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ISSUES IN THE PHYSICAL INTEGRATION OF TERMINAL AREA PRODUCTIVITY (TAP) SYSTEM AND DISPLAYS INTO COMMERCIAL AIRCRAFT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ACO	Aircraft Certification Office
ADI	Attitude Director Indicator
ADS-B	Automatic Dependent System - Broadcast
AEEC	Airlines Electronic Engineering Committee
AHRS	Attitude and Heading Reference System
AILS	Airborne Information for Lateral Spacing
AIM	Aeronautical Information Manual
AMC	Airlines Maintenance Committee
ARINC	Aeronautical Radio, Incorporated
ATA	Air Transport Association
ATC	Air Traffic Control
ATM	Air Traffic Management
CAT III	Category III
CAT 3A	Category 3A
CDU	Control Display Unit
COTS	Commercial Off-the-Shelf
CPDLC	Controller - Pilot Data Link Communications
CRM	Crew Resource Management
CSPA	Closely Spaced Parallel Approaches
CTAS	Center TRACON Automation System
DA	Descent Advisor
DAR	Designated Airworthiness Representatives
DER	Designated Engineering Representatives
EADI	Electronic Attitude Director Indicator
EAEC	European Airlines Electronics (Engineering) Committee
EDU	Electronic Display Unit
EFIS	Electronic Flight Instrument System
EHSI	Electronic Horizontal Situation Indicator
EICAS	Engine Indicating and Crew Alerting System
EGPWS	Enhanced Ground Position Warning System
EMI	Electro-Magnetic Interference
EMM	Electronic Moving Map
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FAST	Final Approach Spacing Tool
FO	First Officer
FMS	Flight Management System
GA	General Aviation
GC	Ground Control
GCAW	Ground Collision and Warning System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HGS	Head-Up Guidance System
HIRF	High Intensity Radio Frequency (Interference)
HSI	Horizontal Situation Indicator
HUD	Head Up Display

I/O	Input/Output
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IRS	Inertial Reference System
IMC	Instrument Meteorological Conditions
JAL	Japan Air Lines
LCD	Liquid Crystal Display
LH	Left Hand
LNAV	Lateral Navigation
LVLASO	Low Visibility Landing and Surface Operations
MCDU	Multi-Purpose Control and Display Unit
NASA	National Aeronautics and Space Administration
NBAA	National Business Aircraft Association
ND	Navigation Display
OEM	Original Equipment Manufacturer
PF	Pilot Flying
PMD	Panel Mounted Display
PNF	Pilot Not Flying
RA	Resolution Advisory
R&D	Research & Development
RH	Right Hand
ROTO	Roll Out and Turn Off
RSO	Reduced Spacing Operations
RVR	Runway Visibility Range
SA	Situational Awareness
SAS	Scandinavian Airlines System
SIL	System Integration Lab
SOP	Standard Operating Procedures
STC	Supplemental Type Certificate
SVS	Synthetic Vision System
TA	Traffic Advisory
TAP	Terminal Area Productivity
TCAS	Traffic alert and Collision Avoidance System
TMA	Traffic Management Advisor
T-NASA	Taxiway Navigation and Situation Awareness
TRACON	Terminal Radar Approach Control
USAF	United States Air Force
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VSD	Vertical Situation Display
V&V	Verification & Validation

EXECUTIVE SUMMARY

NASA is developing a set of cockpit displays to aid aircraft crews during low visibility approach, landing, and surface operations as part of the Terminal Area Productivity Program (TAP). The goal of the program is to increase airport throughput and safety under visibility conditions down to 300 ft RVR. The displays are intended to provide pilots with sufficient information to allow use of TAP elements such as Airborne Information for Lateral Separation (AILS), Roll-Out and Turn-Off (ROTO), and Taxi Navigation and Situation Awareness (T-NASA). The functional information for the latter two displays will be presented on a head up display (HUD) at the left seat, and on a panel mounted display (PMD) easily visible to the Captain and First Officer position.

Monterey Technologies, Inc. (MTI) was asked to do a preliminary investigation of what would be required to integrate the TAP system and displays physically and procedurally into aircraft. Physical integration and procedural integration were investigated concurrently but independently. The findings are reported in two separate reports. The companion to this report is Initial Identification of Procedural Issues for the Future Deployment of Terminal Area Productivity (TAP) Technologies (Hooey, et. al., 1998).

MTI engaged John Cotton and Associates (JCA) and Flight Dynamics (FD) as subcontractors to determine the total installation integration tasks involved for the current and future commercial aircraft fleets. The personnel of JCA are highly experienced in the installation, integration and certification of avionics. FD has similar experience with particular expertise in design, manufacture, installation, and certification of HUDs for commercial transport aircraft.

Objectives of the Physical Compatibility Analysis

The specific objectives of the analysis were to determine what existing equipment must be moved or displaced to allow installation of TAP equipment, what additional computational resources and data sources would be required and what software changes and additions would be necessary.

Aircraft Examined

A total of five aircraft types operated by major air carriers were surveyed for physical compatibility of the TAP system and displays. The specific aircraft types (and models representative of the type) examined are:

1. Commonly used Commuter (EMB120)
2. Confined Cockpit Medium Range Regional (MD-80 Series)
3. Longer Range Regional (B737-300/400/500)
4. Glass Cockpit (B747-400, B757-100/200, B767-200/300, B777, and MD11)
5. Long Range, Classic (B747-100/200/300, L1011, and DC10-30/40)

The aircraft were selected to represent a range of aircraft size, service use, and cockpit instrumentation. The oldest aircraft have electro-mechanical instrumentation known as a classic cockpit. Newer aircraft have an Electronic Flight Instrument System (EFIS), with two or more electronic displays in the cockpit. The most recent development is the full glass cockpit EFIS that incorporates six large multi-function color displays. All of the types selected are operated in substantial numbers by passenger and cargo carriers and will continue to be in service in large numbers for the next ten years.

Conclusions and Recommendations

The basic conclusions from the analysis are as follows:

1. The TAP displays, both head-up and panel mounted, could be retrofitted into all five types of aircraft examined. The cost of retrofit could be great, in the range of four hundred thousand to a million dollars per aircraft. Retrofitting the long range, classic-type aircraft would cost the most. Perhaps surprisingly, retrofitting the newest, glass-cockpit type aircraft, would likely be the next most expansive. The work and costs involve physical installation, requiring, in some cases, movement of existing equipment, software additions and modifications, and re-certification of the software. This last element can be very expensive, especially for glass cockpit configurations, and can range from one to four million dollars for the first certification and thereafter about eight hundred thousand to three million dollars per aircraft of the same type.

2. The retrofit approach requiring the least effort appears to be a separate system as opposed to integration into existing systems. Using a generic, self-contained TAP Processor Unit, with a centrally mounted display should be considered as the basic approach for retrofitting a current aircraft package, because it requires minimal change to current drive electronics, computers, and software. For EFIS equipped aircraft with full glass cockpits, an existing display may be used. The alternative is to modify existing systems to assimilate the TAP display functions. For the complete TAP display suite, this is likely to be more costly than the stand-alone alternative. However, it may be a more cost-effective approach if only one or two of the TAP system functions are retrofitted.

3. Achieving the TAP objective of increased productivity depends on several factors, of which technical feasibility is merely the first requisite. Ultimately, it will be the air carriers who determine the success of the TAP program. The most potent influence on adoption of TAP technology by air carriers is the economic benefits expected to accrue to each particular company.

4. It is important to recognize that as the TAP program evolves and migrates to implementation, the four different TAP functions and displays (CTAS/FMS, AILS,

ROTO and T-NASA) may not have equal appeal and be operationally justifiable by all air carriers.

The primary technical recommendation is that NASA should adopt the generic, stand-alone TAP system as the primary means for retrofitting. NASA should engage in a follow-on phase to this study to develop generic designs for TAP aircraft equipment and installations for non-glass as well as glass cockpits.

The primary programmatic recommendation is that an economic analysis should be performed to determine the retrofit costs and cost-benefits to air carriers (as a function fleet composition, type of routes, airports used, and weather). Costs should be determined both for retrofitting individual TAP displays into a variety of aircraft, and for the complete package. The costs will be sensitive to whether the approach to retrofitting the TAP system and displays is by incorporation into existing systems, or as a stand-alone add-on system.

INTRODUCTION

Air Carrier operations under low visibility conditions cause delays of fifteen minutes or more for 180,000 flights annually in the United States. Delays in excess of fifteen minutes for other reasons affect an additional 120,000 flights annually. The costs associated with these delays are estimated to be in excess of three billion dollars. The National Aeronautics and Space Administration (NASA) in conjunction with the Federal Aviation Administration (FAA) has initiated the Terminal Area Productivity (TAP) program. The objective of the program is to reduce the number of delays and increase the safety of terminal area operations during low visibility conditions to those associated with clear weather operations. TAP will increase capacity and reduce delays by reducing spacing requirements between aircraft approaching an airport, and by expediting ground operations. Working with the U.S. air carriers, aircraft industries, airport owners and operators, and the FAA, the TAP Program is expected to increase low-visibility operations for single-runway throughput by 12-15 percent. It is also expected to reduce lateral spacing to less than 4,300 feet for independent operations on parallel runways, demonstrate equivalent instrument/clear weather runway occupancy time, and reduce taxi times, while meeting the public s expectation for safe operations.

Four TAP technologies are being developed in order to meet these goals.

1. Flight Management System/Center TRACON Automation System (CTAS/FMS)
2. Airborne Information for Lateral Spacing (AILS)
3. Roll Out and Turn Off Guidance (ROTO)
4. Taxi Navigation and Situation Awareness (T-NASA)

The functional information for the first two items will be presented to the Captain and First Officer on Panel Mounted Displays (PMDs) on the instrument panel. The third and fourth items will present information on a Head-Up Display (HUD) for the Captain.

The HUD will also contain flight information for approach and landing as well as the ROTO and T-NASA information. In general TAP information is expected to be displayed on one or more of the existing displays in aircraft equipped with an electronic flight instrument system (EFIS). However, for aircraft equipped with electro-mechanical instruments, one or more electronic displays will be required in the cockpit to display TAP data.

PHYSICAL AND PROCEDURAL COMPATIBILITY OF TAP SYSTEM

A substantial amount of effort has been expended developing each of the TAP systems and displays. Looking ahead to a realization of the practical benefits of the TAP system capabilities and displays, it is important to determine what will be required to actually fit the TAP system and displays into aircraft, and how their use will affect current flight procedures. What are the technical, regulatory, and cost impediments to the migration of the TAP system and displays from the laboratory to every day use in flight operations? Early identification of problems allows adjustments in design and planning, and promotes an orderly introduction of the TAP system and displays into commercial aviation. To this end, Monterey Technologies, Inc. was asked to do a preliminary investigation of what would be required to integrate the TAP system and displays physically and procedurally into aircraft. Physical integration and procedural integration were investigated concurrently but independently. The findings are reported in two separate reports. The companion to this report is <u>Initial Identification of Procedural Issues for the Future Deployment of Terminal Area Productivity (TAP) Technologies</u> (Hooey, et al., 1998).

METHOD

The technical approach was based on an engineering evaluation of representative aircraft to determine the physical requirements and estimated costs for retrofitting the TAP system and displays to the aircraft. Feasibility of retrofit is viewed as a judgment based on the physical installation requirements and the costs of doing so. The general principle followed in the study was that the purpose is to identify problems and not necessarily to find solutions to them. However, to consider costs, some notions must be developed about how the TAP system and displays would be retrofitted into the various types of aircraft.

Investigation Team

MTI engaged John Cotton and Associates (JCA) and Flight Dynamics (FD) as subcontractors to determine the total installation integration tasks involved for the current and future commercial aircraft fleets. The personnel of JCA are highly experienced in the installation, integration and certification of avionics. FD has similar experience with particular expertise in design, manufacture, installation, and certification of HUDs for commercial transport aircraft.

Overview of Technical Approach

The technical work was conducted in six steps. The first step was to gain an appreciation of the functional and physical characteristics of the TAP system and displays as currently envisioned. The descriptions of these systems and displays were described briefly in the preceding section and are described in detail in Appendix A. The second step was to select aircraft types to be examined. The third step was to develop a list of the features and attributes of the aircraft that were selected, for compatibility with the TAP system and displays. The fourth step was to identify cooperative operators of the type of aircraft selected, and to conduct examinations and gather the necessary information. The fifth step was to organize the information and conduct an analysis to establish the requirements for retrofitting TAP system and displays to each of the representative types of aircraft. The sixth step was to estimate the costs of the retrofit requirements for each type of aircraft.

Characteristics of the TAP Technologies

A brief description of each of the four TAP technologies is presented below starting with CTAS/FMS, followed by AILS, ROTO, and T-NASA. Further descriptions of the flight deck displays and intended usage procedures can be found in Appendix A.

Center TRACON Automation System /Flight Management System (CTAS/FMS)

The integration of on-board Flight Management Systems (FMS) with the Center-TRACON Automation System (CTAS) is being conducted as part of the Air Traffic Management (ATM) sub-element of TAP. The (CTAS/FMS) Flight Management System/Center TRACON Automation System integration effort proposes coordination of ground-based automation tools (i.e., CTAS) with the aircraft FMS to increase safety, efficiency, and capacity in and around the terminal airspace. To accomplish these goals, ATC may use CTAS tools with scheduling algorithms to control arriving aircraft.

The controller CTAS tools (shown in Figure 1) include: Descent Advisor (DA) which provides conflict free, fuel efficient descent information, Traffic Management Advisor (TMA) which plans sequence and landing times, and a Final Approach Spacing Tool (FAST) used to advise on accurate spacing on final approach. Flight deck modifications will include adjustable FMS leg types that will support simple FMS route adjustments (e.g., downwind leg length) in the TRACON airspace. While it is presently undecided, future implementations may also include the addition of a datalink display and response buttons that will support automatic loading of, and heads-up assessment and response to, uplinked CTAS routes.

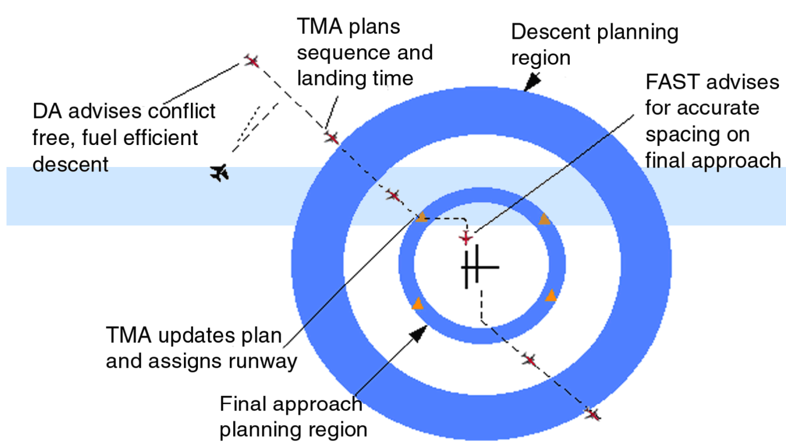


Figure 1. CTAS/FMS Integration.

Airborne Information for Lateral Spacing (AILS)

Airborne Information for Lateral Spacing (AILS), a Reduced Spacing Operations (RSO) sub-element of the TAP program, will apply on-board precision navigation and communications technology in conjunction with onboard safety surveillance systems [i.e., Traffic Alert and Collision Avoidance System (TCAS)] to permit safer, reduced runway separation requirements for Closely Spaced Parallel Approaches (CSPAs). At airports with parallel runways spaced less than 4,300 feet apart, CSPAs may only be conducted in Visual Meteorological Conditions (VMC), when both pilots can see the runway and the other aircraft. In IMC, airport capacity is significantly reduced - only one runway may be used, or the two runways may be used with aircraft spacing equivalent to the spacing used for a single runway. The purpose of the AILS system is to maintain aircraft separation during closely spaced parallel approaches of less than 4,300 ft separation in IMC. Traffic advisories and resolution advisories (similar to TCAS) are provided to the flight crew to alert them of an encroaching aircraft.

