nominal cases that are dealt with at later stages of the research.
6. TRACON airspace sectorization and handoff between controllers are part of the ATSP-FC procedures of CE-11.

5.2 Traffic Mix and Equipage

It is assumed that some or all aircraft in the CE-11 scenarios will be equipped with traffic displays with common information and spacing cues presented to the flight crews. Those aircraft without CDTI equipment will be vectored and cleared manually by the controller, as is done today. Two parameters that will affect the use of and operational procedures for the CDTI during approach are the variations in (a) the types of aircraft within the approach, and (b) the avionics equipment (data link and FMS/CDTI capability) that is on the aircraft.

Users of the approach airspace range from piston engine to turboprop to turbojet aircraft, each with a different speed range. At certain TRACONs, there are different approach routes used to segregate the slower turboprops from the turbojets. These different route possibilities need to be preserved as a test case for the three modes of operation. The flexible route free maneuvering mode accommodates different speed envelopes of each aircraft if the RTA-at-common-merge-point methodology is used to space the aircraft at the merge point. This assumes that after the merge point each aircraft can fly at compatible speed with respect to the other aircraft in the approach string. Also, within this mode, different speed classes can be segregated onto different non-interfering routes.

Another aircraft type factor is the different type-dependent nominal separations that are used to maintain safety due to wake vortex considerations. These nominal separations are usually defined in spatial terms at the point where the Lead aircraft crosses the runway threshold, and they are a function of the weight of the aircraft – light, large, or heavy. For CE-11 purposes, these nominal separations are converted to time separations and projected back to the FAF. Thus, for example, if two consecutive B737 aircraft each have V_{ref} speeds of 120 kt as they cross the runway threshold, with a minimum of 2.5 nmi separation, this would represent a minimum time separation of 75 sec. If each aircraft crosses the FAF at 170 kt, this 75 sec separation would represent a minimum spatial separation at the FAF of 3.54 nmi. Some nominal buffer spacing is added to these separations to account for the uncertainty in the spacing that will occur between two consecutive aircraft to ensure wake vortex separation safety. Likewise, if two consecutive B747 aircraft must be greater than 4.0 nmi apart as they cross the threshold with V_{ref} of 140 kt, this represents a minimum 103 sec separation. Again, if 170 kt is the nominal FAF crossing speed, this translates into 4.85 nmi minimum separation at the FAF point.

The approach airspace can be used by air carrier, air taxi, corporate, and private aircraft, each of which will have FCs with different levels of experience and proficiency as pilots. This will affect how well a given pilot maintains the desired spacing with respect to the Lead aircraft in a string. This is largely a function of training, flight currency, and motivation on the part of the different FCs to maintain tight separation tolerances.

It is assumed that a certain minimum set of avionics equipment is required for an aircraft FC to participate in the three modes of flight of CE-11. Candidate equipment or capability includes:

1. A suitable traffic display with appropriate cues to allow the FC to guide the aircraft during free maneuvering, merging, and in-trail spacing.
2. A navigation system with required navigation performance (RNP) rating that supports (a) broadcast of aircraft state with sufficient accuracy to support the traffic display requirements; and (b) adequate adherence to the intended route to provide safe separation assurance.
3. An ability to sense accurately the state of adjacent traffic and the designated Lead aircraft. This may be via ADS-B, existing TCAS mechanization, or TIS-B.
4. An FMS that can be used to compute preferred routes for free maneuvering, achieve RTA in-trail position control, and possibly for automatic merging and in-trail spacing control to the FAF.
5. An autonomous operations planner (AOP) that the FC can use to organize and manage the three modes of CE-11. The AOP is considered an extension and enhancement to the FMS.
6. A two-way data link to allow exchange of digital information between FC and ATSP. This may also be used for data exchange between Lead and following aircraft.

Aircraft that don't have at least some subset of these capabilities cannot participate actively in CE-11 processes. Aircraft that don't have these capabilities are termed "unequipped", and they could represent targets that could serve as Lead.

The equipped aircraft may have the FMS with longitudinal autopilot/ autothrottle so that relative spacing can be automatic after the Lead aircraft has been designated. However, each aircraft can also be flown manually where the pilot uses the CDTI as a flight director to control airspeed and relative spacing to the designated Lead.

In the merge mode, it is assumed that the traffic display cues are extended to depict an indicated location/state of a designated Lead that may be on another route segment that will merge with the current aircraft route at a later point. This indicated Lead location could be the projection of the actual Lead location onto the current route with the same range to go to the common merge point of the two routes. This location projection is often referred to as a "ghost" and it could be used by both FCs and ATSPs for spacing [30].This type of projection would have to take into account the difference in winds along the route segments that would manifest in differences in ground speeds which would affect the associated desired spatial distance between consecutive aircraft.

For the free maneuvering mode, it is desirable for aircraft that follow flexible routes to have the following capabilities:

1. An FMS that can provide lateral and vertical position, and longitudinal speed guidance along a curved approach reference route or trajectory, and can store and use approach zone and restricted airspace boundaries;
2. FMS ability to compute an optimum DOC or fuel burn curved trajectory from present position to the FAF within ATSP constraints. This includes ability to use an RTA at some future desired merge point or FAF. This path is stored as the nominal reference trajectory;
3. Data link ability to link flight path intent to the ATSP for monitoring purposes. In the far term, this may include the ability to receive and use up-linked ATSP modifications;
4. FMS ability to modify a nominal route to take into account and avoid restricted airspace defined by the approach zone boundaries and restricted convective storm cell locations within the zone;
5. Data link, FMS, and CDTI ability to receive, display in graphical form, and use for trajectory computation and steering guidance storm cell volume boundaries or other restricted airspace boundaries; and
6. A CDTI that can depict the curved reference path, boundaries of restricted airspace, and spacing cues to ghost projections, as appropriate. This includes ability to project the relative position of the designated Lead (that is on a different route) onto the aircraft route in the form of a ghost aircraft.

Some additional traffic and equipment mix questions that need to be investigated to define the CE-11 operational environment are the following:

1. What different mixes of equipage should be investigated in the different experimental scenarios (both simulator and flight test)? How many different combinations are necessary to understand the dynamics of a mixed-equipage environment in terms of the transition to a fully equipped fleet?

2. What mix of turboprop and turbojet aircraft should be examined? Should these aircraft be isolated onto different approach routes or into different approach zones? Which TRACONS have representative mixes of aircraft types that would be good test cases?

5.3 CNS Infrastructure

It is assumed that the aircraft states are very accurately measured (via GPS WAAS / LAAS) and available to each flight deck and ground ATSP through some suitable form of data exchange (e.g., ADS-B) or surveillance (e.g., TIS-B). Furthermore, it is assumed that digital data link is available to send digital clearances, flight information, and traffic information if needed to the flight deck. It is assumed that each aircraft can be flown manually or automatically via FMS autopilot / autothrottle.

For communications, required data and information are assumed to be available to provide in digital form, controller advisories and clearances to the FC, graphical information concerning weather cells and zone boundaries, and adjacent traffic states not available through ADS-B. However, voice clearances for merging and in-trail spacing represents viable means for the ATSP to clear the FC to enact these modes of flight. Also, the ATSP DST may be able to up-link necessary information to define the desired profile for a Lead aircraft that defines the beginning of a string. Alternately, each aircraft FC could have a standard speed profile per aircraft type that is automatically followed if the aircraft is the string leader.

In terms of navigation, differential GPS provides adequate means for CE-11 applications. The FMS will use this information for precise guidance, and to compute state and intent messages for ADS-B. Aircraft without FMS will be assumed to have area navigation (RNAV) to follow routes defined by sequences of waypoints. Aircraft without autopilot or autothrottle will have flight director information on the CDTI to enable the FC to capture and track desired spacing relative to the Lead aircraft.

ADS-B is assumed to be the standard for aircraft data exchange/surveillance both from the CDTI perspective and the ability of the ATSP / DST to monitor progress of each of the aircraft. Ground broadcast (TIS-B) traffic information can be used by subject aircraft to track those aircraft without ADS-B but with transponders tracked by the ground radar.

Some of the CNS infrastructure questions that need to be answered further to define the CE-11 operational environment are the following:

1. Communications - For the free maneuvering mode, can we assume that the ATSP or other service provider sends graphical weather data to the flight deck to show to the FC as a layer of information on the multi-function display (MFD)/CDTI? Can we assume that ATSP and FC have access to the same graphical weather picture?

2. Navigation - What variations in FMS equipment, autopilot / autothrottle, and RNP should be investigated in terms of ability of the aircraft to hold tightly in altitude, lateral deviation, and speed variation from the route represented by the flight plan?

3. Surveillance - Is the period of transition from radar to ADS-B surveillance of interest here? Do we need to consider the situation where some aircraft are ADS-B equipped, some are tracked by a secondary surveillance radar (SSR), and the two sets of data are fused for a common surveillance picture? How about a mixture of CDTI systems with sources of traffic information from either ADS-B, TIS-B, or TCAS II/Mode S?

5.4 ATM Environment

Three different ATM environments exist in which CE-11 merging and spacing modes may take place:

1. No special DSTs beyond today's environment are used (e.g., such as being tested by the Safe Flight 21 Cargo Airline Association Operational Evaluation of ADS-B for approach spacing).Here, the controller/ATSP determines the desired string position of each approaching aircraft. The controller advises the pilot which aircraft is the immediate Lead, the controller clears the pilot to use the CDTI to maintain a certain spacing relative to the Lead, and the pilot uses the CDTI to capture and track a specific spacing relative to that aircraft.
2. Extension of CTAS Active FAST (or equivalent DST) where the desired approach trajectory (including waypoints of where to decelerate and where to turn) is communicated to at least the String Leader aircraft in the string. This ensures that the reference speed profile for starting each string is efficient. The DST would also be extended to allow the controller to monitor the progress of aircraft in the string to ensure compliance with the planned arrival schedule. Furthermore, the DST would be used to determine the positions of aircraft on merging routes, possibly compute the ghost positions of these aircraft as projected onto other routes (as a function of range to go to the next merge point), and provide the up-link message to communicate these positions to the flight deck/CDTI.
3. Special non-CTAS TRACONS where the ATSP provides information and capability that facilitates use of CDTI for merging and spacing by the aircraft and monitoring of the process by the controller. This would include the features of the first two environments, but it might not have all the features of the FAST DST. This scenario represents a point somewhere in the range of capabilities defined by the first two environments.

6. Operational Characteristics

A basic premise of CE-11 is that a designated "string leader" aircraft follows a desired speed profile from TRACON entry to the FAF or threshold. The next arriving aircraft is cleared by ATM to merge behind the immediate Lead and then to self space according to some accepted spacing criterion. This second aircraft then becomes the Lead aircraft for the next (third) arrival aircraft in the string, etc. Various specified spacing gaps are used to account for different wake vortex spacing constraints based upon aircraft type, and allowances for departing aircraft on the runway. Also, natural spacing gaps will occur because of the distribution of arrival aircraft over time. Thus, there will be need to re-start the strings from time to time.

The desired spacing of the aircraft behind the designated Lead may be based upon one of the following cues (discussed further in Appendix B):

1. History trail of the Lead (e.g., where the Lead was 90 sec ago); or
2. Constant time predictor with acceleration cue (e.g., where the CDTI-equipped aircraft will be 90 sec from now).