Both pilots primary flight display (PFD) will be modified to display the following: a parallel traffic window which indicates the location (left or right) of the traffic; a slant range indicator, which shows the distance (in hundreds of ft) between the ownship and the traffic; and a horizontal motion arrow, which indicates that traffic is moving away from its centerline and toward the ownship. A traffic advisory accompanied by an aural alert is issued if parallel traffic executes a blunder that results in an intercept course. If the alerting system determines that a maneuver is necessary to maintain separation, a resolution advisory is issued and pitch & turn guidance cues and go-to bars appear on the PFD (see Figure 2, left).

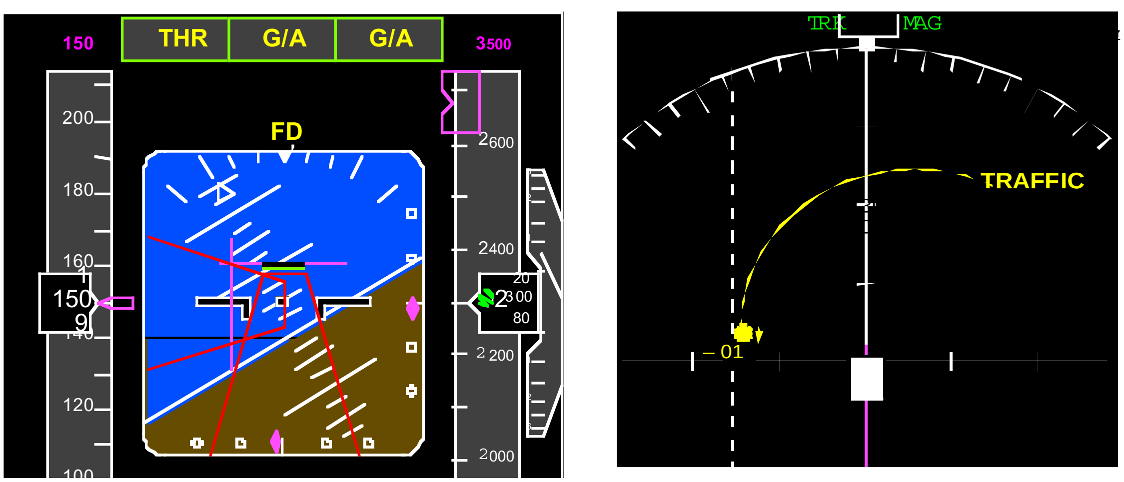


Figure 2. Primary Flight Display (with AILS Resolution Advisory, left), AILS Navigation Display enhancements, right)

AILS also includes modifications to both pilots navigation display (ND) including: a parallel runway and centerline cue, which indicates the location of the parallel runway and intended path for the other aircraft; and a traffic trend vector which indicates what direction the traffic is heading (see Figure 2, right).

Roll Out and Turn Off (ROTO)

Roll Out and Turn Off (ROTO) is a component of the Low Visibility Landing and Surface Operations (LVLASO) sub-element of the TAP program. ROTO is being developed to reduce the amount of time an aircraft needs to spend on the runway after landing. ROTO will assist the pilot to quickly and safely exit the runway by providing visual guidance, braking and turn advisories to the Captain via a head-up display (HUD).

While airborne the pilot can set ROTO to either automatic or manual exit selection. In the automatic mode, ROTO will select the first safe runway exit, while the manual mode allows pilots to manually select a desired runway exit. The selected exit appears in the upper right hand corner of the HUD (See Figure 3, left). At touch down, ROTO ground symbology appears (See Figure 3, right) which provides current and predicted speed information.

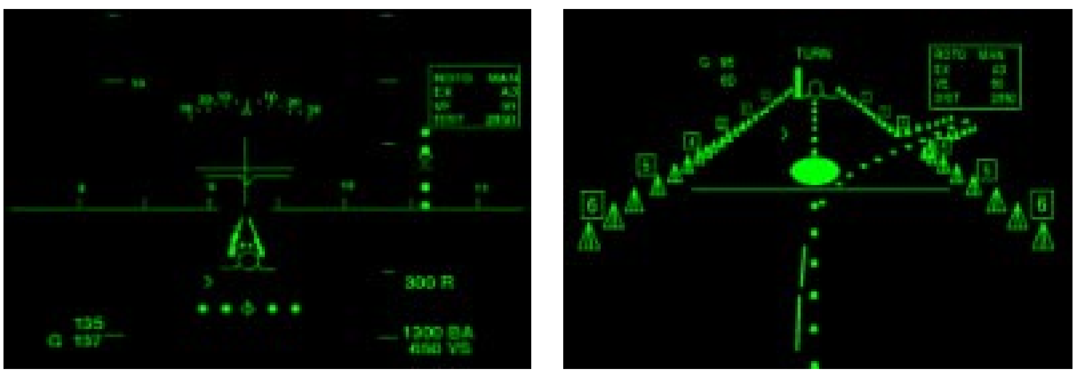


Figure 3. ROTO Airborne Symbology (left) and Ground Symbology (right).

A ground speed error bar (on the left wing of the aircraft symbol) indicates whether the deceleration rate is too high or too low for the selected turn off. As pilots approach the turn-off, guidance is provided to indicate when the pilot should begin the turn. Two 2-second trend vectors provide information to aid pilots in positioning the aircraft on the exit centerline during the turnoff from the runway. If while in automatic mode, the pilot cannot decelerate safely to make the selected exit, ROTO will automatically switch to the next turn off.

Taxiway — Navigation and Situation Awareness (T-NASA)

Also under the LVLASO sub-element, the Taxiway Navigation and Situation Awareness (T-NASA) system is being designed to improve the efficiency of taxiway operations in IMC and at night. The T-NASA system is comprised of a perspective, head-down display taxi map, a HUD with scene-linked symbology, and a Directional Audio Ground Collision and Warning

System (GCAW). All components are designed to increase taxi speed, route navigation accuracy, and situational awareness in low visibility conditions. It is expected that near term implementation of T-NASA will augment, but not replace, current day Ground Control operations. However, future implementations are also being considered that may place a greater emphasis on datalink communications over voice communications.

The T-NASA Taxi Map can operate in two modes: perspective and overview. In the perspective mode, a view of the airport from above and behind the ownship (see Figure 4, left) is presented. The taxi map presents the cleared taxi route via a magenta path. Hold short instructions, ground speed, compass heading, and cardinal direction bars are also presented with four levels that show progressively greater levels of detail. In the overview mode, a fixed view of the entire airport surface, runway and concourse locations, is presented much like a paper taxi chart (see Figure 4, right). This may be best used for airborne preview, or on the ground to aid in planning a route before taxiing.

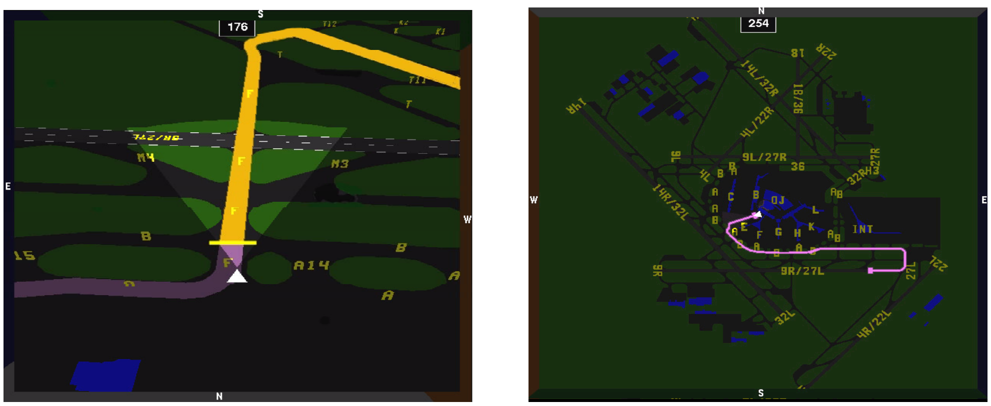


Figure 4. Taxi Map Perspective Mode (left) and Overhead Mode (right).

The T-NASA Taxi HUD displays the cleared taxi route in the form of a series of virtual "cones" located along both edges of the cleared taxiway and a series of small squares that overlay the taxiway centerline (see Figure 5, left). The taxiway that the aircraft is currently on, as well as the taxiways that are coming up on the right and left, are presented in text form as is ground speed. The taxi HUD also provides turn angle and hold bar information.

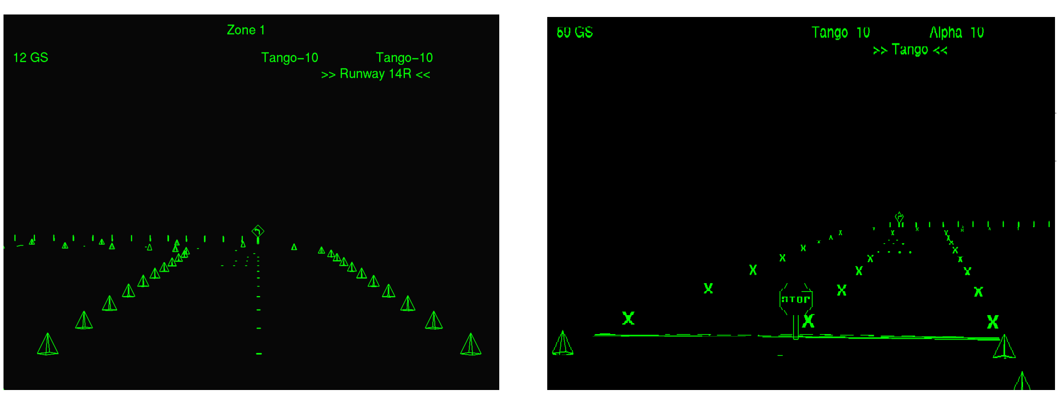


Figure 5. T-NASA Taxi HUD and T-NASA Taxi HUD Hold Short graphics.

T-NASA directional audio GCAW sounds when the aircraft is in danger of collision with another aircraft or vehicle on the airport surface. If the collision is coming from the right, the auditory alert will be presented through the right earphone or speaker whereas collisions from the left are alerted via the left earphone or speaker. This directional auditory alert system helps pilots identify the location of the problem faster.

Selection of Aircraft for Examination

The introduction of the TAP system and displays into use will necessarily be accomplished by retrofitting existing aircraft. Since this is a preliminary feasibility study of limited scope, every type of transport aircraft in use could not be examined. The first step toward determining the feasibility of retrofitting the TAP system and displays was to identify a set of aircraft that would meet several criteria. The first criterion is that the aircraft type exists in substantial numbers and is expected to continue to be an important segment of U.S. air carrier operations for at least the next ten years. The second criterion is that the types of aircraft represent the major types of operations, i.e., long range, regional, and commuter and operate out of a variety of airports. Highly correlated with this criterion is the size of the aircraft. The third criterion is that the aircraft cockpit instrumentation technology spans the range of old, or classic electro-mechanical, instruments to the newer Electronic Flight Instrument Systems (EFIS), including the most recent full glass cockpit EFIS that incorporates six, large, multi-function, color displays.

Population of US Air Carrier Aircraft

Considering the various aircraft types used in U.S. commercial air carrier fleets, the likely population (and types) of aircraft that would be potential users of TAP program technologies (commencing at Year 2000) were identified.

The 1997 fleet sizes (most recent available data) were analyzed to determine the baseline distribution of number and types of aircraft. The results are shown in tables 1 and 2.

Table 1. Number of Air Carriers and Aircraft by Type of Operation at FAA Controlled Airports

Aircraft Type Using FAA Controlled Airports	Number of Air Carriers	Number of Aircraft
Passenger with limited freight*	20	4,462
Regional Airline Affiliates	26	1,383
All-Cargo*	21	943
Total	67	6,788

* Includes foreign air carriers using U.S. airports.

Table 2. Aircraft Types, Models, EFIS Characteristics and Number in Fleet

Aircraft Type	Models	EFIS Characteristics	Number
Commuter (small cockpit)	Embraer EMB-120	Partial	223
	Saab S340	Partial	245
Regional (narrow body)	Boeing B737-300/400/500	Partial	752
	McDonnell Douglas MD-80 Series	Partial	636
Medium and Long Range (glass cockpit)	Boeing B747-400	Full	41
	Boeing B757 Series	Full	497
	Boeing B767 Series	Full	242
	Boeing B777 Series	Full	30
	McDonnell Douglas MD-11	Full	54
Long Range (classics)	Boeing B747-100/200/300	None	173
	Lockheed L1011	None	115
	McDonnell Douglas DC-10 30/40	None	174

It should be noted that although initially the study was to concentrate on U.S. manufactured aircraft, the overwhelming number of foreign built commuter aircraft in use in U.S. airspace became a major consideration.

Further, due to the diversity of the potential uses of the various facets of TAP technology it was virtually impossible to determine whether TAP or parts thereof, were all cost effective for commuter, short range or long range operational application. However, it was noted that the commuter and short range categories are vital to an air carrier s hub and spoke operations.

It was further noted that there is a strong industry tendency to convert the classics to full freight operation to meet the increasing Global economic needs, and therefore this type of aircraft has to be considered for TAP operations.

After substantial qualitative deliberations, it was decided that the selection of aircraft types (for the study of retrofit of TAP data displays into commercial aircraft cockpits through the Year 2010) had to be based on the expected cost savings of TAP to the air carriers operating at airports having a significant number of days with low visibility weather conditions. Obviously, this was achieved using a good deal of subjective judgement.

Choice of Aircraft

Three groups of aircraft types were considered for examination and five specific aircraft were examined. The aircraft types of primary concern are those that are most likely to be frequent users of air carrier hub airports. Therefore, a group of aircraft types was defined on the basis of high fleet counts. The aircraft types within this group are the following:

Commuter	Embraer EMB-120
Medium range regional	McDonnell Douglas MD-80 series
Longer range regional	Boeing B737-300/400/500

A second group of aircraft types was defined to include long range aircraft with full glass cockpits. Although these have a lower frequency of arriving and departing from regional hubs or even major international connecting airports, the cost impact of their delays on any air carrier s overall system reaches astronomical levels. Aircraft within this group include the B747-400, B757, B767, B777, and the MD-11.

A third group of aircraft types was defined as the classic aircraft. The population of this group are primarily B747-200/300s. Many of these are being converted to freighters, for which the commercial cost of not delivering freight on time is very high. It is these aircraft that are fitted with the old electro-mechanical primary instruments. These aircraft are a major retrofit challenge for TAP digital data technology.

Having defined the groups of aircraft types to consider, five specific aircraft were chosen for examination. The five aircraft are:

1. Embraer EMB-120
2. McDonnell Douglas MD-87
3. Boeing B737-400
4. Boeing B747-400
5. Boeing B747-200F

The following paragraphs present the reasons for selecting these five specific aircraft models to examine.

EMB-120

The EMB-120 is the most heavily utilized, reliable and populated commuter aircraft in the major airline inventories. According to the commuter pilot community it is a highly popular aircraft to operate. The aircraft allows for installation of an Electronic Horizontal Situation Indicator (EHSI) display and this option is commonly ordered. Embraer (in Brazil) has reopened the standard EMB-120 production line in response to continuing orders, in spite of the availability of the EMB-145/135 jet.

MD-80 SERIES

The MD-80 series aircraft are high usage, medium range, narrow-body airplanes with relatively low operating costs. They are used by the major airlines as hub feeders, and are being sought after by second tier reduced fare airlines for extended service. Furthermore, the later models optionally include an Electronic Attitude Director Indicator (EADI) and an Electronic Horizontal Situation Indicator (EHSI). The MD-87 was selected to represent this group because of its availability for examination.

Boeing B737-300/400/500

The generic B737 aircraft is a workhorse of the longer range regional services and is also popular as a short range shuttle aircraft which supports hub and spoke operations. In terms of total regional aircraft availability, it is the most popular aircraft in production. The B737-300/400/500 series versions all provide for installation of an EADI and an EHSI. However, many are still being purchased with electro-mechanical attitude and guidance instruments. Some B737s have been modified to include a HUD. The next generation of B737s will have a full glass cockpit. The B737-400 was selected to represent this group because of its availability for examination.

B747-400, B757, B767, B777, MD-11

The B747-400, with a full-up glass cockpit comprising six 8 x 8 multi-function color displays, is representative of the primary and secondary instrument/display technology present in the B757, B767, B777, and MD-11 families of aircraft. TAP retrofit issues for the B747-400 will be similar to those for these other aircraft. Therefore, the B747-400 was selected to represent this aircraft group.

B747-100/200/300, L-1011, DC-10 30/40

The B747-200/300 classic aircraft are representative of a family of valuable aircraft that have been depreciated to zero several times by their various owners, and for which the life is being maintained and extended to an indeterminate date. The B747-100 series are being retired to third world air carriers, whereas the B747-200 series is being sought by the air cargo industry for conversion to full freighters. On the other hand, the smaller fleet of 747-300s with the extended upper deck and long range endurance is being sought by cost conscious non-scheduled, long range, passenger, and charter operators. Modification of the existing analog displays to EADI & EHSI is already in progress by several second tier air carriers. They have commenced aggressive modernization programs to ensure that the aircraft can use the same airspace with identical navigation accuracy as their full glass cockpit equivalents. Therefore this type of modernization encompasses provision for some, if not all of the TAP requirements. The L-1011 and DC-10 aircraft were also considered, but the B747-200 was selected to represent this group.

Aircraft Items to be Examined for TAP System Compatibility

Implementation of TAP functionality requires certain external and internal data sources, computational resources, symbol generation capability, controls to interact with the systems, and display devices to present the information. In addition to the TAP specific software, a great deal of new software is likely to be required for integration of TAP functionality into existing aircraft systems. This task focuses on identifying the elements of aircraft hardware and software that are to be considered in the examination for TAP system compatibility.

In general the technical engineering challenge in integrating TAP into existing aircraft is a more complex matter than might be recognized. This is in spite of the fact that the changes are seemingly simple. They primarily involve a change in data flow for the panel mounted displays, the addition of a HUD, and the potential upgrading of various aircraft sensors for each aircraft type (to provide the data accuracy and resolution required for the display of TAP information). The issue is more complex as a result of integration with an existing system, which typically already has many interconnections for functional performance as well as for internal monitoring.

However, beyond the purely engineering considerations is the issue of certification of the modified aircraft. The certification cost for the new TAP capabilities must include not only the direct costs for verification and validation of new hardware and software, but must also include the cost of re-verification of all previously existing software that could be affected by the addition of the TAP system. This is typically a larger undertaking than one imagines, because it requires verification that none of the existing functionality, integrity and availability has been adversely affected. Verification includes both analysis and testing.

The broad objectives to be accomplished during the aircraft examinations are the following:

1. Determine what existing equipment must be moved or displaced to allow installation of TAP equipment. The scope includes but is not limited to displays, processors, sensors, and connectors.
2. Determine if existing symbol generation and display capability (primarily capacity) is adequate where existing avionics equipment, hardware and software has to be adapted for use with the TAP system and displays. Where existing capacity is inadequate, identify required upgrades or enhancements.
3. Determine adequacy of available processing capability and memory needed to support the TAP system and displays, and identify shortfalls.
4. Determine if sufficient data transfer for TAP display information is available. Where existing capability is inadequate, identify required upgrades or enhancements.
5. Determine software modifications necessary to support TAP display operation. Identify the scope of changes required, including estimating the effort or costs required for: a) modifications to the code; b) documentation of changes; and c) the re-certification process.

Scope of Aircraft Examinations for TAP System Compatibility

A checklist for aircraft examinations is given in Table 3.

Table 3. Aircraft Checklist for TAP Systems Compatibility

A. BASELINE OEM INSTALLATION	C. SUBSEQUENT RETROFIT INSTALLATION BY AIRLINE(S)
With mechanical ADI/ HSI	Head Up display
With EFIS EADI/EHSI	Center Panel electronic display
With FMS & Nav data base	GPS Sensor
With Inertial Reference System	GPS with DGPS provision
With modern AHRS	GPS based FMS
With ancient VG/DG	ACARs data link
With all analog interfaces	CPDLS data link provision
With part digital/analog interfaces	S Band data link provision
With all ARINC 429 interfaces	
With AFCS CAT II	
With AFCS CAT IIIA	
With AFCS CAT IIIB	
B. SENSOR PARAMETERS	**D. INSTALLATION & REGULATORY COMPLEXITY**
Pitch/Roll/Heading angles	Mechanical installation
Pitch/Roll/Heading angular rates	Electrical installation
Radio altitude	U.S. approval
X Y Z velocities	European JAA approval
Localiser/Glide Slope deviations	Need for additional head down display
Heading/Track/Drift Angles	

Aircraft Examinations

During July 1998, JC&A and FD engineers, highly experienced in flight deck design and avionics systems, examined the aircraft listed in Table 4.

Table 4. Aircraft Models Inspected, Operators, and Inspection Location

Model of Aircraft	Operator	Location of Inspection
EMB-120	Skywest	San Luis Obispo, CA.
MD-87	Alaska Airlines	Portland, OR
B737-400	Alaska Airlines	Portland, OR
B747-400	Cathay Pacific Airways	Hong Kong
B747-200F	Cathay Pacific Airways	Hong Kong

Note: Both models of B747 were inspected during other project activities with Cathay Pacific Airways.

In each of the five inspections, airline management people were present to answer questions and generally operate specific aircraft systems.

For each specific aircraft inspected, a series of photos of the cockpit were taken which included the general arrangement of instruments and overhead panels. It should be noted that the Alaska B737-400 cockpit included a Flight Dynamics HUD installation. Selected photographs of the cockpits are shown in Appendices B through F.

In studying the photos, the reader should consider the following important existing cockpit physical conditions that are major installation considerations for the introduction of TAP technology.

EMB-120 (Skywest configuration)

The following characteristics were noted for the EMB-120 (see Appendix B):

- It has a small, but well laid out cockpit.
- Both the left side & right side instrument panels are fitted with a limited area EHSI that is also used to display various types of navigation data as well as TCAS information.
- There is a centrally located weather radar display that is readily viewable by both pilots.
- There is no FMS installed.
- The cockpit roof area above the left side pilot s head, which would normally be used to mount the HUD projector and combiner plate when stowed, is obstructed by the overhead control and circuit breaker panel.

MD-87 (Alaska Airlines configuration)

The following characteristics were noted for the MD-87 (see Appendix C):

- It has a small cockpit with provision for dual FMS CDUs (control display unit) in the forward center pedestal.
- Both the left side & right side instrument panels are fitted with EADI and EHSI.
- Navigation data, weather radar map and TCAS information can be displayed on the electronic display unit (EDU), which is typically a CRT.
- The center part of the yoke tends to obscure the EHSI display in normal flight.
- The engine operating data is displayed on a centrally located LCD flat panel display.
- The cockpit roof area above the left side pilot s head, which would normally be used to mount the HUD projector and combiner plate when stowed, is obstructed by the overhead control panel, cockpit speaker and air outlet. The use of the left side upper eyebrow window would also be obstructed by the HUD installation.

B737-400 (Alaska Airlines configuration)

The following characteristics were noted for the B737-400 (see Appendix D):

- It has a somewhat spacious, well laid out cockpit with provision for dual FMS CDUs in the forward center pedestal.
- Both the left side & right side instrument panels are fitted with EADIs & EHSIs.
- Navigation data, weather radar, map and TCAS information can be displayed on the EDUs.
- The engine operating data is displayed on a centrally located LCD flat panel display.
- The HUD installation can be made in the left side cockpit roof without any alteration to the overhead control panel.

B747-400 (Cathay Pacific Airways configuration)

The following characteristics were noted for the B747-400 (see Appendix E):

- It has a spacious clean cockpit with five multifunction display units side-by-side with a sixth unit located beneath the center display. Two CDUs are located forward on each side of the center pedestal.
- The display complex is designed with extensive redundant switching in the event of the failure of one or more displays of attitude, heading navigation, weather radar, TCAS, electronic map and data message information.
- The cockpit roof area for HUD mounting is considered adequate. Physical alignment of the HUD projector with the pilot s line of sight needs further investigation.

B747-200(F) (Cathay Pacific Airways configuration)

The following characteristics were noted for the B747-200 (see Appendix F):

- It has a spacious well laid out cockpit, but the head room (with pilots in their normal flight operating position) is limited due to the outside shape constraints of the aircraft structure.
- Electro-mechanical ADIs and HSIs are standard configurations.
- Weather radar displays are located at the outer cockpit sidewalls at approximately knee level.
- There are provisions for dual FMS CDUs in the forward center pedestal.
- Although the engine operating instruments are normally electro-mechanical, on an increasing number of B747-200s the complete engine instrument panel is replaced by a split screen LCD flat panel display.

- The cockpit roof area for HUD mounting is considered adequate. Physical alignment of the HUD projector with the specified pilot s line of sight, needs further investigation.

Analysis of Results and Implications for TAP Systems Retrofitting

It can be assumed that the physical cockpit configurations of the five aircraft inspected are representative of their respective models. A summary of the characteristics of each aircraft relevant to TAP systems retrofitting is given in Table 5.

An assessment of the implications of the characteristics of each aircraft type for retrofitting the TAP systems is summarized in the nine by five matrix in Table 6. The five columns are the aircraft types and the nine rows are the nine principal issues in retrofitting TAP systems.

Table 5. Summary of Aircraft Characteristics Relevant to TAP Retrofit Sheet 1 of 2

Aircraft Model	EMB-120	MD-87	B737-400	B747-400	B747-200(F)	Notes
Displays **HUD Installation**	None but limited space available for custom installation	None but limited space available for custom installation	Certified installation to CAT 3A landings.	None but limited space available for custom installation	None but limited space available for custom installation	2
Primary Attitude Display	4_ x 4_ Electro-mechanical ADI display with command bars & raw ILS & Rad Alt Indicators	4_ x 4_ EADI	5_ x 4_ EADI	8 x 8 EADI	5 x 5 Electro-mechanical ADI display with command bars & raw ILS & Rad Alt Indicators	1 & 2
Primary Nav Display	4_ x 4_ EHSI	4 x 5 EHSI	5_ x 6_ EHSI with limited horizontal map features	8 x 8 EHSI with extensive horizontal map features	5 x 5 Electro-mechanical HSI display	1 & 2
Center Panel Display	7 W x 5 H color radar display	Dual section 5 x 8 + 3 x 8 LCD engines & system monitor display	8 x 8_ LCD engines & system monitor display	8 x 8 engines & system monitor display	8 x 9 mechanical engine instrument display (can be updated to LCD display)	2
Interface Avionics	Hybrid analog/digital	Hybrid analog/digital	Digital	Digital	Analog	
Flight Management System	None	None	Dual MCDU	Triple MCDU	None	

Table 5. Summary of Aircraft Characteristics Relevant to TAP Retrofit Sheet 2 of 2.

Aircraft Model	EMB-120	MD-87	B737-400	B747-400	B747-200(F)	Notes
Interface Sensor Types **Attitude**	Analog	Digital	Digital	Digital	Analog	
Heading	Analog	Digital	Digital	Digital	Analog	
Air Data	Digital	Digital	Digital	Digital	Analog	
Radio Alt	Digital	Digital	Digital and Analog	Digital	Analog	
Communications	Dual VHF	Dual VHF	Dual VHF	Triple VHF	Triple VHF	
Landing Category	2 Auto-pilot	3A Auto-pilot	3A HUD & Auto-pilot	3B Auto-pilot	2 Auto-pilot	

Notes:

1. With the exception of the B747-400 (and similar 757, 767, 777) attitude/direction and navigation displays, all other aircraft types are considered too limited to add additional information on top of existing display contents.
2. See photographs in Appendices B-F.

Table 6 TAP Retrofit Issues by Aircraft Type

Issue or Observation	EMB-120	MD-80 (82,83,87,88)	B-737 (300,400,500)	B-747-400 (757, 767, 777)	B-747 classic (100,200,300)
HUD overhead (OH) operating volume available	limited with overhead projector	Limited with overhead projector	OH projector already installed	limited due to OH panels — but757/767 ok due to likeness to B737-300	OH designs exist none installed -
HUD avionics interface with aircraft for normal flight ops	requires upgraded AHRS	MD-82/83/85 require AHRS MD-87/88 ok	IRS installed - OK	IRS installed - OK	IRS installed - OK
Existing display capability for T-NASA electronic map	7" x 5" center mounted radar display	Maybe with radar -82/83 4"x5" EHSI 87/88	5"x5" EHSI	Qty 2, 8"x8" centrally located	none
Proposed display capability for electronic map	as above. requires independent TAP data computing source with specialized symbol requirements compatible with Wx radar symbol generation.	use 7"h x 4"w existing engine flat panel display in center panel requires independent TAP data computing source with specialized symbols for engine symbol generation	use 7"hx4"w existing engine flat panel display in center panel requires independent TAP data computing source with specialized symbols for engine symbol generation	use either centrally located8"x8" displays with TAP data computing source with specialized symbols compatible with central display symbol generator	remove existing engine boiler gauge panel and replace with B&D Instruments flat panel engine displays with TAP data computing source with specialized symbols compatible with B&D panel
Interfacing HUD with AILS, ROTO, T-NASA and ATC Controller-pilot datalink For TAP operations	requires independent TAP computing source with specialized symbols compatible with HUD symbol set	Requires independent TAP computing source with specialized symbols compatible with HUD symbol set	requires independent TAP computing source with specialized symbols compatible with HUD symbol set	requires independent TAP computing source with specialized symbols compatible with HUD symbol set	requires independent TAP computing source with specialized symbols compatible with HUD symbol set
Compatibility of separate TAP computer with center Display and HUD	100% controllable by industry	100% controllable by industry	100% controllable by industry	100% controllable by industry	100% controllable by industry
Existing avionics system additional hardware	interface module between TAP computer and Wx radar	Interface module required-will need new color capable flat panel display	interface module required-will need new color capable flat panel display	interface module required will need new color capable flat panel display	interface module required will need new color capable flat panel display
Existing avionics unit software changes	non-critical certification-manufacturer dependent-significant software alteration	critical certification - manufacturer dependent - significant software alteration	critical certification - manufacturer dependent - significant software alteration	non-critical certification-manufacturer dependent-significant software alteration	critical certification - manufacturer dependent - significant software alteration
Certification tasks beyond HUD physical installation and operational approval	None	re-certify critical engine indications	re-certify critical engine indications	None	re-certify critical engine indications

Retrofitting of all Types of Aircraft is Potentially Feasible

An important, general conclusion is that the TAP systems and displays, both head-up and panel mounted, could be retrofitted into of all five types of aircraft examined. A first take on the retrofit problem is that each aircraft type will require significant, unique changes and additions to accommodate the TAP systems. The work will involve physical installation, requiring, in some cases, movement of existing equipment, software additions and modifications, and re-certification of the software. However, the work and costs will vary with type of aircraft. Retrofitting the long range, classic type aircraft would be the most expensive because of hardware and software additions required. Since there is no underlying software system, all costs for installation and certification would be based on new equipment.