6.1 ATSP View

It is assumed that the ATSP/DST determines the desired sequence and spacing of arrival aircraft and this information is provided to the flight crew by voice or data link. The ATSP transfers responsibility for merging and spacing to the flight deck until the aircraft crosses the designated end point. (The ATSP maintains responsibility of protecting the arrival aircraft from crossing intruder aircraft and of monitoring the performance of each aircraft along the string to ensure that each aircraft maintains safe separation limits.

The primary roles of the ATSP are indicated in Fig. 1. These include the following activity:

1. calculate and communicate the assigned separation (spacing) time with respect to the designated Lead for each participating aircraft;
2. estimate and possibly uplink trajectory predictions of non-FMS, non-state broadcast equipped aircraft as needed;
3. provide separation assurance between streams and for non-participating aircraft;
4. monitor the arrival merging, flow rate, and conformance to the assigned spacing time;
5. using some kind of alerting mechanism, advise participating aircraft of predicted deviations from the designated separation value; and
6. provide means to terminate the CE-11 process because of abnormal situations such as airport closure, equipment failure, or pilot request for route deviation.

Some questions that need to be addressed to further define the ATSP operational role are as follows:

1. What information is needed on the ATM display to enable the controller to monitor merging and spacing performance? What is the minimum ATSP equipment and capability required?

2. What monitoring and alerting criteria should be used whereby the controller re-takes responsibility of approach control?

3. What operational conditions besides lack of equipage should prevent the controller from transferring merging and spacing responsibility to the flight crew?

6.2 Pilot View

For the in-trail spacing mode, it is assumed that the succession of Own aircraft are positioned such that their FCs can quickly capture and maintain spacing relative to the designated Lead aircraft.

For the merging mode, it is assumed that each equipped aircraft is positioned and is given necessary information to merge behind the designated Lead or Lead Ghost.

For the free maneuvering mode, it is assumed that each aircraft FMS or FC computes the desired path from entry point to exit point, and guides the aircraft along this path. Own either (a) merges and spaces with a Lead Ghost projected onto this path; or (b) uses an RTA to control speed to arrive at the next merge point at a time that is consistent with merging with the Lead aircraft arriving on the other route.

7. NAS Functional Impacts

This section discusses the NAS impacts, including planned NAS architecture components, of the Concept Element 11. Section 7.1 describes functional requirements, and Section 7.2 provides an overview of the functional design resulting from these requirements.

7.1 Functional Requirements

The following functional changes from the NAS 4.0 mature baseline, expressed in terms of technology and infrastructure, are needed to support the concept. These are described in the area of Communications, Navigation, Surveillance, Automation, Weather, and Traffic Management.

7.1.1 Communications

Within the NAS 4.0 baseline, ground-to-air communications with participating aircraft within the approach zones of the TRACON are both by datalink and voice. Datalink communications are both broadcast and addressed. The ATSP broadcasts or provides before flight advisories and information on winds aloft, graphical weather cell location and intensity, and for free maneuvering, the geometric boundaries of the approach zones. For participating aircraft without ADS-B, the ATSP up links state information of adjacent aircraft.

To mechanize CE-11, aircraft specific advisories and clearances, sent via addressed data link include the assigned Lead aircraft and the assigned time spacing the following aircraft applies to self spacing behind the Lead. For environments with ATM automation and DSTs, the desired speed profile may be computed and linked up to the first Leader Aircraft in a given string. For the merging mode, either the ghost image or actual position of the Lead aircraft on a merging route may be linked up to be projected onto the following aircraft's route. If the RTA capability of the FMS is used to facilitate merging, that RTA is linked up to the aircraft.

Air-to-ground communications include the participating aircraft accepting assignment of following the specified Lead or ghost, acceptance of assigned RTA if appropriate, and acceptance of approach speed profile if up linked from ATM automation.

Air-to-air communications occurs through ADS-B discussed in Section 7.1.3.

Voice communications are procedurally used when the ATSP takes over control of specific aircraft because of emergency or non-compliance with intended merging and spacing assignments. In an airport environment where a DST is not used, the controller may use voice communications to vector aircraft for proper merging followed by assignment of Lead aircraft and desired spacing to a CDTI-equipped aircraft.

CE-11 requires that special messages be created for ground-to-aircraft and aircraft-to-ground communication, as just described. Special avionics software will be required to facilitate implementation of the CDTI with proper presentation of other aircraft, spacing cues, and airspace constraints. Similarly, DST software will be required to extend planned NAS capabilities to include mechanization of CE-11. However, no new communications systems or hardware should be required for flight deck or ATSP implementation.

7.1.2 Navigation

There are no new functional navigation requirements imposed on the ATSP by CE-11. GPS and suitable backup (i.e., DME-DME) are used as means of navigation.

In terms of the aircraft avionics, the CDTI is an additional layer of information on the multi-function display; its design is primarily one of software. It is assumed that the on-board navigation system has a Required Navigation Performance (RNP) level with sufficient accuracy to support merging and in-trail spacing applications. It is also assumed that this information is used for state and intent broadcast.

7.1.3 Surveillance

Participating aircraft within CE-11 will be equipped to broadcast their state and possibly their intent information computed in the FMS and to receive this information from adjacent aircraft. State and intent information are broadcast at 1 Hz. Intent information extends to the runway threshold, and contains the FAF as a waypoint. Participants without FMS will not broadcast intent.

The ATSP surveillance function will fuse broadcast state information with that obtained from area RADAR. The intent information provides the ATSP with a forward look of the intended path the participating aircraft will fly.

The only new surveillance function beyond current plans for NAS is the added capability of the ATSP to monitor the progress and relative states of the participating aircraft during the three flight modes. This includes the capability to assess actual and future separations, to determine when the aircraft is outside of acceptable separation assurance conformance limits, and to provide alerts to the controller for immediate response.

7.1.4 Automation

The ATSP functions within CE-11 are presented in Figure 1. As described previously, new ATSP automation within the DST beyond current NAS plans includes capabilities to compute and display:

(a) the desired sequence and pair-wise spacing between consecutive aircraft in the sequence strings;

(b) the RTA for each participating aircraft to facilitate smooth merging;

(c) possible means to change approach zone boundaries to adapt to convective weather cell locations;

(d) means to monitoring the merging and in trail spacing processes for desired separation conformance; and

(e) alerting mechanism when conformance is not met to point of affecting safety.

These automation functions are supported by appropriate two-way data link between aircraft and ATSP DST.

Automation functions required on the flight deck are summarized in Section 5.2.

7.1.5 Weather

The ATSP or commercial weather service provides accurate winds aloft, atmospheric conditions, and graphical weather information to aircraft and ATSP DST. These data are updated regularly by down linking of measured wind and temperature by participating aircraft. This function is expected to be part of the future NAS architecture.

7.1.6 Traffic Management

There are no changes required for strategic traffic management, that is at the Command Center level. Local traffic management participates in setting the arrival acceptance rate the airport can handle which in turn affects metering up to the TRACON. It also sets up the arrival sequence as manifested by the sequence and schedule of aircraft crossing into the TRACON. If CE-11 is in use, the runway throughput should increase which will be reflected in the acceptance rate used for traffic management. Thus, no new traffic management functions within the projected NAS architecture are required.

7.2 Functional Design

Figure 4 is a high level functional design diagram showing those NAS systems and services that are essential for supporting CE-11. Current and future air traffic systems and services which are general to ATM but not specifically utilized in CE-11 are not shown.

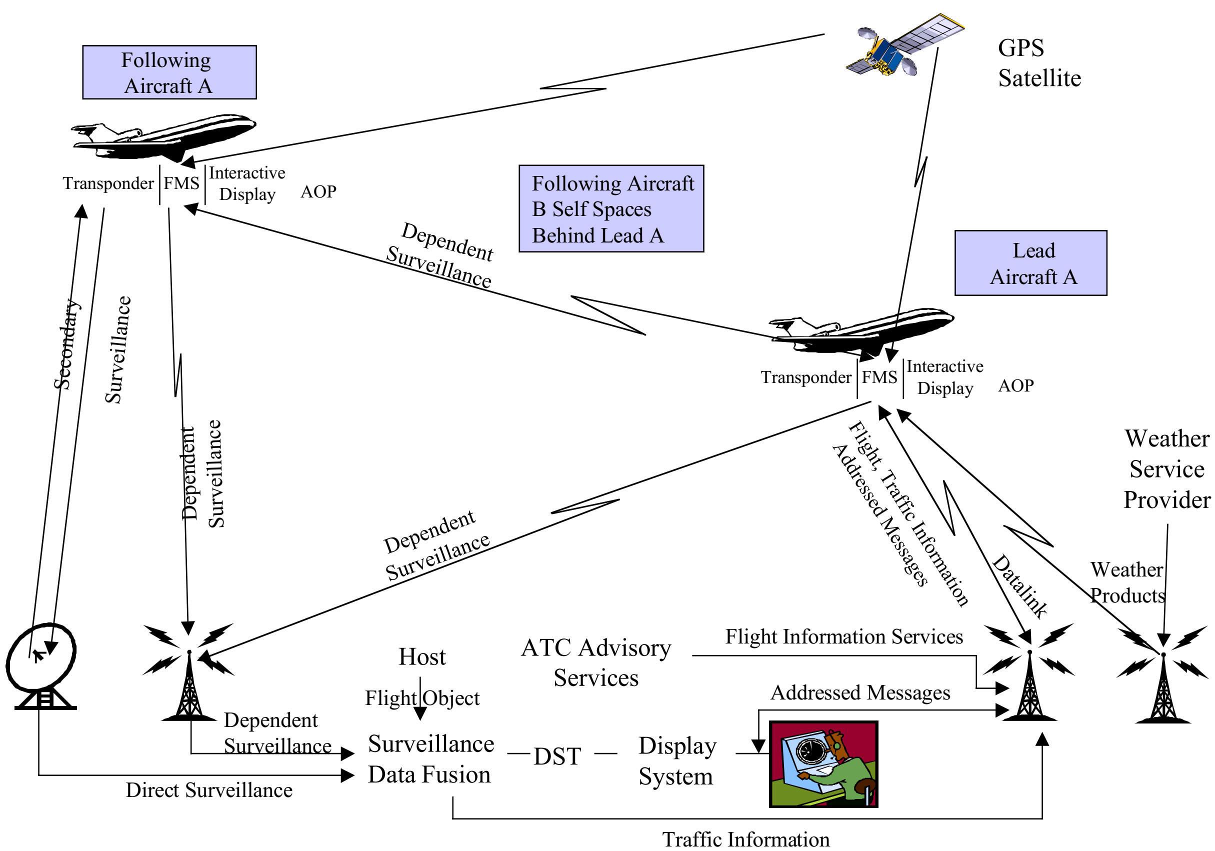

Figure 4. High Level Depiction of CE-11 Functional Design (Modification to original layout provided by courtesy of Charlie Phillips, Titan SRC.)

The two aircraft (Lead A and Follower B) shown are members of a formed string. Each maintains accurate state information and trajectory conformance using GPS as the primary navigation input to the FMS. Each aircraft broadcasts state and intent information to aircraft and ground receivers. The ATSP uses secondary surveillance as a backup to the aircraft broadcast information, and the SSR measurements are fused with the state broadcast data for improved total situation awareness.