Retrofitting the newest, glass-cockpit type aircraft, e.g., B737-400/800, B767, B747-400, B777, etc. would likely be the next most expensive. The equipment installation costs would be relatively small but the certification, or rather, the re-certification of affected software, would be very expensive, even if amortized over a number of aircraft. A recognized major cost of adding new equipment such as a HUD to an aircraft is the process of gaining the airworthiness & operational certification. However, a cost that is often overlooked is the effort required to re-certify the changes to existing hardware and software necessitated by the introduction of the new technology. For the most modern glass cockpits, the original software used for the EFIS instruments and displays is complex and critical.

TAP Retrofitting Issues

The main TAP retrofit issues are 1) fitting a HUD; 2) provide a panel display; and 3) provide for the TAP avionics including the necessary data inputs, computational capability and symbol generation required by all the TAP systems.

<u>HUD</u>

The HUD is a common requirement for at least the AILS, ROTO & T-NASA functions. Based on the information in Table 6, the HUD physical installation must necessarily be unique for each cockpit type. However the main difficulty in HUD physical installation will be for the EMB-120 and MD-80. Also, only the EMB-120 and early MD-80s require an upgrade to their attitude and heading reference system (AHRS).

<u>Panel Mounted Display</u>

A reasonable assumption is that at least a 6 x 6 panel display is the minimum size required for the T-NASA map display. Except for the 747-400 and aircraft with similar glass cockpits the displays are all smaller in at least one dimension. The EMB-120, MD-87 and B747-200 have, or can have, a flat panel display between 4.5 x 4.5 and 5.0 x 5.0 . It is questionable if these displays are large enough for a useful T-NASA map display. Alternatively, the panel mounted display requirement can be met by the EMB-120 7 x 5 radar display. An MD-80 radar display may also serve for the T-NASA map in this aircraft. The largest display in the 737-300, 400, 500 is the 5.75 x 4.5 EADI. For the older aircraft, replacing the electro-mechanical engine instruments with a 4 wide x 7 high display may provide a large enough display for the T-NASA electronic map.

An alternative is to add a new panel-mounted display. A flat panel 6 x 6 color LCD display can be installed in the center instrument panel on at least four of the aircraft types (EMB-120, MD-80 series, B737-300/400/500 and B747 classic). Note that the B747-400, B757, B767, B777 already have glass displays in the center instrument panel location whereas an LCD flat display panel of the same type has already been installed on several B747-classic aircraft. Obviously an intelligent, software-controlled sharing of the display for TAP data and engine data is a prerequisite for this arrangement.

<u>TAP Avionics</u>

In all five types of aircraft, additional computing and symbol generation capabilities are required. This is expected since this is the heart of the TAP systems and they are unique relative to current information displayed in the cockpits. A TAP common avionics unit can be specified to suit the various aircraft configurations for the TAP CTAS, AILS, ROTO & T-NASA systems as well as the various operating modes. The avionics unit can have a common but partitioned software program for CTAS, AILS, ROTO and T-NASA with standard interfaces to the HUD and the T-NASA display controller. This would also provide for the flexibility of selection or deletion of the various TAP features considered necessary for air carrier operators to suit their individual operational needs.

Alternative to Individual Retrofitting by Aircraft Type

At the outset of this study it was expected that finding a substantially common, one-size fits all for TAP system retrofitting would be impractical and costly relative to integration schemes specific to each aircraft type. However, as the analysis of the requirements for each aircraft type proceeded, it became evident that the collective costs would be great for individual initial type certification of the new hardware and software and for re-certification of the affected, existing hardware and software. Any practical approach must necessarily focus on reducing the multitude of differences (summarized in Tables 5 and 6) that must be addressed individually to retrofit the TAP systems. Consequently, the possibility of implementing the TAP systems as a stand-alone, add-on unit appears to be the more attractive option.

As a largely independent unit, the TAP software would have minimal interaction with the existing aircraft software. Being aircraft-independent, the TAP systems would require only one major certification cycle and preclude costly initial certifications for a multiplicity of aircraft types. This design approach would also reduce the otherwise considerable re-certification costs.

The proposal of a common TAP installation architecture for multiple types of aircraft is predicated on well established commercial air carrier industry practice to accommodate the introduction new avionics technologies. In practice, an authoritative body, e.g., the Airlines Electronic Engineering Committee (AEEC) will specify common installation conceptual guidelines applicable to a variety of aircraft types and model configurations.

Tap Installation Considerations

The following proceeds on the assumption that a common TAP architecture will be the most acceptable and cost effective way of introducing and retrofitting the various (but selectable) TAP features for U.S. commercial air carriers. Figure 6 is a diagrammatic representation of a concept for a common TAP installation architecture.

There are four generic topics that have to be considered in the development of the common installation specification for the TAP systems.

1. Installation of production HUDs in various cockpits
2. Development of the TAP common processor units and display
3. Installation of the TAP common processor and display
4. Hardware and software regulatory certification of the avionics units and the TAP installation

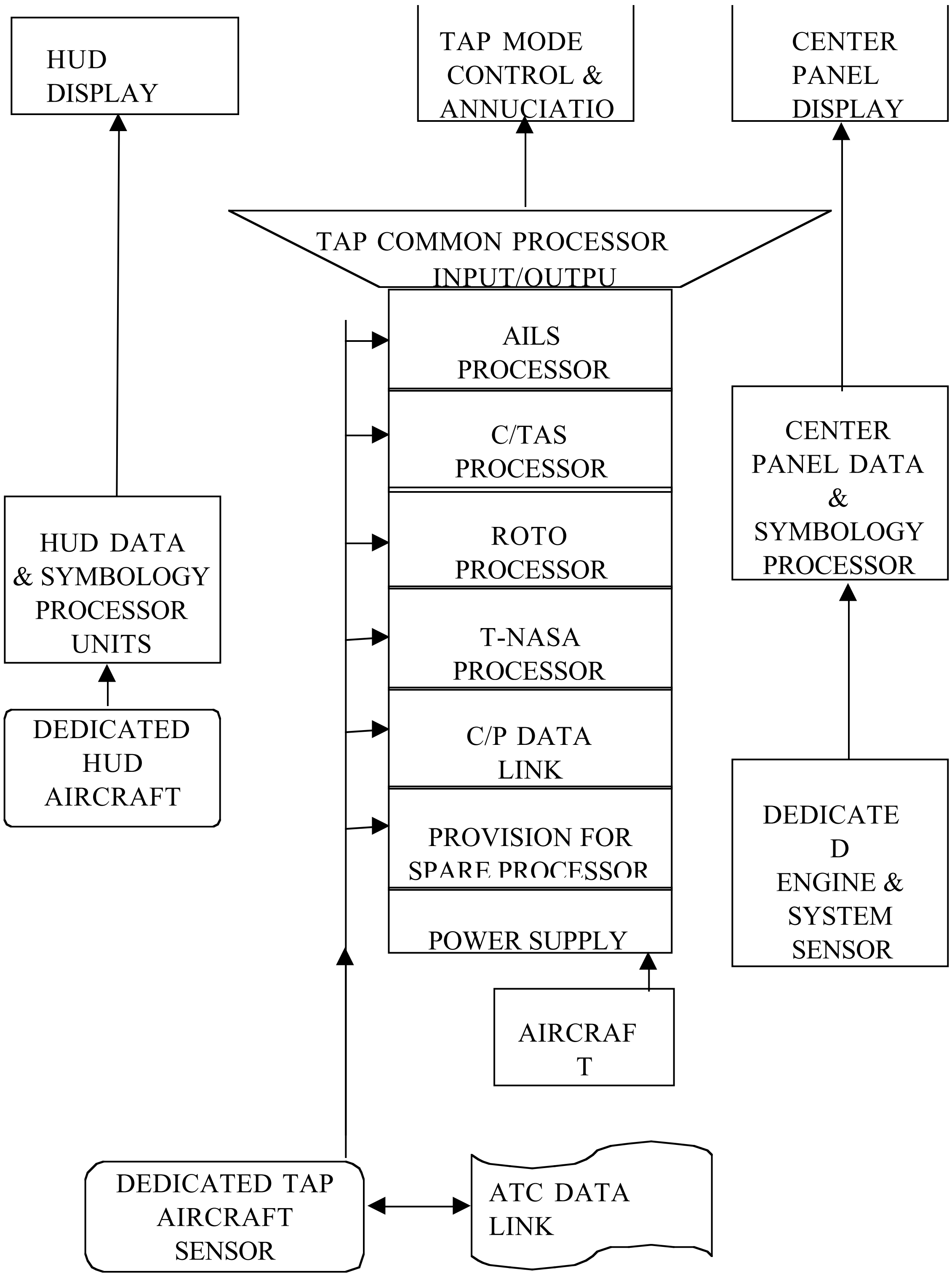


Figure 6. Schematic of architecture for common TAP processor and

Installation of Production Head Up Displays

HUD s are a generic part of most military tactical aircraft, but have only recently been adopted in significant numbers by air carriers. The principal advantage of a HUD on a civil transport aircraft is the ability to take-off and land under lower visibility conditions than permitted with conventional instruments. For example, to take off without a HUD the Runway Visual Range (RVR) must be at least 700 ft, but with a HUD it can be as low as 300 ft. (Note that there are no autopilot take-offs.) Low visibility approaches and landings can be achieved in a variety of ways. The least sophisticated alternative is a manually flown approach using head-down instruments. Other alternatives (with increasing levels of control sophistication) are a coupled autopilot approach, a manually flown approach using a HUD (with guidance), and an approach using an autoland . Approved weather minima are different for each of these control alternatives. The weather minima for transport aircraft are defined in terms of Categories of approach, which are themselves defined in terms of a minimum Decision Height (DH) and a minimum RVR. These Categories are defined below, along with the current minimum approved control means for each Category.

<u>Category 1:</u>
DH at least 200 ft, and RVR at least 2400 ft (1800 ft with certain airport lighting)
(can be flown manually without guidance, using HUD or head down displays)
<u>Category 2:</u>
DH below 200 ft (but not less than 100 ft), and RVR at least 1200 ft
(if flown manually must use flight director guidance on HUD or head down display)
<u>Category 3a:</u>
DH below 100 ft (typically 50 ft) and/or RVR below 1200 ft (but not less than 700 ft)
(if flown manually must use flight director guidance on a HUD)
<u>Category 3b:</u>
no DH (or DH below 50 ft) and/or RVR less than 700 ft (but not less than 150 ft)
(must use a fail-operational autopilot, or a HUD with guidance)

It is also becoming accepted that HUDs help maintain situational awareness. For the TAP application, symbology that is conformal to the outside scene is required for the ROTO and T-NASA systems. However, other systems are being developed that do not have completely conformal displays.

There are several generic requirements for installing a HUD in an aircraft. The physical design requirements are to provide approximately a 24 degree high by 30 degree wide field of view with adequate head clearance and low obscuration, with HUD symbology readable under all lighting conditions. These translate into mechanical and optical design requirements. The requirement for HUD symbology to be conformal with the outside world translates into a need for accurate alignments of overhead projector, combiner (for displaying the projected symbology) and the design eye point. A requirement for the pilot to see the full display

while allowing normal head motions leads to an eye box requirement, which translates into optics design requirements and combiner geometry.
Functionally, each system is custom designed to provide the required parameters for flight control and monitoring from whatever sensor set is available. Additional sensors may have to be installed to support data redundancy and TAP requirements.

HUD installations in commercial aircraft include, among other things, an overhead projector and a combiner. With regard to the installation of an overhead projector the task can be characterized as embedding it in the ceiling. As the aircraft structure in this area is different on every aircraft, the physical design considerations for installing a HUD into a limited overhead volume is unique to each aircraft type. To achieve an acceptable installation, the design must integrate two elements. First the design of the mechanical hardware of the overhead projector (which houses the optical lens array) must allow for adequate pilot head clearance for a wide range of pilot sizes. Second, the relative position, distance, and angles, among the projector, combiner, and design eye point will affect the projector and combiner positioning, and the projector lens and combiner optical designs.

Using an iterative process, a solution can be found for most aircraft types. Problems in achieving an acceptable design for one element can be resolved by design modifications in other elements. However, it should be noted that each installation has to be calibrated to eliminate effects of manufacturing variability.

The mechanical design and installation of a HUD is always a challenging task. However in addition to the physical considerations, the software generating the symbology has to be functionally tuned to the dynamic performance of each aircraft type, and sometimes of each aircraft model within a specific type. This often involves the installation of more accurate digital and occasionally analog sensors than those for which the aircraft type/model was originally certified.

Development of the Tap Common Processor and Display

Avionics and displays that have been functionally characterized by the Airlines Electronics Engineering Committee (AEEC) are competitively manufactured in the U.S. for air carriers. Companies such as Allied Signal, Honeywell, Rockwell Collins and several other companies manufacture to high standards of design integrity and workmanship to meet the exacting FAA certification requirements. Therefore, little needs to be said about the physical or hardware development of a modular avionics TAP Processor Unit. Similarly, nothing more need be said about the airworthiness or operational requirements for the flat panel, color displays to retrofit into the center instrument panel of those aircraft not configured with a full glass cockpit. In both cases, the form, fit and function should be specified under the auspices of the worldwide industry supported AEEC activity.

However, it is the functionality of the TAP Processor Unit, and to a lesser extent, the optical design of the display and its Symbol Generator, which are critical to the success of the TAP program. The following factors are considered central to the development of a TAP compatible Processor Unit.

1. It should be configured as a modular unit to account for the various TAP operational functions. Not all air carriers may want all TAP functions, but would rather choose options. Nevertheless, it will probably be less expensive to develop and certify the TAP processor unit with full functionality.
2. Each module should contain its own software processor to support FAA or NASA controlled standard software compatible with the various TAP program ground elements. This would be similar to the procedure used for the core software program common to all TCAS units.
3. The input/output interface design with the supporting aircraft sensor systems must have enough analog and digital ports to support a large variety of currently retrofitable and new production aircraft avionics systems.
4. The software executive program should be certifiable to a high level of integrity to successfully manage safety related critical data such as that required for the HUD which it will have to handle for some phases of TAP operations.

Similar considerations apply to the retrofitable TAP display and its related symbol generator. In addition, the viewing angle of the display becomes critical when it is intended that it shall be easily seen from both sides of the cockpit under all lighting conditions. This is not easily attainable with current LCD technology. Further, it should be noted that popular, and commercially available, LCD symbol generation and programmable display formats have not been readily accepted by air carriers. This is principally due to the fact that proof of software integrity has not been forthcoming from the software developers of that industry. It should also be realized that there is a growing air carrier safety need beyond the TAP program to display data for other developing aviation awareness technology, which includes:

- Enhanced Ground Proximity Warning System (EGPWS)
- Automatic Dependent Surveillance - Broadcast (ADS-B)
- Instantaneous world wide weather mapping
- Forward looking LIDAR based atmospheric environmental analyses (upper & lower level winds/windshear etc.)
- Enhanced local traffic information
- Controller - Pilot Data Link Communications (CPDLC)

This bodes well for TAP. It is becoming more apparent to air carriers that there are several reasons to install a multi-purpose, multi-mode situational awareness display. When installed, the display would be well suited for presenting TAP information.

Tap Processor Display Manufacturing and Installation Issues

The foregoing discussion asserted the concept of a stand-alone TAP system as the likely means for retrofitting of current aircraft because individually developed systems for each aircraft type would, in the aggregate, be more expensive. Development of this concept was necessary to sensibly discuss the technical and cost issues for installing the TAP systems in a range of aircraft types. However, the purpose of this report is to identify issues arising from the introduction of TAP technology to the U.S. air carrier fleet and not to develop detailed solutions. What has been described as the common TAP Processor/ Display system is only a superficial treatment, and there are numerous issues raised by this concept, which require further analysis. The following are the most immediate and obvious issue questions.

1. Where shall the TAP mode controls be located? The most desirable position for the HUD controls is on the glare shield. If automatic TAP mode switching is proven to be impractical, then consideration should be given to a combined HUD/TAP Control Unit instead of trying to accommodate another control unit in an already overcrowded glare shield.
2. Is it cost prohibitive to modify existing aircraft displays and symbol generators to include the TAP function, in contrast to manufacturing a separate black box to incorporate the functions?
3. As the landing phase of an aircraft is safety critical, especially in low visibility conditions, is it practical to entrust several functions to one black box ?
4. Due to the critical part which the TAP Processor/Display plus its input sensors play in low visibility conditions, a comprehensive self-test system which evaluates not only the TAP elements, but that of its sensors appears to be mandatory. How readily achievable will this be?
5. Will the TAP Processor functions provide any critical software generated landing data to the HUD during the final approach, e.g., from 500 ft AGL through flare to touch down? If not, then the extent of the FAA DO178B software verification and validation (V&V) required could be level C which is at least one order of magnitude lower in cost to the V&V requirements of DO178B, Level A .
6. The TAP Processor/Display can be specified as a stand-alone installation package. However, the overall TAP success is dependent on the presence of other on-board capabilities. These are: a) a dedicated ATC-to-aircraft data link, b) a highly accurate GPS, and c) a navigation database. The maintenance and performance of these latter elements have to be tightly controlled if TAP is going to be effective as an enhanced landing and surface operations aid. Will these additional systems and efforts be forthcoming to support TAP?
7. Will those air carriers interested in utilizing the TAP technology be able to gain enough AEEC member support to commission an AEEC sub-committee activity to characterize the form, fit and function of a TAP Processor and Display? Note that if there is an

AEEC activity on this matter, it will attract a lot of avionics manufacturer competitive attention, which will keep costs down relative to development by a single source.

8. Which type of air carrier aircraft (Commuter, Regional or International long range) is likely to achieve the maximum cost benefits from TAP technology? (This factor has a significant influence on installation costs and return on investment to an air carrier.)
9. Will there be a core TAP software program controlled by the FAA or NASA (analogous to TCAS), which is applicable to all TAP technology aircraft, irrespective of size, utilization and ownership?

Obviously, the foregoing are only the beginning of a plethora of aircraft issues which the design and fielding of a cutting edge technology application like TAP generates.

HUD Interface Issues

A TAP computer would have to support a data link and pilot interface. Among other things, it would transfer taxi clearances (including cleared path, hold points, and current deviation from the path centerline) to a HUD computer. This can be accomplished using a format similar to that currently used for transferring information between an FMS and an EFIS. Integration of a HUD computer into a TAP computer would likely be in later generation equipment. Initial systems would be separate, though cooperative , functioning in separate black boxes.

Airworthiness Certification and Operational Approval

When equipment is added to an aircraft it must be certified for airworthiness and operational use. Certification is one of the most costly elements in the introduction of new equipment aboard an aircraft.

Airworthiness certification is an approval granted by a regulatory organization verifying that the installed equipment or software is safe to fly aboard the aircraft. In the U.S. the process is administered by the FAA Aircraft Certification Service. The approval is normally executed for retrofit installation by adding a Supplemental Type Certificate (STC) to the Aircraft Original Type Certificate (TC). For installations made by manufacturers prior to the delivery of an aircraft, the original Type Certificate is amended to indicate approval of the installation.

Operational approval is administered by the FAA Flight Standards Service and signifies that specific air carrier operational procedures, personnel training and maintenance practices for the specific installed systems are adequate for its intended use. For the TAP system, this would be airport and runway specific.

In spite of the fact that TAP improvement is a mandated overall FAA responsibility, the development of which is contracted to NASA, the responsible organization for the airworthiness approval is the Large Transport Aircraft Directorate located in Renton, Washington. This Directorate controls the activities of two Aircraft Certification Offices (ACOs) located in Los Angeles and Seattle. The Directorate has available to it several but different, aviation-oriented National Resource Specialists who advise on the safety issues of new aviation technologies in the areas of human factors, flight deck design, system development, software engineering and air carrier operations. An important practical step in the TAP installation implementation development would be to bring these groups of FAA personnel in early to help mitigate certification problems before they impact the outcome of the program.

Airworthiness Certification

The process of obtaining HUD airworthiness and operational certification on a first-of-a-kind aircraft has been performed several times and serves as a model for what can be expected for the first-of-a-kind certification of the TAP system on a particular aircraft type. A great deal of development and test will precede the certification process. When certification is sought, the system should be in a stable, final state. The following is a brief summary of typical areas of review by the FAA in the certification process of a full-flight regime/CAT 3 system involving a HUD:

1. Mechanical design of a combiner and overhead projection unit to fit within the constraints of an existing aircraft structure, while providing adequate pilot head clearance for a HUD control panel, and a computer with cards, card slots, etc.
2. Optical design of a lens assembly housed in the overhead projection unit and a combiner in front of the pilot to satisfy optical requirements as well as cockpit structural constraints and pilot head clearance requirements.
3. Electrical design of power supplies, I/O, power and data busses, etc.
4. Flight control design of control laws and flight performance monitors.
5. Symbology design and functional operation to satisfy customer operational needs.
6. System design and analysis to assure safety requirements are met and proven.
7. Documentation of specifications for systems, control laws, etc.
8. Software design to achieve the intended functions and provide monitoring.
9. Software verification and validation to determine that the software does what is expected, and what is expected is what is intended and desired.
10. Environmental testing of hardware to determine its ability to withstand the effects of temperature, vibration, shock, EMI, HIRF, etc. to meet regulatory requirements.
11. Functionality testing to ensure system hardware and software components meet design requirements such as echoing the primary flight display data on the HUD.
12. Documentation of standards applications to prove that the system design has been implemented to rigorous systems standards such as DO-178B for software development protocols.

13. Simulator testing of components to verify overall system operation for evaluating HUD displays and aircraft performance during flight phases that typically includes; take off, climb, cruise, windshear recovery, descent, approach and landing; under environmental conditions that may include windshear, turbulence, TCAS advisories and sensor corruptions.
14. Flight testing of components to fine tune the system and verify performance in the real world.
15. Simulator and Flight Certification tests of overall system in an approved moving base simulator and in an actual aircraft. Typically this involves over 1000 simulator landings under a wide variety of simulated environmental conditions, turbulence being the most critical, and over 100 landings in an actual aircraft under the most adverse wind conditions available. Statistical inferences are made from the simulator touchdown data and are compared with required levels of performance.
16. Documentation of tests performed and results obtained for each type of test.

Operational Certification

If successful, the above review results in an airworthiness certificate. However, before a system can be used in a low visibility environment in actual flight operations, the air carrier needs to satisfy their FAA Principal Operations Inspector that operational approval is warranted (by demonstrating acceptable training activities, successful system usage in good weather conditions, and/or other such means). Only then is an operational approval granted. However, the initial operational approval is commonly granted for relatively high minimums until operating experience justifies lower minimums.

Certification Lessons Learned Applied to TAP

The following are some lessons learned in various certification efforts that are relevant to certification issues for the TAP system.

Certification Planning

There are no specific airworthiness rules that could be reasonably applied to TAP as a whole, or its individual components. Historically, this is not a new situation. At this stage of the TAP development a plan for certification should be developed and coordinated with the FAA National Resource Specialists. A certification plan that is acceptable to the FAA ACO is required early in the certification implementation program.

Transfer of Certified Data

Although a TAP installation may gain an STC on one type & model aircraft (using one set of specific manufacturers sensors), the extent to which the technology is inherent in the installation certification, enables certified data to be transferred to another type of aircraft. The extent to which this can happen needs to be determined with the FAA early in the certification implementation program. This is the certification path that developed with HUD installations.

Manufacturer s Internal Work can Shorten Certification Process

Some avionics manufacturers have their own capability to thoroughly test and evaluate a new system function and evaluate it in their own company aircraft. For these manufacturers the time is relatively short for achieving a first time installation STC for a specific air carrier aircraft type and model. Their internal work substantially reduces much of the system integration laboratory test time and flight test requirements. When avionics vendors without such in-house capabilities defer the system integration laboratory and flight test activities to the STC project aircraft, the test and certification process is greatly lengthened.

Choose Experts Wisely

Much of the advisory and certification routine work for air carriers is performed by consultants who are licensed by the FAA as Designated Engineering or Designated Airworthiness Representatives (DERs & DARs). Selection of such personnel who may not be experienced in the application of new technology, especially in the aspect of specific systems engineering analyses, can be a detriment to the project.

Concerted Effort will be Required to Facilitate Acceptance of TAP

HUD installations initially proved to be exacting and frustrating programs to target for airworthiness certification. The reason for this dilemma was, to some large extent, that aircraft manufacturers and their vendors, who spent millions of dollars in developing automatic landing systems, politically resisted the proof-of-concept. While NASA is classified as an R&D organization, TAP enhancement has to be pushed by the FAA and NASA people in unison to air carrier upper management and their technical operations staff as soon as the TAP proof-of-concept becomes firm, in order to preclude the hiatus that was experienced with HUD certifications.

TAP Training Development Should be Part of TAP Program

Air carrier operational approval is the last and much more practical phase of any new technology overall certification program. However, its success is highly dependent upon the training of flight and ground personnel. NASA should include in the TAP program the development of a generic, air carrier flight-staff-training program. This would substantially accelerate the operational approval phase and create optimal, standard operations for all air carriers irrespective of aircraft type.

Projected Costs for Aircraft TAP Improvement Installations

The cost elements for any new technology installations for air carriers, such as the TAP system, can be characterized as: 1) system development; 2) production; 3) initial installation and certification; and, 4) subsequent installation and certification. Each of these is discussed below.

System Development

System development costs includes the non-recurring engineering, including system specification, hardware design and prototyping, software design and development, testing and documentation.

A major avionics manufacturer s costs for a first article TAP common Processor and Display would be of the order of twenty to twenty-five million dollars. This cost would be recovered by amortization over subsequent units sold. The cost-per-unit issue then develops into a best estimate prediction of the quantity of units that the air carriers are likely to procure. A common objective is to realize a positive return on investment over a 10-year period.

It is probable that two thirds of the development costs for the TAP Processor and Display will be attributable to software design and verification. Much of the HUD s current non-recurring system engineering design is common to several current production aircraft types and models. However, the mechanical installation design of the symbology projector and combiner screen can be significantly different because of variations in overhead space above the left-hand pilot s seat. An estimate of the HUD non-recurring engineering cost to accommodate these variations for each aircraft type is between two hundred thousand and four hundred thousand dollars.

Production Equipment Costs

The cost of production units includes parts, assembly labor, quality control inspections and tests and product support. An estimate of these costs is relatively easy for a reputable avionics manufacturer to make, based on the production of similar equipment. However, the manufacturer is still confronted with the issue of determining the quantity of units that air carriers are likely to procure, and this affects the price of the unit.

A price for a production quantity of 100 ship sets of the TAP common Processor and Display is estimated to be fifty to seventy-five thousand dollars each, depending on which TAP functional modules are provided.

For production HUDs, the estimated price is two hundred thousand dollars. This price can rapidly escalate to five hundred thousand dollars if the cost of additional or replacement aircraft sensors are added.

Note that for the preceding estimates Price is used in contrast to Cost.   The latter does not include the sales cost and profit loading added to product cost. The mark-up is highly sensitive to the quantity ordered by the customer.

STC Installation and Certification Costs

There are five major cost elements to be considered:

1. Installation of the HUD and its interface to the aircraft systems
2. Installation of TAP Processor interface to the aircraft systems
3. Installation certification which includes flight-testing and re-certification of the original aircraft systems which have been modified.
4. Aircraft down time from revenue service.
5. Training, maintenance and procedures development by the air carrier for Operational certification

A first time installation of TAP equipment and certification of the first type of aircraft selected is estimated to cost between one million and four million dollars.

To produce a more accurate estimate for a specific first time aircraft would require a comprehensive work breakdown analysis. As a minimum, the work breakdown structure would have to consider the following cost elements:

A. Labor hours for production of system mechanical and electrical data and substantiating airworthiness analyses and reports.

B. Labor hours for physical changes to the cockpit configuration - instrument panels, glare shields, center console, overhead panel above the left-hand pilot s seat.

C. Labor hours content for wiring addition and changes behind the cockpit and the avionics compartment - opening up of the interior for access, cable assembly manufacturing etc.

D. Equipment costs and labor hours for the replacement of existing aircraft avionics to provide improved attitude and velocity performance as required by the HUD, plus greater navigation functionality and data link radio communications required by the TAP Processor.

E. Extensive testing of software components to insure that all new functionality and monitoring is correct, and that no existing functionality/monitoring was adversely affected.

F. Development and execution of a flight-test plan which proves that the total system performs its intended function under all expected flight and landing conditions. (Note that the certification plan is highly dependent on prior-development, flight-test data of a similar TAP configuration, and the number of functional modules to be certified on the first time aircraft.) Also, certification costs will be significantly reduced if the aircraft type has received a prior HUD STC.

G. The costs for the time the aircraft is out of service are obviously dependent on the size of the air carrier s aircraft selected for the first time TAP certification program. This information is usually confidential. However, it is likely that the aircraft will be out of service for about twenty days, much of which would be scheduled with current major maintenance.

Installation and Certification Costs for Subsequent Types of Aircraft

Given that a prior full up configuration TAP installation has been granted on a first STC on a previous type of transport aircraft, then it can be expected that follow-on installation and certification estimated costs will fall between eight hundred thousand and three million dollars.

The cost elements A through G summarized in the preceding section will apply, but there should be a reduction in the flight test requirement, element F, because of prior experience with the TAP system. Down time for the aircraft will also likely be less than twenty days.

Installation and Certification Costs for Subsequent Aircraft of the Same Type

Installation and certification on different models of the same type of aircraft will incur about the same costs for cost element A above. Cost elements B, C, D, E and G will be about the same initially, but will decrease as the installers gain experience.

A nominal cost for each installation is estimated to be between sixty thousand and ninety thousand dollars. The amount is highly dependent on the cost of addition or replacements being required for each aircraft.

Whether one aircraft or many, each air carrier will incur costs associated with receiving operational certification. The cost elements include pilot training, flight simulator modifications, line maintenance, technical training, operational/maintenance, publications and the purchase of test equipment. For a mid size air carrier employing 400 pilots, an initial cost of five million dollars would not be unreasonable.

Summary of Costs

The reader is strongly cautioned that the cost estimates for installation of the TAP technologies should not be taken as reliable data derived from a methodical cost analysis procedure. The values are casual, and are only intended to give some notion of what the high and low bounds for cost of installation may be. As will be seen in the final portion of this report, one of the recommendations is that a proper cost versus operational benefits economic analysis of TAP technologies should be performed by a person or persons with expertise in the air carrier business. Cost data, so derived, would useful for decision purposes.

Several factors conspire against performing a useful economic analysis at this time. First, the TAP technologies are not sufficiently mature to make estimates of production development or end-unit costs. The final system specifications for the TAP technologies can take on several forms. This report suggests one approach - an integrated, stand-alone system. But this is only one possibility. Moreover, it is not certain that all four of the TAP technologies will be technically mature at the same time.

Second, the avionics and cockpits examined during the course of this study are likely to change significantly before TAP technology installations are seriously considered. A number of new avionics systems are already in the queue for retrofit to existing aircraft. These include, for example, the Enhanced Ground Proximity Warning System (EGPWS), Automatic Dependent Surveillance (data) - Broadcast (ADS-B) and other forms of data linked messages. These constitute changes to the baseline configuration and potential competition for the limited cockpit display resources.