Two possible additional uplink messages come from the ATSP to the participating aircraft. One is the ATSP flight information including weather, winds, atmospheric conditions, zone boundaries, and regular ATIS information. The weather data may be generated by either the ATSP or a commercial weather service. The other message is the ATM clearance and advisory information such as assigned Lead aircraft, assigned spacing (time) interval, RTA for merges, and general clearances for setting up the string and turning over self spacing responsibility to the FC of each aircraft.

8. User/Operator Roles and Responsibilities.

In this section, the roles and responsibilities of the ATSP/controller and the participating aircraft/flight deck/FC for CE-11 operations are summarized.

8.1 ATSP Roles and Responsibilities

Here, we first discuss the full responsibility of the ATSP, meaning automation, air traffic manager, and air traffic controller. We then discuss issues related to the controller interfacing with both the automation and the FCs. These functions are depicted in Figure 1.

The ATSP responsibility for enacting the CE-11 methodology begins well before the participating aircraft enter the TRACON. There is a collective activity between airport, TRACON, and surrounding Centers that determines the acceptance rate of the runways, the airspace capacity as affected by weather and other non-approach-to-landing aircraft, and the demand for airport landing operations. (This activity is aided by knowing the flight plans of each aircraft that desires to land; that is, there is an aircraft operator/airline role involved, too.) The runway acceptance rate, airspace capacity, and runway throughput demand set up the traffic management process for the greater terminal area (i.e., out to beyond top-of-descent). This process determines the desired sequence and schedule of aircraft entering the TRACON with intention of landing. In turn, the desired schedule sets up the metering processes to bring aircraft from the surrounding Centers to the TRACON approach zone boundaries and feeder fixes.

Within the TRACON, the ATSP defines the nominal routes and route segments leading to the runway, the merge points for those routes, the FAF, and the approach zone boundaries. If the boundaries are changed because of dynamic density or weather restriction considerations, that also is the responsibility of the ATSP. For the free maneuvering mode, the approach zone boundaries are published in a navigation data base and are static for nominal operations. These geometric definitions are done well in advance of the particular flights involved. In a far term scenario, dynamic zone definition could be done during the flight process, but before the aircraft crosses into the zone.

The TRACON ATSP is also responsible for the traffic management process governing the aircraft sequence and schedule. That is, the TRACON ATSP takes over sequence management of the aircraft from the Center ATSP. Landing schedules are accepted or modified depending upon the dynamics of the TRACON, airports, and runways involved. The ATSP determines which runways are in use using information on flight plans, winds, weather, and departing traffic. It determines the desired schedule of landing operations taking into consideration departing traffic, conditions of the runway (e.g., wet surface, icing), weight and class of the aircraft, wake vortex and runway occupancy factors.

Inherent in the landing schedule are the safety reasons which established relative minimum-plus-a-buffer acceptable spacing between successive aircraft at or just before the time points that each Lead of each aircraft pair crosses the runway threshold. The ATSP sets these threshold crossing time points in the schedule to maintain minimum spacing (a spatial distance) and to allocate enough additional buffer to account for variations in the final approach trajectory of each aircraft because of differing speed profiles and winds. This variation in spacing is illustrated in Figure 5. The role of ATSP controlled landing scheduling is to remove unnecessary “gaps” between aircraft and to reduce the “buffers” within the landing schedule by reducing the trajectory uncertainties. (The premise of CE-11 is that the FCs can control the relative spacing between

Own and Lead aircraft better than ground ATSP thereby allowing for reduced buffers. Never the less, it is still the ATSP responsibility to set the minimum plus buffer spacing parameters based upon safety considerations.) The desired spacing is converted to an equivalent time spacing between consecutive aircraft, which is built into the landing schedule.

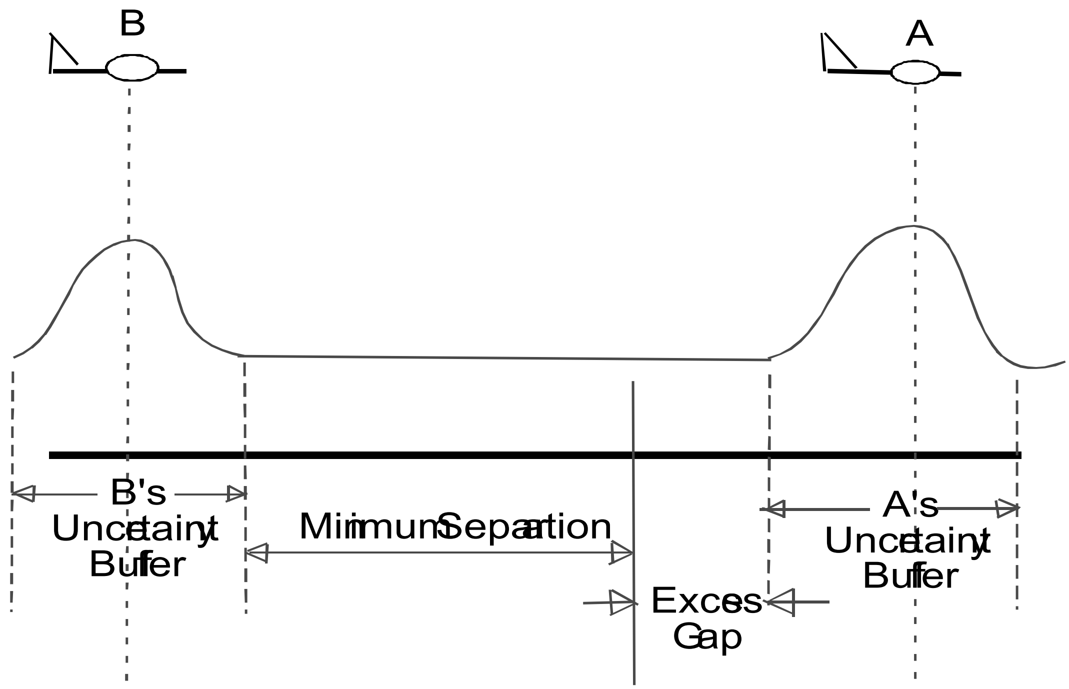

Figure 5. Illustration of minimum spacing, spacing (uncertainty) buffer, and excess spacing gap between consecutive aircraft in an approach string.

The ATSP takes the landing schedule and backs it upstream along each route and route segment leading to the particular runway. This process then establishes the schedules for crossing the FAF and the merge points (route waypoints in the flight plan) for each aircraft approaching the given runway.

The ATSP uses the waypoint schedules to assign required time-of-arrival (RTA) to each FMS equipped aircraft to be used by the aircraft FC to facilitate safe merging at particular merge waypoints. The ATSP also uses the landing sequence and relative time spacing between aircraft to assign first the Lead aircraft for each participating aircraft to follow and then the incremental time spacing that the following aircraft is to maintain relative to the Lead.

The ATSP is responsible for determining if conditions warrant allowing the properly equipped aircraft and FCs to choose their own flexible approach route, to merge with other participating aircraft, and to self space thereafter. The ATSP issues the clearances to each participating FC to designate its Lead aircraft, to set its spacing parameter and RTAs, and to take over responsibility for merging and self spacing until the ATSP takes that responsibility back.

Thereafter, it remains the responsibility of the ATSP to monitor the progress of the self merging and in trail spacing process to ensure that this is done with some pre-established threshold of spacing compliance. The ATSP is responsible for issuing warning if compliance is not being met and to take over the separation control if safety is being compromised. At the same time, the ATSP remains responsible for protecting the approaching aircraft from other traffic such as departures, over flights, and pop-ups.

Even in busy terminal areas and during rush periods there will be necessary gaps in the approach traffic because of the somewhat random nature of arrivals from the Centers or deliberate gaps to allow for departures or crossing traffic. Thus, each string that is formed by the ATSP is of specific duration, and new strings must be started throughout a day's operations. The String Leader aircraft sets the reference approach trajectory for subsequent aircraft in each string, and so it is important for good traffic flow that these String Leader reference trajectories are fast and efficient. It is the ATSP responsibility to ensure that the String Leader follows such an efficient trajectory, either by FC reference to one published in the airport approach charts or one in which the ATSP clears the String Leader FC along an efficient speed profile.

The ATSP maintains the ability to take over responsibility of the approach process at any time to account for non-normal events such as runway change, missed approach, emergency operation, non-compliance to spacing standards of one or more aircraft in a string, or some other dynamic situation. The ATSP is responsible for making the call – employ the CE-11 applications or not.

The ATSP continues to be responsible for those non-equipped or unable to participate aircraft involved in the approach process. This includes determining if such aircraft need to be segregated from participating aircraft or mixed into the strings but still controlled by the ATSP.

Much of the ATSP responsibility for the CE-11 service pre-supposes a certain level of automation on the part of the ATSP. For terminal areas without this automation, many of the previously mentioned ATSP roles and responsibilities can still be executed, but without the precision that automation provides. The minimum requirements in ATSP automation to mechanize the CE-11 service remains as a research topic.

8.2 Flight Crew Roles and Responsibilities

Here, we discuss the combined roles of the flight crew interacting with their on-board avionics (e.g., FMS, CDTI, data link interface) in terms of mechanizing and utilizing the CE-11 processes and associated ATSP services.

Up to crossing into the TRACON, the FC responds to clearances given by Center ATSPs to arrive at the approach zone boundary or entry fix according to a metering schedule. The FC receives and evaluates from the ATSP the conditions of the operational environment within the approach zone in terms of boundaries of the approach zones, any restricted airspace defined by weather cells or other traffic, airspace and surface winds, availability of flexible maneuvering, and conditions of the assigned runway. The FC determines their desired reference speed Vref for runway threshold crossing. The FC evaluates the airspace ahead based on up linked graphic weather and that sensed by aircraft weather radar.

If a flexible route is to be used within the approach zone, the FC may interact with the FMS in computing that reference trajectory. Alternately, the FC manually guides the aircraft within the space allocated for free maneuvering.

At the time the participating aircraft crosses into the TRACON approach zone, the FC is assigned its position in an arrival string, the immediate Lead aircraft, and the desired spacing parameter via up link or voice clearance from the ATSP. If one or more RTAs are to be used for merging control, these are also up linked to the FC. The FC enters or approves entry of these parameters into the FMS and CDTI logic. The FMS regulates speed along the approach path if RTAs are used. The logic computes and displays the appropriate spacing cue with respect to the Lead or Lead's ghost on the CDTI.

The ATSP clears the FC to use their avionics to enact flight along the flexible reference path, to use RTAs or a ghost Lead to control merging, and to use the spacing cues on the CDTI to control subsequent in-trail spacing. This transfers the in-trail spacing responsibility to the FC. This FC responsibility remains in effect until either the aircraft has crossed the FAF or landed, or the ATSP/controller has resumed control.

The FC steers their aircraft along the reference (lateral and vertical) path and controls speed to maintain tight spacing within a pre-specified tolerance. The FC informs the ATSP if they are unable to accept this responsibility or they are unable to continue self spacing after the process has begun. At the appropriate time after crossing the FAF, the FC transitions to the normal landing process.

9. Operational Conditions and Scenarios

In the following discussion, we illustrate three conditions of CE-11 operation – nominal, off-nominal, and failure. Each is defined, and narrative scenarios are used to describe the interplay between FC and ATSP during the operational process.