Third, each air carrier is unique. Important factors affecting cost, such as the type and numbers of aircraft operated, airports utilized, route structure, and maintenance practices differ among the carriers. Some equipment, prerequisite for the TAP technologies equipment, such as a HUD display or sensor capabilities, may or may not be present in particular fleets of aircraft. Also, it is far from certain that the ultimate customers, the air carriers, will want all TAP capabilities or want them concurrently. When it comes to retrofitting equipment to commercial aircraft, one size decidedly does not fit all.

Fourth, as in any business, list price or estimated cost is frequently not what the customer ends up paying. Price is always negotiable and profit margin, high or low, can be a major element of the price paid. Price varies with demand, size of the order, value of the customer, market size, and sophistication of the vendor and customer.

Fifth, a competent economic analysis is not a trivial exercise and requires a great deal of work by a knowledgeable specialist. Assumptions and constraints must be adopted that are reasonable and these must then be made explicit. Current engineering and operational cost data must be verified and validated. This is impossible at this time because the TAP technologies are not sufficiently mature to characterize accurately. Of equal importance in the analysis, and perhaps more intractable than developing reliable cost data, is determining the benefits, or value received from the TAP technologies. The value of more rapidly transiting the terminal area, and reducing delays are relatively easily to quantify in dollars. On the other hand, important considerations such as increased safety and greater situational awareness are difficult to quantify in monetary terms. Often these are matters of perceived, rather than tangible, value. Nevertheless, both sides of the cost-benefit equation must be defined for the analysis to be meaningful. There is not much point in only estimating development and installation costs. And, as mentioned earlier, the foregoing can be summarized by saying that there are simply too many unknown and variable factors that significantly affect the ultimate cost of installation of TAP technologies for particular aircraft for particular air carriers to provide meaningful cost estimates. Moreover, without any idea of the expected value or return on investment to make informed decisions, TAP cost estimates have very little practical meaning.

All of the entries discussed individually in the foregoing sections are gathered together in tabular form simply for the convenience of the reader. In Tables 7 and 8, accordingly, the entries must be regarded as numerical labels. They are more akin to qualitative indicators of valuation such as inexpensive or costly than to numbers you can add up in a column.

With these considerations in mind, the various inter-related cost estimates given above are summarized in Table 7. Table 8 then presents an accumulation of the individual cost estimates to arrive at a range of estimated costs for a fleet of aircraft. These estimates are neither minimums nor maximums, but are merely low and high estimates for the determination of feasibility of installing a TAP system.

Finally, note that at this point of the TAP technology development effort, it is virtually impossible to determine comparable costs of modifying and re-certifying an aircraft configuration if the TAP common Processor approach is not used.

Table 7. Estimates of Elements of Cost for Retrofitting TAP System

Cost/Price Element	Low Estimate	High Estimate
Non-Recurring Engineering		
TAP Processor and Panel Display Development	$ 20,000,000	$ 25,000,000
Non-recurring Engineering Adaptation of HUD to A/C types (per type)	$ 200,000	$ 400,000
Production, Installation and Certification		
TAP Processor and Panel Display Price (not cost) per Unit, for Run of 100	$ 50,000	$ 75,000
HUD — (high estimate if additional sensors required)	$ 200,000	$ 500,000
First TAP Installation and Certification	$ 1,000,000	$ 4,000,000
Installation and Certification for Second and Subsequent Types of A/C	$ 800,000	$ 3,000,000
Installation for Second and Subsequent A/C Models of Same Type	$ 60,000	$ 90,000
Operational Development Costs to User for Flight and Maintenance Procedures, Training and Test Equipment	$ 5,000,000	$ 5,000,000

Table 8. Example of Costing Method for 200 Aircraft of 2 Types for First TAP Carrier

Cost Element	Low Estimate	High Estimate
TAP Non-recurring Engineering Costs	$ 10,000,000	$ 12,500,000
HUD Non-recurring Engineering Costs (for 2 types)	$ 400,000	$ 800,000
Cost for TAP Processor and Panel Display	$ 10,000,000	$ 15,000,000
Cost for HUD	$ 40,000,000	$ 100,000,000
TAP First Installation and Certification	$ 1,000,000	$ 4,000,000
TAP First Installation and Certification on Second Type	$ 800,000	$ 3,000,000
TAP Subsequent Installation on 198 Aircraft	$ 11,880,000	$ 17,820,000
Operational Development Costs	$ 5,000,000	$ 5,000,000
Lost Revenue (AC down Time)	$ 0	$ 40,470,000
Total Cost to User to Install TAP on 200 AC	$ 78,080,000	$ 198,590,000
Average Cost per AC to Install TAP System	$ 395,000	$ 995,000

Note 1: Non-recurring cost is based on amortization over 400 units.

Note 2: Lost revenue based on AC1 generating 1,830,000 revenue passenger miles (RPM) per day with a net yield (revenue minus operating costs) of $0.027 per RPM, and AC2 generating 56,000 RPM per day with a net yield of $0.15 per RPM, and down time for installation of 0 days (low estimate) or 7 days (high estimate) per AC for 100 of each AC type.

Influences on the Entry of TAP System into U.S. Air Carrier Fleets

A number of factors will influence the adoption of TAP systems by air carriers. The influences affecting entry of the TAP system in to the air carrier fleets are summarized graphically in Figure 7.

Economic Benefits

The foremost factor in determining the introduction and spread of the use of the TAP system is the economic benefit to the air carriers. A secondary economic impetus is the perceived benefit to the public whose tax dollars fund the early development and demonstration. The cost effectiveness will be obvious when the TAP system can rapidly and safely deliver an aircraft to the air carrier terminal ramp or to the beginning of the take-off runway in 300-ft RVR conditions. However, air carriers do not invest in technology today for a payoff tomorrow. The cost effectiveness of TAP must be evident from the earliest introduction and throughout the period of expansion in both number of aircraft equipped, as well as capability.

Technical Performance

While economic benefit to the air carriers who must invest in the TAP technology is essential, there are other factors that will influence the tempo of adoption of the TAP system. Clearly technical viability is essential; the system must be shown to work. It is expected that aircraft installations and the use of new products for TAP data display will take place only after the TAP functions have been thoroughly demonstrated to the satisfaction of the air carrier community. NASA has the responsibility of developing and demonstrating the technology The first field trial installations will most likely be a cooperative effort with cost sharing among NASA, the FAA and an air carrier that has a particular problem at specific airports.

Marketing Push

Another influence on TAP system adoption is publicity to generate enthusiasm for the benefits of TAP. That is, there must be a marketing push to the air carrier management, pilots, air-traffic controllers, airport managers and the public. Creating a sense of familiarity and awareness of its potential usefulness will help TAP technology permeate more quickly into airplanes. The marketing push should come from the government, NASA, and eventually, from the avionics companies whose job it will be to sell the TAP product to the air carriers.

Given the fact that it pays to advertise , it should be possible for NASA to advertise TAP improvement technology, and economic advantages thereof, at the various air carrier trade shows, symposiums and technical meetings. The purpose would be to make air carrier management aware of the economic advantages to support the FAA TAP implementation funding requirements from Congress.

During discussions with air carrier personnel related to gathering information for this report, it was obvious that very few of the air carrier operations management staff had ever heard of the FAA s TAP program, or its objectives and the part that NASA is playing in the program development. However, after a few brief words, especially with air carrier pilots, it was applauded as a very necessary and good idea. Preparing for acceptance of the TAP system should not be a difficult marketing exercise provided it is done in a timely manner.

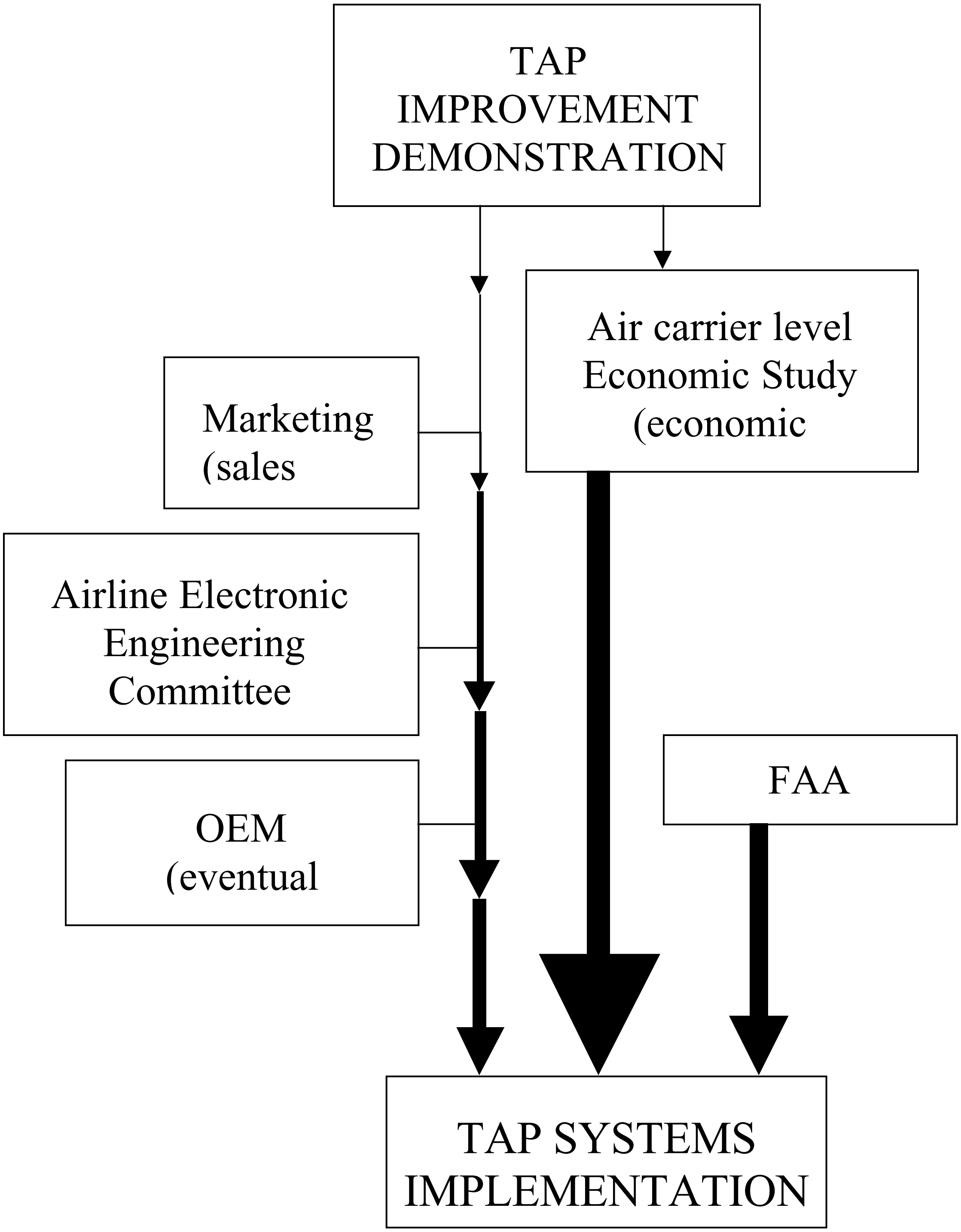


Figure 7. Factors Influencing entry of TAP system in air carrier

Regulatory Mandate

The FAA may have a role in promoting the TAP system. It may be the position of the FAA that they should be one of, if not the organization to be the active proponent of TAP. However, the air carriers tend to look on the FAA as regulators and initiators of mandatory safety system installations, not the purveyors of new cost effective technology. However, it should be mentioned that the FAA s regulatory authority could also be used to assure the eventual incorporation of the TAP system in most of the U.S. air carrier fleets. The system could be made mandatory for operating in or out of certain airports based on safety considerations. The presence of a Ground Proximity Warning System (GPWS) in every commercial aircraft would not have occurred if the FAA had not mandated it. The air carrier industry is extremely slow to introduce new technology developments unless it is done by an Original Equipment Manufacturer (OEM) as was the case when Boeing introduced full glass EFIS and dual FMS as standard equipment on B757s and B767s.

TAP System Offered as an OEM Item

The TAP system will initially be utilized by U.S. air carriers in the form of a viable, cost-effective retrofit system. After some period of time and widespread use, the airframe manufacturers will eventually incorporate the TAP system in newly produced aircraft. Such an action is a sure sign that a technology has been fully accepted as standard and that most customers expect it to be part of the aircraft package.

Retrofit Market Will Predominate Over OEM Market

This, in turn should spur additional increases in retrofitting of the TAP system. This is entirely due to the fact that for the years through to 2010, it is estimated that there will be a lot more TAP retrofitable aircraft remaining in service than the accumulation of new production aircraft entering service in the same period. This can be inferred from the data in Table 9 that shows the number of aircraft, and percent EFIS equipped aircraft, by size and year for a twenty year span. It is also interesting to note that already more than 50% of the aircraft flying are EFIS equipped and the proportions will increase to 75% by the year 2007. The conclusion that can be drawn from this is that EFIS equipped aircraft will be a large market for TAP retrofit.

Technical Facilitation

In addition to the economics and marketing influences on TAP system adoption, technical facilitation will also be necessary. That is, for commercial development of the TAP technology, some standard definition of the TAP functions and architecture will be required to insure commonality in operations.

Table 9. Number of Aircraft, and Percent with EFIS, by Size and Year

year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
World-wide Jets																					
Single aisle																					
50-90	615	681	748	814	880	947	1013	1079	1145	1212	1278	1344	1411	1477	1543	1610	1676	1742	1808	1875	1941
91-120	2897	2933	2968	3004	3039	3075	3110	3146	3181	3217	3253	3288	3324	3359	3395	3430	3466	3501	3537	3572	3608
121-170	4258	4467	4677	4886	5096	5305	5514	5724	5933	6143	6352	6561	6771	6980	7190	7399	7608	7818	8027	8237	8446
171-240	1213	1354	1496	1637	1779	1920	2062	2203	2345	2486	2628	2769	2910	3052	3193	3335	3476	3618	3759	3901	4042
Twin aisle																					
230-310	1273	1373	1473	1574	1674	1774	1874	1974	2075	2175	2275	2375	2475	2576	2676	2776	2876	2976	3077	3177	3277
311-399	1007	1115	1224	1332	1440	1548	1657	1765	1873	1981	2090	2198	2306	2414	2523	2631	2739	2847	2956	3064	3172
>400	1016	1051	1086	1120	1155	1190	1225	1260	1294	1329	1364	1399	1434	1468	1503	1538	1573	1608	1642	1677	1712
total jets	12,279	12,975	13,671	14,367	15,063	15,759	16,455	17,151	17,847	18,543	19,239	19,934	20,630	21,326	22,022	22,718	23,414	24,110	24,806	25,502	26,198
EFIS penetration %																					
Single aisle																					
50-90	45	48	50	53	56	59	61	64	67	69	72	75	77	80	83	86	88	91	94	96	99
91-120	45	48	50	53	56	59	61	64	67	69	72	75	77	80	83	86	88	91	94	96	99
121-170	40	43	46	49	52	55	58	61	64	67	70	72	75	78	81	84	87	90	93	96	99
171-240	65	67	68	70	72	74	75	77	79	80	82	84	85	87	89	91	92	94	96	97	99
Twin aisle																					
230-310	55	57	59	62	64	66	68	70	73	75	77	79	81	84	86	88	90	92	95	97	99
311-399	60	62	64	66	68	70	72	74	76	78	80	81	83	85	87	89	91	93	95	97	99
>400	65	67	68	70	72	74	75	77	79	80	82	84	85	87	89	91	92	94	96	97	99
World-wide EFIS a/c																					
Single aisle																					
50-90	277	325	377	432	491	554	620	690	763	840	920	1004	1092	1183	1278	1376	1478	1584	1693	1805	1922
91-120	1304	1399	1496	1595	1696	1799	1904	2010	2119	2229	2342	2456	2572	2691	2811	2933	3057	3183	3311	3440	3572
121-170	1703	1919	2147	2387	2640	2904	3182	3471	3774	4088	4415	4754	5105	5469	5845	6234	6635	7048	7473	7911	8362
171-240	788	903	1023	1148	1277	1411	1550	1694	1843	1996	2155	2318	2485	2658	2836	3018	3205	3397	3594	3795	4002
Twin aisle																					
230-310	700	785	875	969	1068	1171	1278	1390	1506	1627	1752	1881	2015	2153	2296	2443	2594	2750	2910	3075	3244
311-399	604	691	782	877	976	1080	1188	1300	1416	1536	1661	1790	1923	2061	2202	2348	2498	2652	2811	2973	3140
>400	660	701	743	785	829	875	921	969	1017	1067	1118	1171	1224	1279	1335	1392	1450	1510	1570	1632	1695
Total EFIS a/c	6,037	6,723	7,442	8,194	8,977	9,794	10,643	11,524	12,438	13,384	14,363	15,374	16,417	17,494	18,602	19,743	20,917	22,123	23,362	24,633	25,936
EFIS SUMMARY																					
World-wide	6,037	6,723	7,442	8,194	8,977	9,794	10,643	11,524	12,438	13,384	14,363	15,374	16,417	17,494	18,602	19,743	20,917	22,123	23,362	24,633	25,936
North America %	48.0%	47.5%	47.0%	46.5%	46.0%	45.5%	45.0%	44.5%	44.0%	43.5%	43.0%	42.5%	42.0%	41.5%	41.0%	40.5%	40.0%	39.5%	39.0%	38.5%	38.0%
North America	2,898	3,194	3,498	3,810	4,130	4,456	4,789	5,128	5,473	5,822	6,176	6,534	6,895	7,260	7,627	7,996	8,367	8,739	9,111	9,484	9,856
year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

Data courtesy of Flight Dynamics, 1998; compiled by George Kanellis based on unpublished, internal marketing report using data supplied by the Boeing Aircraft Company and Airbus Industries.