9.1 Normal or Nominal Condition

The normal, or nominal, condition for CE-11 is where all air and ground systems function as expected under normal conditions, traffic is in a steady state condition in terms of approach airspace used, routes and zones are not blocked by weather cells, and the runway in use is not changing.

Scenario 1

Delta 452 (DA452), a B757, is CDTI and FMS equipped and is about to enter the DFW TRACON over the boundary whose center point is the Bonham BYP feeder fix after travel from Atlanta. DA452 links down to Approach Control that its Vref speed is 137 kt and that it wishes to use the free MANEUVERING and IN-TRAIL FOLLOWING procedures to expedite the approach process. Approach Control links up acknowledgement and activates computation of landing sequence and desired temporal spacing at landing to meet wake vortex constraint for a B757 following the appropriate Lead (which happens to be an MD80). Seconds later Approach Control assigns DA452 the No. 23 position in the landing sequence behind the previously assigned No. 22 Lead aircraft and assigns the standard separation parameter as 75 sec. No. 22 is American 1088 (AA1088), an MD80 inbound from Chicago on the same STAR. Approach Control clears DA452 to MERGE with and maintain 75 sec behind AA1088 to the Runway 18L FAF.

DA452 FC identifies, designates and enters AA1088 as the Lead and 75 sec as the distance parameter on the flight deck CDTI. DA452 FC chooses to let the FMS define the direct route to the waypoint defining the intersection with the base leg; thereafter the FMS steers the aircraft along this direct path while maintaining appropriates separation with respect to the Lead. Simultaneously, the FMS automatically closes and maintains the specified distance with respect to AA1088, as represented by AA1088's projected position on DA452's route. Thereafter, the FC monitors the separation throughout the approach phase of flight leading to the FAF. Likewise, Approach Control monitors this process to ensure that nominal progress is made.

After DA452 crosses the FAF, the DA452 FMS automatically switches to Final Approach Control frequency, and the FC is cleared to land. DA452 FC resumes manual control of the aircraft, disengages the FMS and CDTI spacing cue, and proceeds to a normal landing behind AA1088. Because tight spacing control was maintained between the two aircraft up through FAF crossing, an average time savings of 8 sec was gained in the inter-arrival spacing.

9.2 Off-Nominal Condition

The off-nominal conditions for CE-11 exist when unusual weather (such as a preponderance of storm cells blocking nominal approach routes or zones) occurs, a runway change takes place, or there is a disruption of a string because of a missed approach or a FC that is not maintaining proper positioning. In the following scenario, a major weather cell blocks the nominal approach zone so that the participating aircraft must be diverted and merged with traffic within a different approach zone.

Scenario 2

AA401, an MD80, is in-bound from DEN to DFW via the BOWIE3 STAR passing through the northwest approach zone defined by the Bowie (UKW) feeder fix. A major summer convective weather storm is passing through the area. At 100 nmi to go to DFW and during the initial part of AA401's descent, Bowie Approach Control communicates with Ft. Worth Center and AA401 that the Bowie approach zone is closed because of a large weather cell. All Bowie traffic is being diverted to the northeast approach zone defined by the Bonham (BYP) feeder fix.

AA401 is FMS and CDTI equipped and so the AA401 FC requests use of a flexible route and RTA to MANEUVER along the direct path to and then MERGE with Bonham traffic. Ft. Worth Center and Bonham Approach Control cooperate to compute an RTA of 0952 GMT at the KARLA intersection within the Bonham zone. This also includes assignment of AA401's sequence number and nominal spacing behind UA55, a B737, approaching from ORD.

The Ft. Worth Center/Bonham Approach ATSP automation links the KARLA waypoint, RTA, designated Lead (UA55), and spacing parameter (65 sec) for use after crossing KARLA to AA401. The ATSP also up-links the latest graphical depiction of weather cells in the immediate area. AA401 FC acknowledges, enters these parameters in the FMS via the CDTI, and activates the FMS to MANEUVER to these parameters. The FMS makes local adjustments to the route leading to KARLA to bypass small cells north of DFW. Thereafter, the FC monitors the flight with respect to on-board weather radar supplementing the up-linked weather data and the CDTI depiction of adjacent traffic leading to the Bonham zone. The ATSP monitors the flights of AA401 and UA55 to ensure that the MERGE at KARLA is smooth and within acceptable spacing tolerances for the subsequent traffic string leading to DFW.

9.3 Failure Condition

The failure conditions for CE-11 are those events where equipment fails, human errors disrupt normal operation, or operational conditions abruptly change so that nominal or off-nominal operation cannot continue. Each of these conditions needs to be defined and analyzed so that safe recovery processes can be developed which revert to a more manual traffic management process. In the following scenario, a surveillance failure causes a major disruption.

Scenario 3

It is in the middle of an arrival rush during a normal busy day at DFW. Arrivals are coming from all four approach zones leading to the "south flow" operations on Runways 18R and 18L. Even though visibility is limited, because of the density of arrivals, CDTI MERGING and IN-TRAIL SPACING procedures are being used to increase landing rates and runway throughput.

Suddenly in the midst of this process, the ATSP surveillance function that fuses radar tracking data with ADS-B state messages broadcast from each participating aircraft fails. The ATSP is no longer able to monitor compliance of spacing constraints between consecutive aircraft in the approach strings. DFW Approach Control automation notifies Ft. Worth Center to shut off all entering traffic. Ft. Worth Center controllers subsequently put approaching aircraft in holding patterns until the DFW problem is resolved.

The Glen Rose Approach controller takes over manual control of each of the seven aircraft in the CDTI-driven approach string within the Glen Rose zone. The controller continues to observe relative positions of the aircraft via radar tracking (today's technology). Starting with the No. 2 aircraft, the controller vectors each aircraft to the right or left of the nominal route and then back to the route to open more space between the aircraft. No. 2 is vectored to the right and then back. No. 3 is vectored to the left and then back, etc. CDTI driven spacings of 60, 75, and 90 sec are opened to the equivalent of 75, 90, and 105 sec in spatial distance terms.

Each participating FC is fully aware of the problem and can optionally cooperates to open the spacing via the CDTI. That is, upon controller clearance, the FC can enter the diversion MANEUVER and new temporal spacing parameter on the CDTI, and then follow the maneuver guidance cues to path stretch to the desired new spacing.

After the last aircraft in the string is re-spaced, Glen Rose Approach notifies Ft. Worth Center that the southwest approach flow can be continued but with a lower acceptance rate than before the equipment failure. This lower rate and manual approach control is continued until the surveillance equipment is repaired or restored to nominal operation.

10. Operational Process/Operational Sequence Diagrams

This section describes and diagrams at a high level, the processes to be followed during the solution created by the CE-11. The processes are based upon the description of roles and responsibilities (Section 8) and operational conditions (Section 9).

In the following, the nominal IN-TRAIL SPACING process is illustrated from both the ATSP and FC points of view.

10.1 ATSP: Nominal In-Trail Spacing Process

Figure 6 shows the operational process that the ATSP approach controller goes through when clearing and then monitoring the actions of a flight crew that is using CDTI for in trail SPACING. The ATSP first determines if the aircraft is appropriately equipped. If not, the aircraft is vectored as is currently done during the approach. If equipped, then the ATSP determines if the aircraft is positioned properly to easily capture the designated spacing behind the Lead for subsequent following. If not, the controller vectors the aircraft into a position that facilitates ease of capture. Then the ATSP clears the aircraft in terms of issuing the identity of the Lead and the desired spacing that Own aircraft is to maintain behind the lead; these quantities come from the DST.

After the Own aircraft is cleared for in-trail SPACING, the ATSP continues to monitor the spacing process as the aircraft transitions through the approach zone. If Own's spacing falls outside of some acceptable tolerance with respect to the Lead, the ATSP issues a corrective advisory to Own. If the resultant action on Own's part is not satisfactory, the controller takes over spacing responsibility and vectors the aircraft to the FAF. If Own does an adequate job of spacing relative to Lead, the ATSP continues to monitor the progress until Own crosses the FAF. Thereafter, Own is cleared to land.

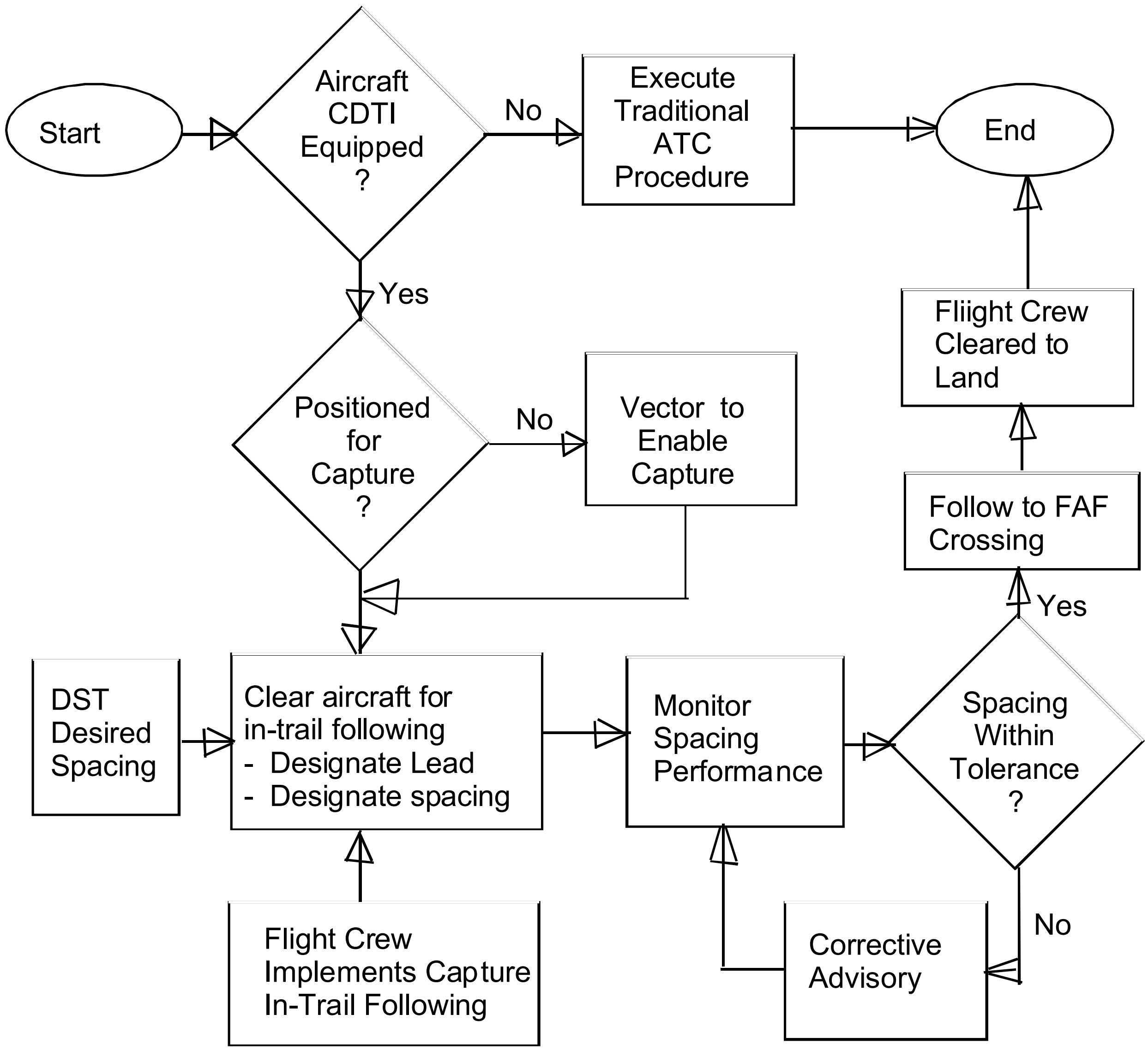

Figure 6. Operational Sequence Diagram for ATSP: Normal In-Trail SPACING Process

10.2 Flight Crew: Nominal In-Trail SPACING Process

Figure 7 shows the operational process that the flight crew goes through when cleared to use their CDTI to capture and then maintain a designated SPACING behind a designated Lead aircraft. On or before the FC enters the TRACON, the request in-trail SPACING permission. ATSP determines if airspace conditions warrant and if the aircraft is properly equipped. If not, the ATSP denies the request and continues to vector the aircraft through the approach.

If the FC and aircraft are trained and equipped, and conditions warrant, the ATSP clears the FC to execute the in-trail SPACING procedure. This includes issuing the designated Lead aircraft and the desired spacing. These parameters are entered into the CDTI. Thereafter, the FC capture and maintain desired spacing behind the Lead until FAF is reached. They are then cleared to land.

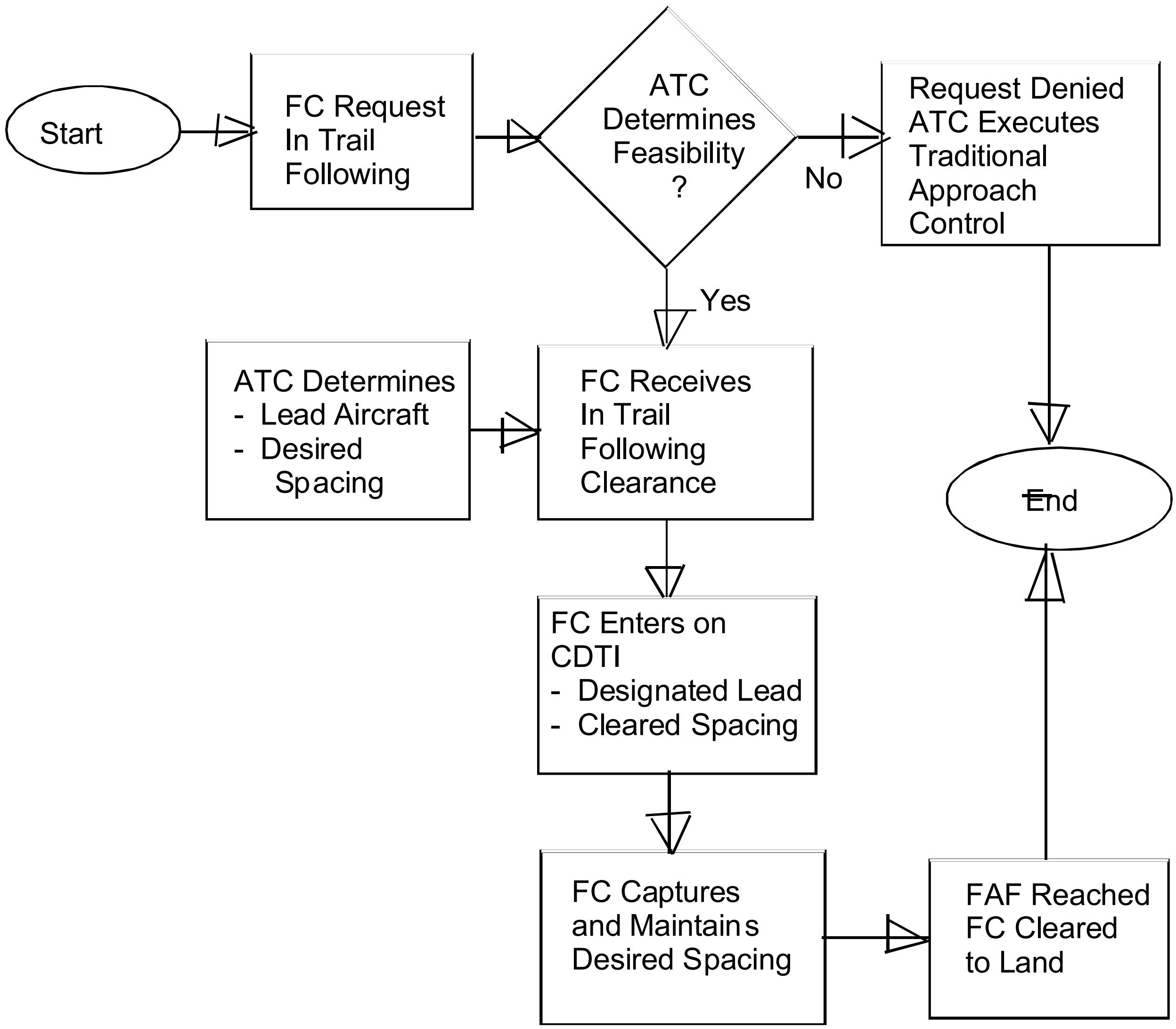

Figure 7. Operational Sequence Diagram for Flight Crew: Normal In-Trail SPACING Process

11. Benefits

Concept Element 11 is directed at increasing terminal airspace and runway capacity (throughput), flight efficiency, and airspace flexibility. These primary benefits occur through use of CDTI and FMS technology for in-trail merging and spacing control as well as being enabled to fly along flexible routes within the approach zones. Additional benefits regarding trajectory predictability, airspace access, and scalability of the controller work force to increased traffic volume also exist. These benefit mechanisms are now described.

Capacity

The capacity-related potential benefits of CE-11 service are:

1. CDTI-equipped aircraft provide the FC increased situation awareness and the ability to maintain tighter in-trail SPACING control. Thus, excess safety-related separation buffers used by controllers today can be reduced, increasing operational densities and runway throughput.
2. An increased volume of airspace can be utilized by FMS-equipped aircraft in that they are not constrained to follow a fixed route structure. Flexible approach route MANEUVERING capability allows efficient by passing of weather cells and more direct routes from approach zone entry to the FAF.
3. Close trajectory management by FMS-equipped aircraft flight crews allows increased RTA conformance, which leads to increased throughput along a system of merging routes.

Efficiency

The following efficiency-related potential benefits for CE-11 have been identified. These are separated into benefits to Users/FCs and to the ATSP.

<u>Users and Flight Crews</u>

Users should experience reduced operating costs (time and fuel) and reduced delays, due to:

1. Increased predictability of operations;
2. Capability for MANEUVERING along optimized routing;
3. Reduced excess spacing buffers; and
4. Reduced excessive MERGING and SPACING maneuvers.

<u>Air Traffic Service Provider</u>

The ATSP should experience more efficient operations (reduced workload) due to:

1. The ATSP has decision support for ATC clearance advisories.
2. The ATSP has reduced voice communications since there is little voice contact with equipped aircraft after their FCs have been given FMS-CDTI-based MANEUVERING, MERGING and SPACING clearances.
3. Because many aircraft will have MERGING, in-trail SPACING, and self-separation control capability via FMS / CDTI, the ATSP can focus more on aircraft that do not have these capabilities. Therefore, the curve of workload as a function of traffic density will be below that experienced by today's ATC system.

ATSP can focus on traffic management and less on traffic control.

Flexibility

The following flexibility-related potential benefits of CE-11 have been identified.

1. FC preferences of flexible routes for FMS-equipped aircraft are implemented directly by the FC and may not require ATSP approval.
2. The ability to free MANEUVER within designated approach zones increases the FC available and realizable routing options to convective weather cell problems.
3. The option of not needing to adhere to a fixed route structure and ability to use the entire approach zone airspace allows more efficient flight plan options for equipped aircraft.
4. Since FCs can constantly monitor their trajectories relative to adjacent approach traffic, these trajectories can be more tailored to FC preferences in terms of maintaining lateral and vertical separation as well as specified in-trail SPACING.

Additional Benefits

CE-11 benefits of lesser priority include improved trajectory predictability, greater airspace access, and ability to scale the ATC workforce to handle larger traffic volumes. Each is described.

<u>Predictability</u>

Participating FCs can diligently monitor MERGING and in-trail SPACING clearance adherence and provide high predictability of their aircraft trajectory. Increased trajectory adherence increases the predictability of intended path conformance, which in turn increases the predictability of arrival traffic throughput.

<u>Access</u>

This refers to the ability of FCs to obtain greater access to airport, airspace, and ATC services. The concept of MANEUVERING along flexible approach zones to account for dynamic traffic and weather conditions allows greater access to all TRACON airspace and more continuous access to the airport than does a fixed route environment that exists today. Flexible routing within designated approach zones provides improved access to off-route airspace within that zone.

<u>Scalability</u>

Scalability refers to the capability of the air traffic system to continue to operate successfully with continually increasing traffic volumes.

Each additional equipped participating aircraft contributes its own surveillance infrastructure and provides its own separation assurance. This system accommodates growth better than a centralized system that may have limits in capacity to handle traffic growth. Whereas the current paradigm of centralized human planner / controller does not scale with large traffic growth, a distributed system of self separating FCs of participating aircraft that grows with the traffic is readily scalable. In today’s system, controller workload is a strong function of traffic volume since every aircraft is individually managed. Under CDTI/FMS-based MERGING and in-trail SPACING control, equipped aircraft do not need to be continually managed by the ATSP and therefore controller workload is a lesser function of traffic volume. Thus traffic volume could be permitted to increase while using the same level of controller resources.

The CE-11 ideas postulated for approach traffic within TRACON airspace is scalable back through before top of descent within the terminal transition airspace. Furthermore, the concept is scalable to departing aircraft traffic as well.

12. Issues and Key Decisions

This section summarizes the primary issues that must be dealt with in pursuing the CE-11 ideas. Key decision points in the future research are also listed.

12.1 Issues Summary

The CE-11 concept is still in an early stage of development, although there has been substantial human-in-the-loop simulation work to examine the feasibility of using the CDTI for in trail SPACING and the FMS for directing free MANEUVERING. The main issues concerning CE-11 revolve around validation / refinement of the basic concept and development of the operational and technical details. Validation of the concept should be done with airline and ATSP operations staffs at an early stage to confirm the concept is correctly defined and addressing areas with the most potential payoff. Functionality and FC-controller relationships can be refined through discussions with the same staffs. Lessons learned from previous NASA and Mitre research can be used to directly refine the basic technical areas of investigation.

Concurrently, development of key technologies for the concept can progress in preparation for the development of a CE-11 prototype system. A list of required avionics development efforts includes:

1. Development of the FMS so that it can compute flexible routes that are within the confines of zonal boundaries, adequately spaced from convective weather cells, able to meet an RTA at a downstream merge point, and are fuel optimal. This includes abilities to change boundary and weather cell constraints as defined by up-linked information from the ATSP.
2. Development of the CDTI in trail spacing cues and other information to allow the FC to designate the Lead aircraft, to set the desired temporal spacing, to guide to the spacing parameter either via flight director or automatically via the FMS, to monitor spacing adherence, and to monitor lateral and vertical separation from adjacent aircraft. This includes ability to compute and use ghost projections of Lead aircraft if the Lead is not on the same route as the participating aircraft.
3. Development of data link interface to enable the FC to interact with the ATSP when requesting a flexible route, being cleared to use the RTA or ghost for merging control, being cleared to maintain a fixed temporal spacing with respect to the designated Lead, and returning primary separation responsibility back to the controller.