Previous reference has been made to the Airlines Electronic Engineering Committee (AEEC) and its combined air carrier and equipment manufacturers form, fit and function specification activities. This organization, which is led by national and international air carrier avionics engineering managers, is significantly influential and powerful at pushing forward the implementation of new technology developments such as the TAP system. This occurs both for retrofit and OEM activities once they are directed to do so by their individual air carrier upper management. Table 10 is The following current listing of the AEEC members gives a good impression of the committee s representation of the aviation industry.

Table 10. Current Members of the Airlines Electronic Engineering Committee

Continental Airlines	Air France
ATA	United Parcel Service
AMC (ARINC)	Federal Express
Northwest Airlines	American Airlines
IATA	EAEC (British Airways)
Air Canada	EAEC (Finnair)
Delta Air Lines	EAEC (Iberia)
EAEC (SAS)	US Airways
EAEC (Lufthansa)	General Aviation (NBAA)
OAA (JAL)	Trans World Airlines
United Airlines	Alaska Airlines
USAF	

Some air carriers will want to introduce TAP features incrementally. Some will want to implement all TAP system functional features at one time. Others will select only one or two features based on the requirements of their operations, and not all will require a HUD installation. These differing interests and points of view will be aired in the AEEC process. An AEEC industry oriented sub committee will be the forum in which the primary objectives of TAP improvement will be maintained in a standard definition. Rational procedures for the implementation and incorporation into operations will also be developed in the sub-committee process. The AEEC promotes standardization of technology insertion for the common good of the members. It also provides useful information to the avionics manufacturers that must come up with a saleable product to the AEEC member companies.

CONCLUSIONS

The basic purpose of the study was to determine if it is technically feasible and practical to perform a retrofit installation of the TAP systems into a representative range of current air carrier aircraft in the U.S. fleets. The answer is yes.

The TAP displays, both head-up and panel mounted, could be retrofitted into all five types of aircraft examined. The cost of retrofit could be great, in the range of four hundred thousand to a million dollars per aircraft. Retrofitting the long range, classic type aircraft would cost the most. Perhaps surprisingly, retrofitting the newest, glass-cockpit type aircraft, would likely be the next most expensive. The work and costs involve physical installation, requiring (in some cases) movement of existing equipment, software additions and modifications, and re-certification of the software. This last element can be very expensive, especially for the glass cockpit configurations.

Providing the TAP system capability for extended range, classic aircraft such as the B747-200/300 and the DC-10 would require a complete stand-alone TAP system. The existing on-board equipment is simply inadequate to provide the sensor inputs, data communications, data processing, and symbol generation capabilities needed to support the TAP HUD and panel mounted, or Head Down Display . On the other hand, it appears feasible for aircraft equipped with a full EFIS display suite to use the existing sensor, communications, processor and symbol generating facilities to support the TAP system and displays. However, while potentially feasible, it may not be economically practical because of the cost of the required hardware and software modifications. Not only must new capability be added, but it must also be demonstrated beyond any doubt that the TAP modifications do not interfere with the pre-existing functions. In other words, even for aircraft with a full EFIS display suite, the most viable alternative for installing a TAP display system may be a stand-alone system that interacts minimally with existing systems by way of only sharing one or more display surfaces.

A significant cost of new-design or retrofitted avionics is attributable to having to meet certification requirements of the FAA for air transport operations in the U.S. National Air Space.

The retrofit approach requiring the least effort appears to be incorporating the TAP system and displays as a stand-alone add-on package with minimal change to current drive electronics, computers, and software. The alternative is to modify existing systems to assimilate the TAP functions. For the complete TAP display suite this is likely to be more costly than the stand-alone alternative. However, it could be a more cost-effective approach if only one or two of the TAP system and displays were retrofitted.

It is important to recognize that as the TAP program evolves and migrates to implementation, the four different TAP functions and displays (CTAS/FMS, AILS, ROTO and T-NASA), may not have equal appeal or be operationally justifiable by the air carrier.

Achieving the TAP objective of increased productivity depends on several factors, of which technical feasibility is merely the first requisite. Ultimately, it will be the air carriers who determine the success of the TAP program. The most potent influence on adoption of TAP technology by an air carrier is the expected accrual of economic benefits. Without recovery of costs and increased profit within a relatively short time, no additional systems would be installed on aircraft, unless mandated by the FAA. This latter alternative is unlikely in the case of TAP equipment. An additional influence on the incorporation of TAP technology in aircraft would be an agreement on a cooperative, phased, technical implementation plan by the Airline Electronic Engineering Committee.

Few innovations succeed without a sales push. NASA, aided by the avionics equipment manufacturers, should be prepared to publicize TAP capabilities and expected benefits. The TAP aircraft systems culminating success will be when it is included, first as an option, and then as standard by aircraft manufacturers. This is not likely to occur for some time. Retrofitting will be more common in the early years simply because manufacturers will be unwilling to risk the development and certification costs to incorporate a technology in new aircraft until it is well established and customers demand it. In the early stages, it will be the air carriers that will bear the cost of retrofit and certification.

RECOMMENDATIONS

Technical

Using a generic, self-contained, common TAP Processor Unit, with a centrally mounted display, should be considered as the basic approach for retrofitting current aircraft. For EFIS equipped aircraft with full glass cockpits, an existing display may be used.

NASA should engage in a follow-on phase to this study to develop generic designs for TAP aircraft equipment, and installations for non glass as well as glass cockpits.

At an early opportunity, NASA should install a full suite of the TAP system in its B757 for demonstration to any potential air carrier user.

In light of the current size of cockpit displays as given in Table 5, NASA should determine the acceptable envelope of display size, aspect-ratio, and resolvable detail for the panel mounted display.

Programmatic

The utilization of the TAP system by air carriers is a definite economic issue that needs to be addressed. A thorough economic study, oriented toward the cost-benefits to air carriers, should be conducted as soon as possible to determine the individual and collective worth of the TAP system to air carriers. The study could be sponsored by NASA, but should be conducted by economics experts knowledgeable in the area of U.S. air carrier operations. The scope should include type of carrier, types of aircraft used and airports used. The results of this study would also indicate which segment of air carrier operations would gain the most advantage from TAP improvement.

Again, at an early opportunity, NASA should begin informational marketing to air carrier upper management. This should be directed at potential TAP system users, and include air carrier executive meetings hosted by ATA or IATA. Also, general advertising on the progress of the TAP program and its intrinsic benefits should be promoted through air carrier oriented magazine articles. Technical papers should be delivered at symposiums and annual organizational meetings of the ATA, IATA, and ICAO, and at the air carriers AEEC yearly conference.

NASA should solicit the views of foreign air carriers to establish their interest and concerns in using the TAP system for their scheduled operations into specific U.S. airports.

The form, fit and function of the equipment should be in accordance with the air carriers AEEC procedures, based on a system specification controlled by the FAA in conjunction with NASA.

A draft TAP system airworthiness and operational certification plan should be developed at an early opportunity. TAP certification in the lower approach, landing and roll-out realms is likely to require almost the same effort as re-certification of the whole landing system. The certification plan should cover the ground elements as well as the aircraft elements referred to in this report.

REFERENCES

Hooey, B.L., Schwirzke, M.F.J., McCauley, M.E., Purcell, K.P., and Andre, A.D. (1998) Initial Identification of Procedural Issues for the Future Deployment of Terminal Area Productivity (TAP) Technologies. (NASA Contractor Report). Moffett Field, CA: NASA Ames Research Center.

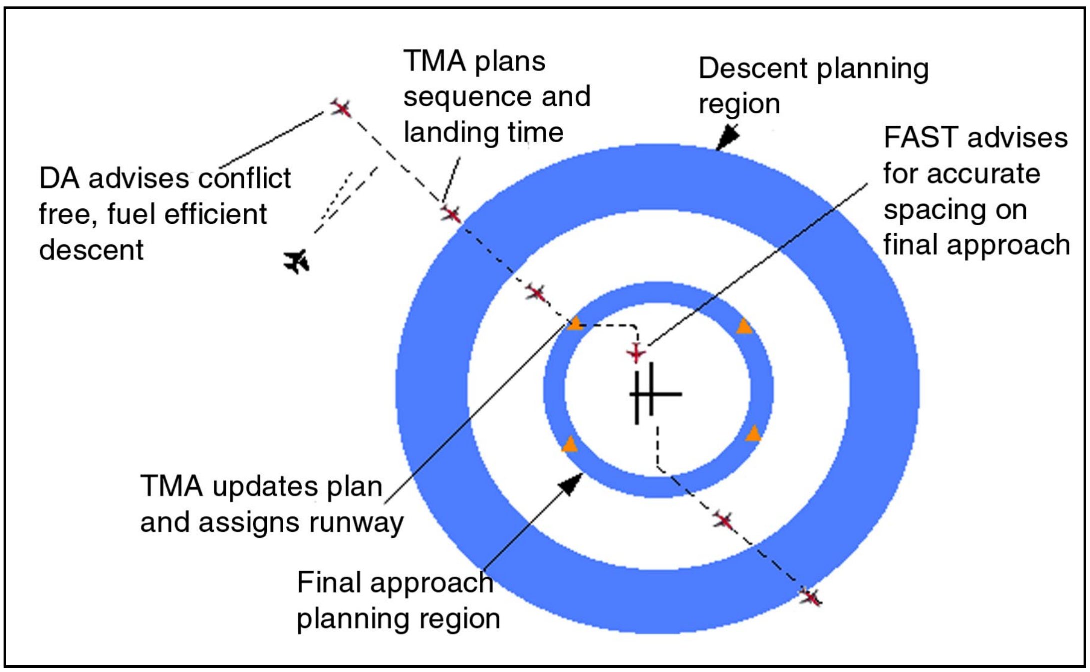
APPENDIX A - DESCRIPTIONS OF TAP SYSTEM TECHNOLOGIES
TERMINAL AREA PRODUCTIVITY (TAP) DISPLAYS

Center TRACON Automation System / Flight Management System (CTAS/FMS)

Purpose

The Center TRACON Automation System/ Flight Management System (CTAS/FMS) integration effort proposes coordination of ground-based automation tools (i.e., CTAS) with the aircraft FMS to increase safety, efficiency, and capacity in and around the terminal airspace. In order to increase safety, efficiency, and throughput in the terminal area, ATC may use CTAS tools with scheduling algorithms to control arriving aircraft. First, ATC will issue a FMS arrival and descent clearance with cruise and descent speeds. Then, if necessary, ATC may issue route modifications to adjust the meter fix arrival time, or speed amendments to adjust threshold arrival times. Also, if necessary, ATC may issue downwind extensions to adjust threshold arrival times.

The controller CTAS tools include a: Descent Advisor (DA), Traffic Management Advisor (TMA), and Fast Approach Spacing Tool (FAST). Flight deck modifications include adjustable FMS leg types, a vertical situation display, and a datalink display and response buttons.



CTAS Concept

Air Traffic Controller Tools

Descent Advisor (DA)

- Designed to support ground-based air traffic control.
- Generates clearance advisories that help sequence aircraft in Center's airspace.
- Used for metering arrivals into the TRACON to ensure fuel-efficient and conflict-free descents with highly accurate arrival times--on the order of 10-20 seconds.
- Conflict Probes generate detailed predictions of conflicts for all traffic.
- Conflict Resolution functionality s range from manual what-if input and feedback to fully automatic generation of resolution advisories.

Traffic Management Advisor (TMA)

- TMA assists, but does not replace, the Center TMCs and air traffic controllers in the following ways:
  - Increases situational awareness through graphical displays and alerts.
  - Generates statistics and reports about the traffic flow.
  - Computes the undelayed estimated time of arrival (ETA) to the outer meter arc, meter fix, final approach fix and runway threshold for each aircraft.
  - Computes the sequences and scheduled times of arrival (STAs) to the outer meter arc, meter fix, final approach fix, and runway threshold for each aircraft to meet the sequencing and scheduling constraints entered by the TMC.
  - Assigns each aircraft to a runway to optimize the STAs.
  - Continually updates its results at a speed comparable to the live radar update rate in response to changing events and controller inputs.

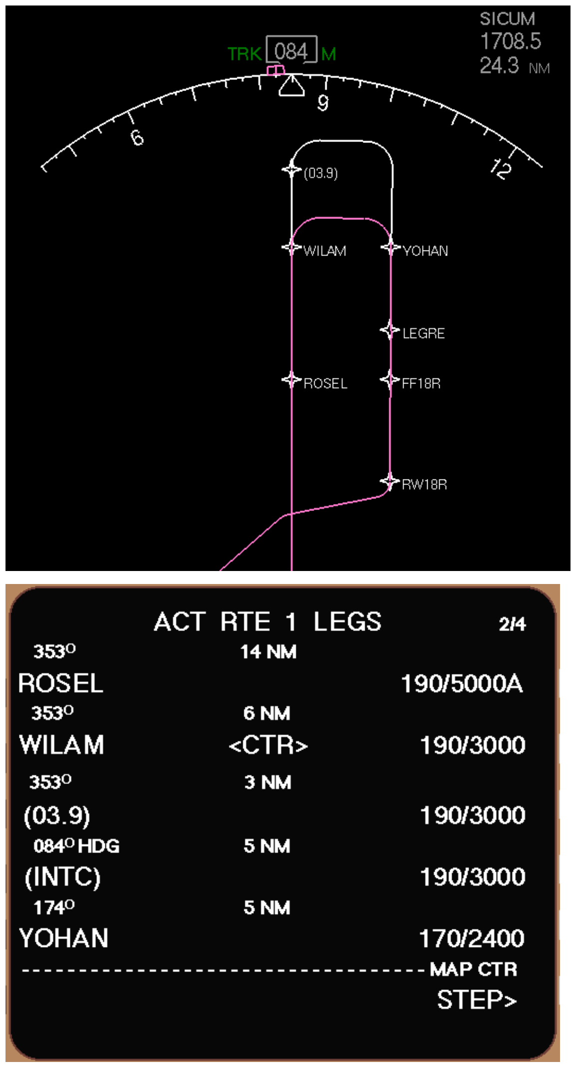
Final Approach Spacing Tool (FAST)

- FAST is a CTAS decision support tool for the terminal area (TRACON) air traffic controllers.
- Provides landing sequences and landing runway assignments, as well as speed, and heading advisories that help controllers manage arrival traffic and achieve an accurately spaced flow of traffic on final approach.
- FAST uses accurate arrival times for sequencing and scheduling aircraft to the runway threshold.
- FAST computes routes for each aircraft entering the TRACON airspace. The controller can generate and display a route for each aircraft on his or her radar display and communicate it to the aircraft as a route modification clearance.