There is a spectrum of ATSP DST requirements ranging from using today's STARS environment where the controller would verbally clear an aircraft FC to use its CDTI for in trail spacing control (and no special DST requirement) to an advanced DST which might build upon emerging Active FAST capability. The different environments need to be defined, and associated DST technology needs to be developed consistent with ATSP needs within CE-11.

For both avionics and ATSP DST requirements, there is the open question of what are the minimum equipment and training requirements for an aircraft or flight crew to participate in CE-11. Also, there is the issue of what terminal areas can actually benefit from the concept in terms of traffic density, airspace constraints, and amount of training required to enable the traffic managers to utilize the concept.

In parallel with needed technology developments, there is also a need to develop the flight crew-traffic manager procedures consistent with the three operational modes described in Section 3 and the three operational conditions describe in Section 9. Furthermore, these need to be expanded to include provision for handling aircraft with different speed envelopes and different levels of equipment.

12.2 Key Decision Points

Key decision points regarding development of CE-11 include the following:

1. It must be shown that there is a legitimate economic payoff in terms of increased flight efficiency and runway throughput that would be enabled by equipping aircraft and training personnel to use the CE-11 technology. Increased flight benefits must exceed costs of obtaining such benefits.
2. It must be shown to be operationally viable that in trail spacing responsibility can be delegated to the FC. This includes the willingness on the part of the FC to accept this responsibility, the ability of the ATSP to continue to monitor progress of an approach string, and the ability of the ATSP to resume spacing responsibility in case of a failure condition preventing the CE-11 procedure to continue in nominal fashion.
3. The current ADS-B OpEval is examining use of ADS-B and CDTI to make approaches into Louisville and Memphis more efficient for the Cargo Airlines. This supposes no additional ATSP DST developments. However, aspects of CE-11 in the 2015 time frame require advanced FMS and ATSP DST capability. Decisions need to be made as to which sets of environments should be explored for which time frames with the associated technology and procedures being developed.

Appendix A. Operational Requirements Table

Operational Requirements – Traffic Management, Synchronization Area

The following operational needs statements are addressed by CE-11, Self Spacing for Merging and In-Trail Separation. The numbers provide a trace to the matrix of operational needs statements supporting the AATT ATM/OPSCON.

ONS #	ONS Text
1_375 4_370	Through a data link to the properly equipped cockpit, provide users- routine communications- updated charts, current weather, SUA status, and other data- basic flight information services, including forecast weather, NOTAMs, and hazardous weather warnings- airport information, including Runway Visual Range (RVR), braking action and surface condition reports, runway availability, and wake turbulence and wind shear advisories - clearances and frequency changes in the form of pre-defined messages.
4_311	Properly equipped aircraft are given authority to maneuver as necessary to avoid weather cells, or to follow such aircraft using self-spacing procedures.
4_315 3_225	When appropriate, clear properly-equipped aircraft to self-separate and maintain sequence (“station-keeping”).
4_316	Appropriately equipped aircraft are given clearance to merge with another arrival stream, and/or maintain in-trail separation relative to a leading aircraft.
4_355	Use collision avoidance and escape guidance logic, real-time wake turbulence prediction, and flight deck situation awareness to perform simultaneous approaches to closely spaced runways in Instrument Meteorological Conditions (IMC).
4_555	Arrival operations also benefit from these tools, {tools that provide more efficient airport surface operations, improved real time assessment of traffic activity in departure and en route airspace, and expanded usage of flexible routes based on RNAV, satellite navigation, and FMS.}
4_575	In the final portion of the arrival phase, decision support systems facilitate the use of time-based metering to maximize airspace and airport capacity.
4_585	On final approach, the service provider may give the pilot responsibility for station keeping to maintain the required sequence and spacing to the runway.
4_646	To enhance operations during peak capacity periods, arrival operations are enhanced by taking advantage of aircraft FMS to enable Required Time of Arrivals (RTAs) at designated approach points.
4_755	the pilot will be able to select which route he wishes to follow.
4_765	pilots ... fly to meet required times of arrival
4_770 5_355	Free maneuvering operations in low density areas is being performed.
5_115	The use of en route airborne holding has been reduced with the implementation of other procedures that improve traffic flow patterns and make maximum use of available terminal capacity
5_145	These metering and merging separation procedures could provide the crew the flexibility to more efficiently manage their flight with respect to aircraft

ONS #	ONS Text
	performance, crew preferences, and ATC considerations by allowing aircraft to stay on the cleared route in cases were ATC would otherwise have to vector the aircraft to achieve the desired spacing.
5_200	remain at that altitude until the point is reached from which an optimum descent profile should commence.
5_345	When appropriate, use a "metering spacing technique" to provide the user the flexibility to efficiently manage a flight.
5_400	Perform some spacing activities that were previously performed by the service provider. These activities will be performed for metering or merging purposes. (Flight Deck)
5_450	Reduced or time-based separation standards will be developed based on technology and aircraft capability, further increasing system capacity and safety.
5_575	Decision support systems will assist in conflict detection and the development of conflict resolutions.
5_685	The service provider will also be involved in the coordination of modified flight trajectories for active flights.
5_885	While vectoring of aircraft is a high workload for both controllers and pilots, only one clearance is given for this metering spacing technique
6_285	Perform some separation and merging activities that were previously performed by the service provider.
6_460 6_370	pilots may coordinate with service providers for clearance to conduct specified cockpit self-separation operations. ... the pilot's view of nearby traffic supplements the service provider's big picture of longer term traffic flow.
6_465 6_375 6_240	Pilots may obtain approval for special maneuvers such as reduced separation in-trail climb, in-trail descent, lead climb, lead descent, limited duration, station keeping as well as lateral passing maneuvers

Appendix B. Previous CDTI and Related Research and Development

The previous work can be divided into two categories - pre-1990 and 1990-2000. In the following, we summarize the results of several references for pre-1990 work. Post-1990 work comes from both literature review and interviews with domain experts who have been involved in this work.

B.1 Pre-1990 CDTI Research

The CTDI concept has been suggested and studied since sometime in the 1940's [3]. The TELERAN system, developed by RCA and tested in a Link trainer and a C-47 in the late 1940's, was based upon television transmission of ground radar information and map overlays to the aircraft. In 1947, the MIT Radiation Laboratory proposed two restricted visibility condition traffic display concepts: an airborne radar capability to derive traffic, terrain, and weather information and presentation of ground radar detected information on a cockpit plan view display. In 1948, the Radio Technical Commission for Aeronautics (RTCA) recommended that future domestic air traffic control (ATC) be based on both ground and airborne pictorial situation displays.

Airborne station-keeping equipment has been employed successfully by the military services for many years to maintain safe air-to-air separation in formation flying. In 1963, the US Air Force flight tested in a system in which ground radar information was transmitted via a TACAN data link to an airborne television to display nearby aircraft. Alphanumeric text was also transmitted and displayed to demonstrate the feasibility of providing flight clearances, weather advisories, and other pertinent information to the pilot. In 1965, a televised picture of the FAA's Boston Terminal Radar Approach CONtrol (TRACON) display was used to test navigation and conflict detection concepts for general aviation. In 1974, MIT Lincoln Laboratory developed a digitized version of CDTI. The target data base was supplied by an Air Force 407L radar system via the SEEK BUS data link; this concept was later reconfigured for the USAF Airborne Warning and Control System (AWACS) flight demonstrations.

CDTI studies were continued in the 1970's and 1980's by NASA to investigate potential applications that could increase airport capacity, reduce controller stress and workload, and enhance safety of flight. These studies used simulations of the TCAS, Mode S radar, and other data link systems. Based on these studies, traffic displays were postulated and tested under simulated traffic conditions. Pilots and controllers participated in these tests, and much was accomplished in understanding the relative vehicle dynamics, the human factors of traffic displays, and the potential of CDTI to provide benefits. The studies also revealed potential problems such as increased pilot and controller workload and possibilities of traffic flow instability, secondary conflicts, and pilot distraction. [3-16]

Airborne traffic displays were developed as optional equipment during the TCAS II program. The functions of these displays are to:

1. Aid in visual acquisition of adjacent traffic;
2. Discriminate threat traffic from other traffic;
3. Provide range and bearing information on adjacent aircraft; and
4. Instill confidence in the resolution advisories.

Installation of TCAS II began about 1990 for all air carriers. The requirement to carry and use a TCAS has been extended to cover all aircraft carrying more than 30 passengers. In all cases, installations have included some form of TCAS traffic display. Thus, via the TCAS program, the inclusion of a cockpit display of adjacent traffic became a reality.

Three elements of the TCAS or other traffic display design are of importance to the CDTI applications:

1. Surveillance – The accuracy, reliability, and volume of spatial coverage of the surveillance and the associated accuracy of the tracking algorithm govern to what extent TCAS/CDTI can be used for merging and spacing applications. The TCAS II surveillance system design was primarily the results of work performed at MIT Lincoln Laboratory.
2. Logic design – The conflict detection and resolution (CD&R) logic used to determine which aircraft to display or to indicate that they may pose a threat. This must be interfaced with merging and spacing cues. The TCAS II threat detection and collision avoidance logic was primarily developed by the Mitre Corporation. Seven revisions of this software design have been released to the TCAS manufacturers. Many aspects of this logic have to be examined in terms of the algorithm and software enhancement requirements for merging and spacing application.
3. Pilot interface – The human factors aspects of the display and other interface mechanisms used by the pilot are critical for adapting the system to merging and spacing. The TCAS II display design format and other aspects of the flight crew interface were investigated at both NASA Ames and Langley Research Centers and MITLL.

These elements must be considered (a) when devising technical enhancements to implement the CDTI applications, and (b) when developing the procedures for using the displays for the applications.

Previous research in CDTI focused to some degree on the in-trail following application. This research consisted of both analytical work and experiments conducted using cockpit simulation. In the mid 1970s, MIT Flight Transportation Laboratory conducted cockpit simulator studies that explored many terminal area applications of CDTI.

During the 1980-1984 time period, NASA Ames and Langley Research Centers both sponsored analytical studies and conducted a series of experiments to determine (a) what were the important elements that allowed pilots to use the CDTI for in-trail following; (b) how could the CDTI be mechanized; and (c) what benefits might be realized from CDTI implementation. Within the NASA research, several questions were posed associated with the CDTI-based terminal area traffic tactical control concepts. These included:

1. What are the basic dynamic phenomena associated with independently controlled aircraft in a string? What condition would produce instability in the string?
2. What information does each pilot need (from the CDTI and other sources) to merge his aircraft adequately into the string and then to maintain appropriate spacing?
3. What are the effects of measurement and display errors, wind shears, aircraft mixes, spacing constraints, and merge trajectories on the dynamics and control performance of the system?

At least six different cockpit simulator studies of aircraft strings were made at NASA Langley and Ames to produce data to analyze in-trail dynamics to address these questions.

A simplified generic CDTI display used for in-trail following is shown in Figure B.1. Here, the pilot views the horizontal positions of his (Own) aircraft and the surrounding aircraft on the cockpit display. Own's position is indicated on the heading up display by the chevron symbol one-third the distance up from the bottom and centered laterally. The route path and other display features move continuously with respect to the Own symbol. Adjacent aircraft are indicated by triangles. The immediate leading aircraft that Own is assigned to follow is referred to hereafter as the "Lead" aircraft. Own and other aircraft symbols are preceded by vectors proportional in length to the ground speeds. These vectors may be curved proportional to bank angle, and they produce a prediction of where each aircraft will be at a future time.

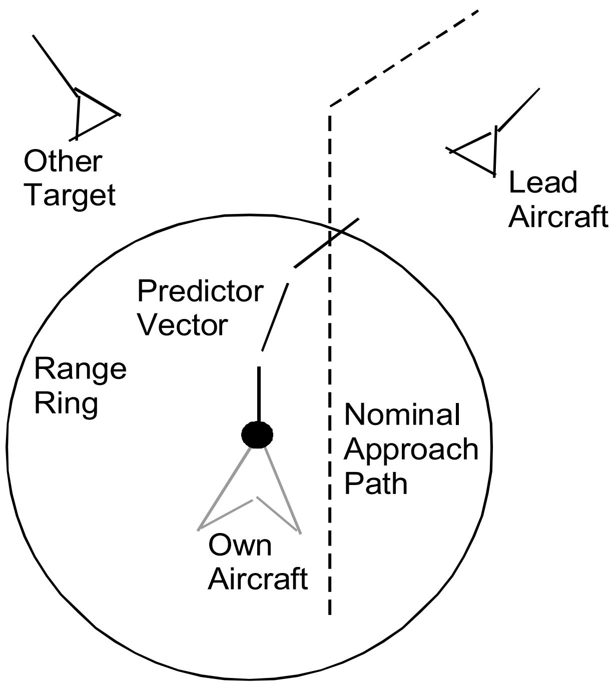

Figure B.1. Simplified generic display format to enable in-trail following.

In Figures B.2-4, three different longitudinal separation criteria that have been investigated are depicted by the symbology. The separation criterion is the mathematical rule used as part of the CDTI display to indicate to the pilot, as a spacing cue, what the desired separation should between his and the Lead aircraft. The criterion must establish a lower separation limit that is safe; yet, it must keep the aircraft close enough to provide for airspace and landing efficiency. The resulting implied acceleration commands must be within the normal limits of the aircraft. Finally, it should be possible to compute the criterion simply from available information and to display it to the pilot without ambiguity. The criteria depicted are:

1. Constant Range (Figure B.2) – This is shown by the constant range ring arc, and the pilot's objective is to steer Own aircraft so that the depicted range ring is on top of the Lead aircraft's current position. Current TCAS displays have fixed distance range rings.

The Constant Range criterion has the advantages of its familiarity to pilots flying with TCAS, its simplicity in terms of understanding, and its immediate applicability for removing large initial distances in separation of aircraft. However, the Constant Range criterion is not suited for tight spacing control. If Own is properly spaced with respect to the Lead, and the Lead aircraft slows down, this requires that Own instantaneously match this deceleration to maintain a fixed spacing distance. This causes a slowdown at an earlier range-to-go for Own aircraft. Successive aircraft will slow down at increasing distances from the runway that would produce significant fuel penalties and operational problems. Effective use of the Constant Range criterion would require that the target spacing range depicted by the rings would, in fact, be incrementally reduced as the aircraft slows down for final approach.

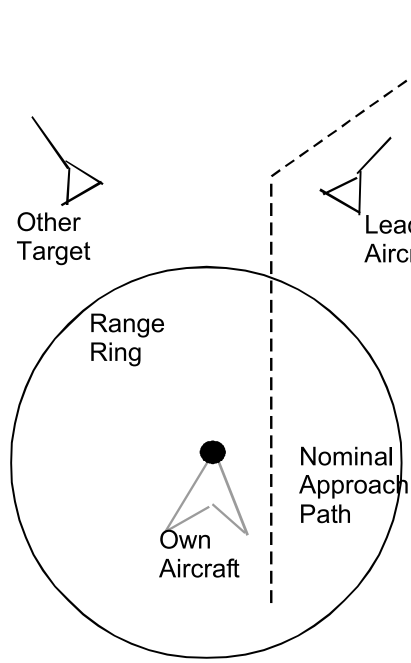

Figure B.2. Depiction of Constant Range separation criterion

2. Constant Time Predictor (Figure B.3) – This is the predictor vector that is in front of Own aircraft symbol; its length is the product of the time constant Tp and the measured ground speed Vg. It shows where Own will ideally be Tp seconds from now. The objective is to steer the tip of Own's predictor vector to be on top of the Lead aircraft's current position. A variation of this separation criterion is called "Acceleration cue." It modified the Constant Time Predictor criterion to include the effect of Own aircraft's measured longitudinal acceleration on the prediction vector.

The advantage of using the predictor vector on the CDTI display is that it is easy for the pilot to visualize his/her future position and to steer around turns to reduce separation error. The disadvantage is that this criterion causes early slowdown of Own followed by later excessive speed. This disadvantage is compensated by adding the acceleration term at slightly more complexity.

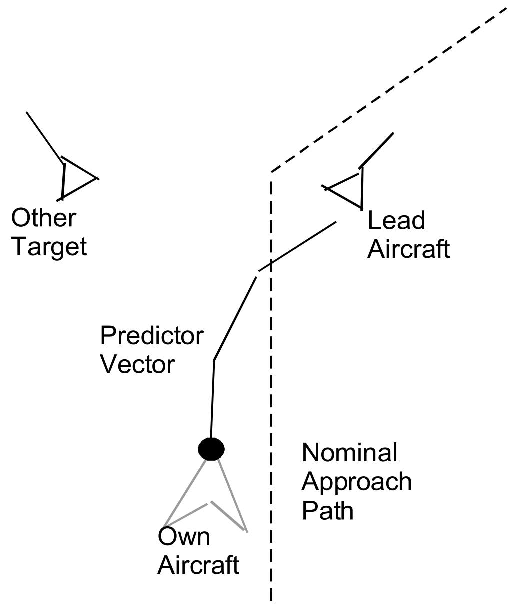

Figure B.3. Depiction of Constant Time Predictor separation criterion.

3. Constant Time Delay (Figure B.4) – This criterion consists of controlling Own to be where the Lead aircraft was Td seconds earlier. This position is indicated on the CDTI display by an enlarged "history dot." Own is steered so that the tip of the chevron symbol is on top of this moving dot.

The advantage of the Constant Time Delay separation criterion is that the history dots (or equivalently, a moving slot tied to the targeting spacing history dot) provide an ideal trail and position for Own aircraft to follow. There is no inherent time delay in using this criterion. A disadvantage of this criterion is that the dots by themselves provide no turn indicator or deceleration cue for Own, so the addition of a predictor vector is desirable. Another complexity is that to implement this criterion requires storage of the Lead aircraft's position relative to the ground.

Either the Constant Time Delay or Acceleration Cue criteria produce acceptable spacing between successive aircraft in a string. The choice will have to be made based upon which is easier to mechanize using the traffic sensor or traffic information broadcast. It may be advantageous to use features from each of the criteria for an overall display to facilitate tight in-trail spacing. For more details on the research on use of CDTI for applications of in-trail following, refer to Refs. 3-16.

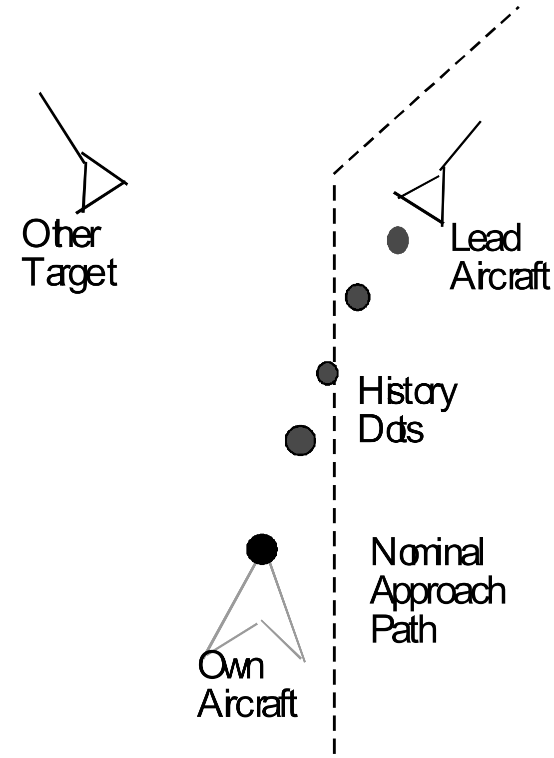

Figure B.4. Depiction of Constant Time Delay separation criterion.

B.2 Post-1990 CDTI Developments

After TCAS was mandated for commercial air carriers, and TCAS I and TCAS II systems with their traffic displays became commonplace, pilots soon began to use these displays for other "unofficial" purposes than collision avoidance. The traffic display could help the pilot/FC with situational awareness of other traffic. Pilots started to use the display for in-trail following when cleared for unconstrained transcontinental routes. It became apparent that the TCAS/CDTI would provide many useful applications and that these applications should be identified, documented, and standardized so that operational use could be orderly.

The first "official" use of the TCAS/CDTI for in-trail following control was for oceanic en route flight [17]. In oceanic airspace where radar information is not available, FCs must provide position reports that include aircraft identification position, altitude, and estimated waypoint crossing time for both the current and the next waypoint. This information is typically provided via high frequency (HF) radio to ATSP so they can conduct flight following and provide separation. The flight crew (FC) can request flight plan changes and ATSP can grant such changes provided that standard non-radar separation exists.

Requests for altitude changes are the most often requested flight plan changes. FCs may desire an altitude change for more efficient fuel consumption or to avoid weather. However, controllers often cannot grant the changes due to "over crowding" on the oceanic tracks. An inability to climb or descend can cause not only inefficient flight operations but also an uncomfortable ride for passengers or non-completion of a scheduled flight segment due to increased fuel usage.

Currently, the United States has authorized the use of the TCAS II traffic display for in-trail climb (ITC) and in-trail descent (ITD) procedures on oceanic routes. The constraints of this operation are that the trailing Own aircraft FC must see the Lead on the traffic display and there must be enough initial separation so that the ITC or ITD can be completed without violating acceptable separation as Own passes through the Lead's altitude. In an enhanced ITC and ITD procedure, the CDTI would provide flight identification, speed, altitude, and range information directly to the FC thereby reducing or eliminating coordination with the Lead aircraft [18, 19].

B.3 On-going CDTI Research and Development

Two on-going technical developments are further enabling the use of CDTI: (a) the broadcast of automatic dependent surveillance (ADS-B) where the aircraft broadcasts its precise state and intent based typically on GPS navigation; and (b) the broadcast of traffic information service (TIS-B) where the ground radar system determines states of aircraft and broadcasts these to those adjacent aircraft as a supplement to ADS-B or TCAS. The minimum aviation system performance standards (MASPS) for ADS-B describe nearly 80 potential applications of CDTI based on ADS-B information [18]. These technologies have spurred activity by RTCA to define further acceptable applications, to develop requirements and operational procedures for these applications, and to develop and document minimum operating standards (MOPS) for the CDTI equipment [19].

Reference 19 describes in further detail the following CDTI applications:

1. Enhanced Visual Acquisition – Capability that aids FCs in visually acquiring other proximate traffic as well as increasing their traffic awareness;
2. Enhanced Visual Approach – Provides the FC additional electronic information to aid in conduct of an enhanced visual approach. Information includes target positions, flight identification, closure rates, and ground tracks;
3. Enhanced In-Trail Climb or Descent – Described previously;
4. Oceanic Climb or Descent to Co-Altitude (In-trail or lead) – Similar to Enhanced ITC or ITD but enables a lead or trailing aircraft to climb or descend to the same altitude as that of the participating aircraft;
5. Approach Spacing – Enables the FC to both accomplish and enhance the controller's in-trail spacing objectives to improve runway throughput but maintain acceptable safety in terms of meeting wake vortex avoidance and runway occupancy constraints. This application is directly related to the motivation of CE11;
6. Airport Surface Situational Awareness – Enables FCs to observe surface traffic positions on a real-time display and, along with any available visual cues and radio communications, infer intent with respect to surface movements;
7. Station Keeping in Oceanic, En Route, and Remote Non-Radar Airspace – FCs use the CDTI to safely conduct IFR in-trail constant or decreasing to minimum distance longitudinal separation for extended periods of time which may last up to the entire duration of a flight.

NASA, FAA, Eurocontrol, and other organizations are addressing the various issues that these potentially near-term CDTI applications pose.

Safe Flight 21 (SF21) is a current FAA sponsored cooperative government/industry effort to evaluate enhanced capabilities for Free Flight based on evolving communications, navigation, and surveillance (CNS) technologies [20]. SF21 will demonstrate the cockpit display of traffic, weather, and terrain information for FCs and will provide improved information for controllers. The primary objective of the SF21 program is to facilitate implementing nine operational categories including "improved terminal operations in low visibility." This category includes enhanced visual approaches with ADS-B and TIS-B, approach spacing for visual and instrument conditions, and departure spacing.

Under SF21, a cooperative government-industry team is conducting a series of operational evaluations (OpEvals) of various ADS-B applications in conjunction with the Cargo Airline Association plans to equip their fleets with advanced TCAS/CDTI based upon ADS-B. In 1999, enhanced visual approaches and see-and-avoid enhancements were the subject of the OpEval conducted by 24 participating aircraft in the Ohio River Valley (Airborne Express facility at Wilmington ILN). This was preceded by extensive cockpit simulation studies conducted to prepare for the OpEval by Mitre CAASD [21, 22]. This year, the OpEval is being continued to examine approach spacing concepts using Constant Range and Constant Time Delay criteria (UPS facility at Louisville SDF).

The goal of Capstone, a related project under SF21, is to implement and test the CNS technologies mentioned previously on general aviation aircraft flying out of Bethel, Alaska. This project is pertinent in that it is bringing the benefits of the cockpit display technology to the low end general aviation (GA) user.

Recent NASA and Mitre research has addressed the related use of ADS-B and CDTI to facilitate dual approaches to closely spaced parallel runways in instrument meteorological conditions (IMC) [24-28]. The objective is to maintain throughput and capacity as under visual conditions (VMC). Here the CDTI is used by trailing Own aircraft to maintain a constrained longitudinal spacing relative to the Lead aircraft approaching the parallel runway. The concept is to provide adequate separation for both wake avoidance and collision avoidance purposes. Specifically, United Airlines has proposed using this application to maintain throughput at San Francisco International Airport, where throughput is cut in half under IMC. NASA has investigated a concept called Airborne Information for Lateral Spacing (AILS) to protect against the case where one of the two parallel aircraft deviates from its nominal path into the airspace of adjacent parallel traffic.

Appendix C. Variations to the Baseline System for CE-11

In the course of the discussions that led to this report, some alternate ideas were discussed that may have merit in terms of future research that can be conducted. These ideas are briefly mentioned here.

Moving Slots

An alternative to following the Lead aircraft directly by use of some kind of cue tied to the dynamics of the Lead aircraft, each FC could instead be displayed an ideal moving slot to stay within, where that slot may be tied to the Lead aircraft or it may be within a stream of slots generated by the DST. The ATSP monitors all aircraft to ensure adequate separation and compliance with the established procedure. For cases where the FC fails to maintain adequate spacing, automated systems or the ATSP will provide a required correction.

The ATSP DST would compute an ideal stream of moving slots and uplink these slots to the aircraft to be displayed on the CDTI. Each FC sees its assigned slot and the slot of the immediate Lead. In this case, there remains the ideal separation between each aircraft in the stream, but a following aircraft is not as subject to the small variations in the speed and position of the preceding Lead aircraft, as the Lead also is working to remain within its assigned slot.

A mechanization requirement would be that the DST computes and up-links the desired position and velocity of all aircraft in the string in the form of a train of moving slots. Then, the job of the CDTI would be to display that slot for the FC to capture and track. This could be largely de-coupled from the immediate Lead trajectory, and the FC would focus not on the position relative to the Lead but the position relative to the assigned slot. In this latter case, the ATSP monitors the position of each aircraft relative to the ideal slot position. The controller takes action to vector an aircraft only if it moves to far outside of the slot, as assigned.

Within this latter environment, the trailing aircraft can either track a moving position tied to the trajectory of the immediate leading Lead aircraft, or it can track an ideal moving slot computed and linked up by the DST. In the latter case, the string of moving slots is anchored to the trajectory of the String Leader aircraft.

Merging

There are three alternate ways in which the Own aircraft may be guided before it merges behind the assigned Lead aircraft:

1. It may be given a “ghost” image of the Lead aircraft as computed and projected on Own’s structured route before the merge point;

2. It may be given an RTA at the merge point that is computed based upon the Lead aircraft crossing that point at the appropriate time separation in front of the RTA; or

3. It may be given a moving slot to capture and track that blends into the track containing the Lead tracking its assigned slot.

References

1. Anon., “Concept Definition for Distributed Air/Ground Traffic Management (DAG-TM) Version 1.0,” NASA AATT Project Internal Document, September 1999.
2. Anon., “DAG-TM Concept Element 11 Research Plan,” NASA AATT Project Internal Document, March 15, 2000.
3. Sorensen, J., Hollister, W., Burgess, M., and Davis, D., “TCAS-Cockpit Display of Traffic Information (CDTI) Investigation,” DOT/FAA/RD-91, Federal Aviation Administration, Washington, DC, April 1991.
4. Love, W. D., et al, “A Concept for Reducing Oceanic Separation Minima Through the Use of a TCAS-Derived CDTI,” NASA CR-172258, Washington, D.C., January, 1984.
5. Chappell, S. L., et al, “Pilots’ Use of a Traffic Alert and Collision Avoidance System (TCAS II) in Simulated Air Carrier Operations,” NASA TM-100094, NASA Ames Research Center, Moffett Field, CA, 1989.
6. Sorensen, J. A., and Goka, T., “Analysis of In-Trail Following Dynamics of CDTI-Equipped Aircraft,” *J. of Guidance, Control, and Dynamics*, Vol. 6, No. 3, May-June 1983.
7. Goka, T., “Enhanced TCAS II/CDTI Traffic Sensor Digital Simulation Model and Program Description,” NASA CR 172445, Langley Research Center, Hampton, VA, October 1984.
8. Connelly, M. E., “Simulation Studies of Airborne Traffic Situation Display Applications,” MIT ESL-R-751, Cambridge, MA, May 1977.
9. Williams, D. H., “Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment,” NASA TM-84601, Langley Research Center, Hampton, VA, 1983.
10. Williams, D. H., and Wells, D. C., “Jet Transport Operations Using Cockpit Display of Traffic Information During Instrument Meteorological Conditions,” NASA TP-2567, Langley Research Center, Hampton, VA, May 1986.
11. Hart, S. G., and Wempe, T. E., “Cockpit Displays of Traffic Information: Airline Pilots’ Opinions about Content, Symbology, and Format,” NASA TM 78601, Ames Research Center, Moffett Field, CA, August 1979.
12. Palmer, E. A., et al, “Perception of Horizontal Aircraft Separation on a Cockpit Display of Traffic Information,” *Human Factors*, Vol. 22, No. 5, October 1980.
13. Abbott, T. S., “A Compensatory Algorithm for the Slow-Down Effect on Constant-Time-Separation Approaches,” NASA TP 2386, Langley Research Center, VA, 1985.
14. Abbott, T. S., “Simulation of a Cockpit-Display Concept for Executing a Wake-Vortex Avoidance Procedure,” NASA TP-2300, 1984.
15. Abbott, T. S., “A Cockpit-Display Concept for Executing a Multiple Glide-Slope Approach for Wake-Vortex Avoidance,” NASA TP-2386, 1985.
16. Swedish, W. J., “Evaluation of the Potential for Reduced Longitudinal Spacing on Final Approach,” Rep. No. FAA-EM-79-7, Aug. 1979.

17. Cieplak, J. J., "Operational Trials of the In-Trail Climb Procedure: Interim Results," Mitre Paper 97W0000121, 1995.

18. RTCA, "Guidance for Initial Implementation of Cockpit Display of Traffic Information, Document No. RTCA/DO-243, 1998.

19. RTCA, "Operations Concepts for Cockpit Display of Traffic Information (CDTI) Applications," Draft 1, RTCA Paper No. 186-98, Sept. 1998.

20. RTCA, "Development and Implementation Planning Guide for Automatic Dependent Surveillance Broadcast (ADS-B) Applications," Paper No. 114-99/SC186-135, August 1999.

21. Safe Flight 21 Steering Group, "Safe Flight 21 Master Plan, Version 2.0," March 2000.

22. Olmos, B. O., Mundra, A., et al, "Evaluation of Near-Term Applications for ADS-B/CDTI Implementation," 98WAC-73, World Aviation Congress Conference, Sept. 1998.

23. Olmos, B. O., "Wilmington (ILN) '99 OpEval: Overview," April 2000.

24. Stone, R., "Paired Approach Concept; Increasing IFR Capacity to Closely Spaced Parallel Runways," United Airlines white paper, Oct. 1998.

25. Waller, M. C., and Scanlon, C. H., "A Simulation Study of Instrument Meteorological Condition Approaches to Dual Parallel Runways Spaced 3400 and 2500 Feet Apart Using Flight-Deck-Centered Technology, NASA TM-1999-208743, Langley Research Center, Hampton, VA, March 1999.

26. Hammer, J., "Study of the Geometry of a Dependent Approach Procedure to Closely Spaced Parallel Runways," 18th Digital Avionics Systems Conference, St. Louis, MO, Oct. 1999.

27. Carpenter, B. D., and Kuchar, J. K., "A Probability-Base Alerting Logic for Aircraft on Parallel Approach," NASA CR 201685, Langley Research Center, Hampton, VA, April 1997.

28. Delzell, S., Johnson, W. W., and Liao, M. "Pilots' Spatial Mental Models for Memory of Heading and Altitude," 17th Digital Avionics Systems Conference, Bellevue, WA, 1998.

29. NASA AVOSS reference.

30. Anon., "Point-in-Space Ghosting Technology," Scientific Consulting & Automated Technological Services (SCATS) viewgraph presentation, DAG TM Workshop, NASA Ames Research Center, May 2000.

31. Anon, "AATT Air Traffic Management Operations Concept,"