FLIGHT DECK DISPLAYS

Adjustable FMS Leg Types

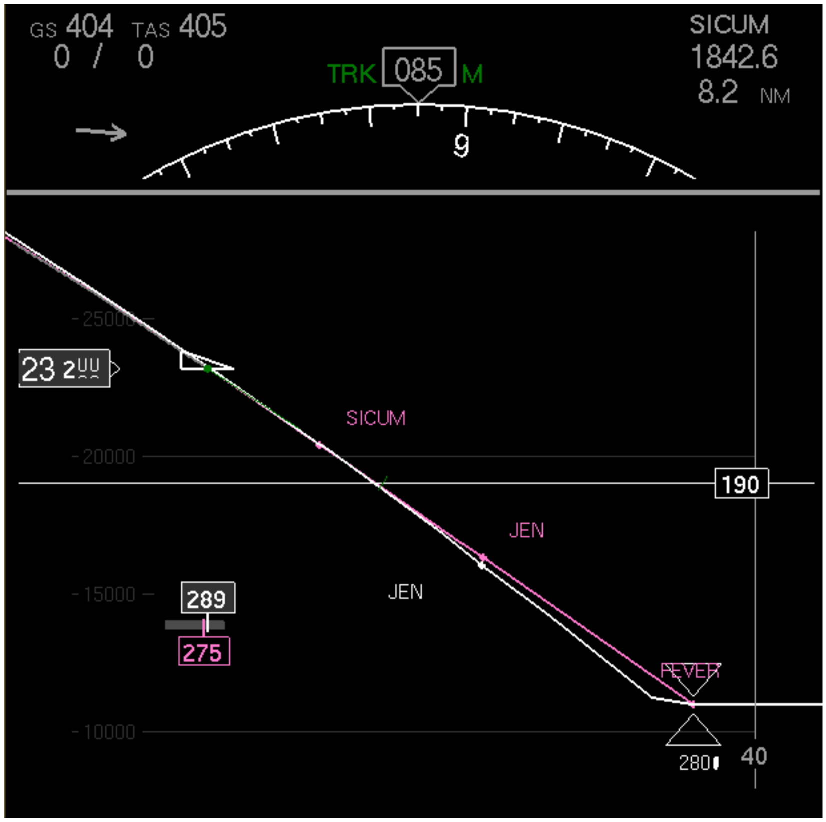
Adjustable FMS leg types will support simple FMS route adjustments (e.g., downwind leg length) in the TRACON airspace. This modified FMS function information is displayed on both pilots Navigation Display. In the graphic below, the base turn routing (shown in magenta) is modified by extending the downwind leg by 3.9 nm. The new base turn routing (shown in white) is pending until loaded, executed, and accepted by the flight crew.



Downwind leg extension provided by CTAS/FMS

Vertical Situation Display (VSD)

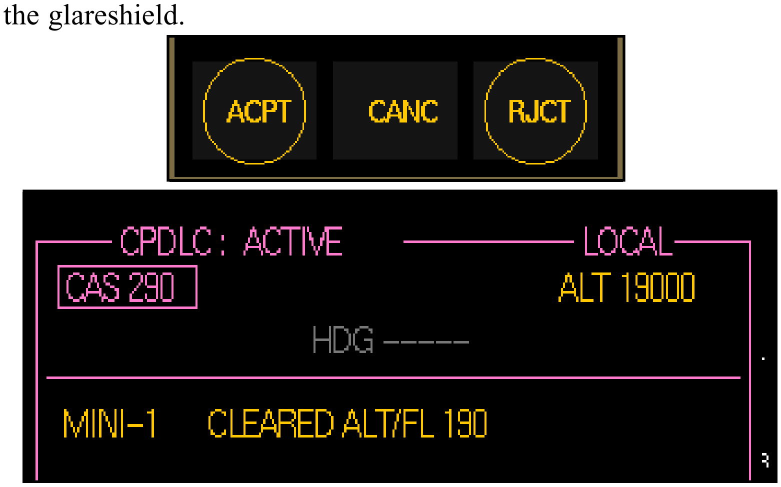
The Vertical Situation Display is intended to aid pilots with vertical management and control of the aircraft during the descent phase of flight. The VSD provides a side view of the FMS computed vertical profile and the position of the aircraft relative to the profile. It also provides trend, crossing restriction, and mode information. Speed and altitude crossing restrictions are depicted at flight plan waypoints with programmed restrictions. Mode information is provided graphically to indicate current and future aircraft behavior. The VSD shares display space with the current Navigation Display and is selectable in three configurations: 1) it can be concealed, 2) displayed in an 80 percent split-view, or displayed in a 20 percent split-view.



Vertical Situation Display

Advanced Datalink Interface

It is envisioned that in the future the advanced datalink interface will support automatic loading of, and heads-up assessment and response to, uplinked CTAS routes. The data-link display will be located on the central EICAS, and two sets of response buttons, one for each pilot, will be located on the glareshield.



Advanced Datalink Interface

ATC-Pilot Interaction Using CTAS/FMS

When using the modified FMS function, the crew must be on a FMS descent procedure that specifies a default downwind (and final approach) distance as measured from a reference waypoint on the route. Prior to reaching this point, ATC will issue a downwind length extension to adjust spacing or arrival time at the threshold.

In the near term, CTAS/FMS will be implemented as follows:

- The FMS procedure will terminate on the downwind leg. Pilots will continue on the downwind leg until they receive a base turn vector from ATC.
- Controllers will be provided with tools that allow them to determine the length of the downwind leg and when the aircraft should begin the base turn. At the appropriate time, the controllers will provide vectors to the aircraft to begin the base turn.
- After the downwind leg, all ATC clearances will be delivered by voice.

In the far term, it is envisioned that CTAS/FMS may be implemented as follows:

- Feeder control will clear the aircraft for a FMS descent route which will include a downwind leg and a default base turn — the default will always allow for the shortest downwind leg possible.
- If necessary, and as advised by CTAS scheduling and planning tools, ATC may extend the downwind leg. Depending on technology availability, this could occur in one of two ways:
  1. ATC advises the pilot of a downwind extension by voice. Pilots acknowledge the downwind extension by voice, make the necessary modification using the CDU, and continue to fly the FMS route.
     or
  2. ATC datalinks the modified FMS descent route to the flight deck and it automatically loads into the modified route buffer of the FMS. The text of the route clearance appears on the center EICAS. The crew reads the message text on the EICAS screen, and confirms and assesses the loaded route on their Navigation Displays. They execute the route (if acceptable) in the CDU, and respond to ATC by pressing an ACCEPT button located on the glareshield. The crew then continues descent coupled to the FMS while flying the CTAS modified routing.

Airborne Information for Lateral Spacing (AILS)

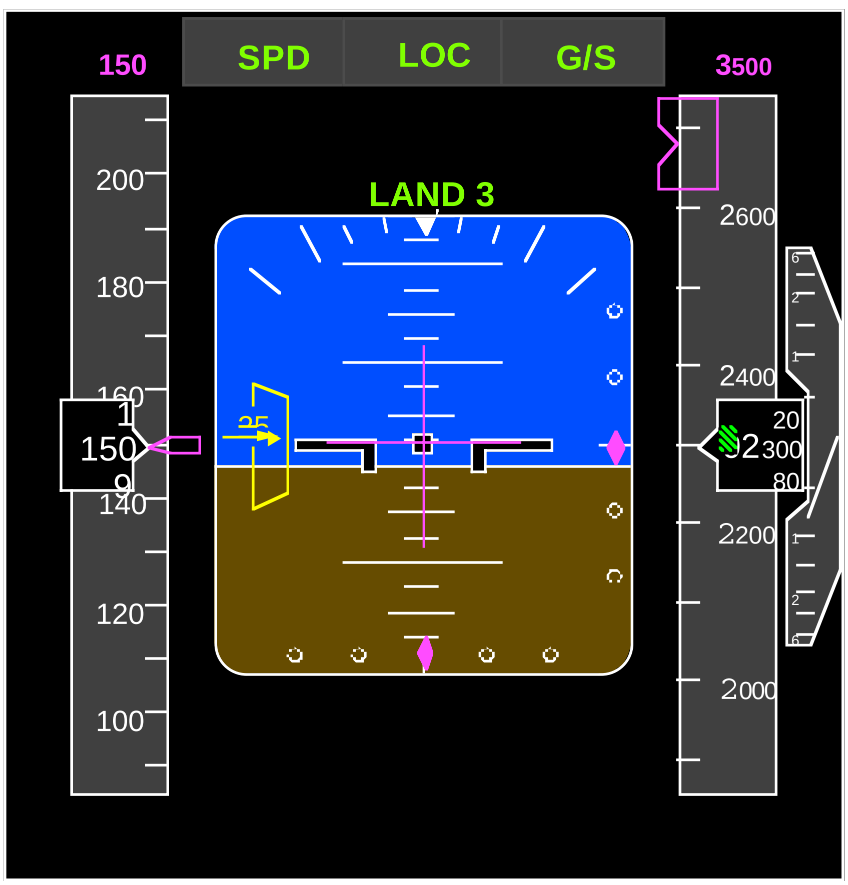
Purpose

The purpose of the Airborne Information for Lateral Spacing(AILS) system is to maintain aircraft separation during closely spaced parallel approaches of less than 4,300 ft separation in IMC. Traffic alert and information is provided to the flight crew, similar to the current Traffic alert and Collision and Avoidance System (TCAS).

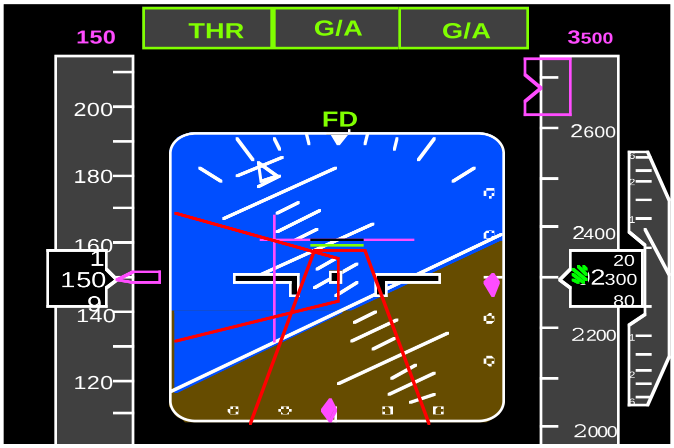
AILS Flight Deck Display Enhancements

On the Primary Flight Display (PFD), AILS includes the following display features:

- The Parallel Traffic Window indicates the location (left or right) of the traffic, pointing toward the ownship reference on the ADI.
- The Slant Range Indicator shows the distance (in hundreds of ft) between the ownship and the traffic.
- The Horizontal Motion Arrow provides additional information on traffic location by indicating that traffic is moving away from its centerline and toward the ownship.

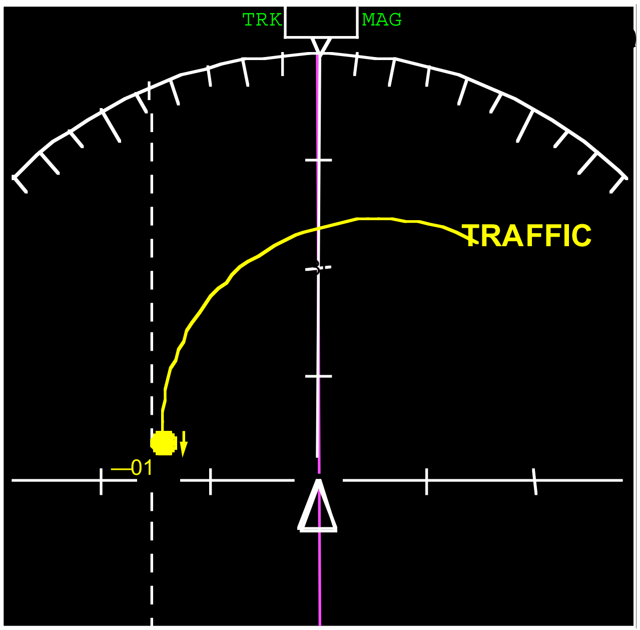


A traffic advisory accompanied by an aural alert is issued, if parallel traffic executes a blunder that results in an intercept course. If the alerting system determines that a maneuver is necessary to maintain separation, a Resolution Advisory is issued and Pitch & Turn Guidance cues and Go-To Bars appear on the PFD.



On the Navigation Display (ND), AILS allows the display to be scaled below the current 10 nm limit and provides a control to select distance in feet or nm. Other AILS features on the ND include:

- The Parallel Runway and Centerline cue which indicates the location of the parallel runway and intended path for the other aircraft.
- The Traffic Trend Vector which indicates what direction the traffic is heading.



HOW TO USE THE AILS DISPLAYS

During the approach phase, the aircrew monitor the AILS traffic information on the PFD and ND. If parallel traffic executes a blunder that results in an intercept course, a Traffic Advisory is issued along with an aural alert. If the alerting system determines that a maneuver is necessary to maintain separation, a Resolution Advisory is provided. Pitch & Turn Guidance cues and Go-To Bars appear on the PFD. For the pilot-flying, the response to the RA is to disconnect the autopilot, engage the Go-Around thrust control on the throttles, and manually fly the presented pitch and turn commands. Typically the pitch guidance is satisfied first, with the bank following. An aural "MONITOR ATTITUDE" alert indicates that both guidance components have been satisfied. With the aural alert "CLEAR OF CONFLICT" indicating that the conflict has been resolved, the pilot-flying is then responsible for following Air Traffic Control directives. The non-flying pilot will typically assist the pilot flying in monitoring the progress of the approach and providing situation awareness in the event of a Resolution Advisory. The non-flying pilot will also assist the pilot flying in executing a modified missed approach procedure.

ATC-PILOT INTERACTION WITH AILS TECHNOLOGY

- The final controller is responsible for aircraft separation until AILS approach clearance is given to the aircraft. The final controller will notify both aircraft of the parallel traffic prior to turning final — and will apply standard separation between aircraft during turn on to final approach.
- Both aircraft will confirm that they have their traffic in sight (under electronic surveillance) and assume separation responsibility prior to losing standard separation. After approach clearance is issued and prior to the final approach fix, communications will be switched from the final controller to the tower local controller. After receiving AILS approach clearance, the aircraft are solely responsible for separation.
- In the event of a blunder or intrusion incident, the flight crew maintains separation responsibility. ATC will not assume separation responsibility until the initial conflict has been resolved by the flight deck crews.
- Once the initial conflict has been resolved and safe separation achieved, ATC will assume responsibility for separating the two aircraft involved in the incident from all traffic, and to vector the aircraft back into the approach sequence.

Roll Out and Turn Off (ROTO)

Purpose:

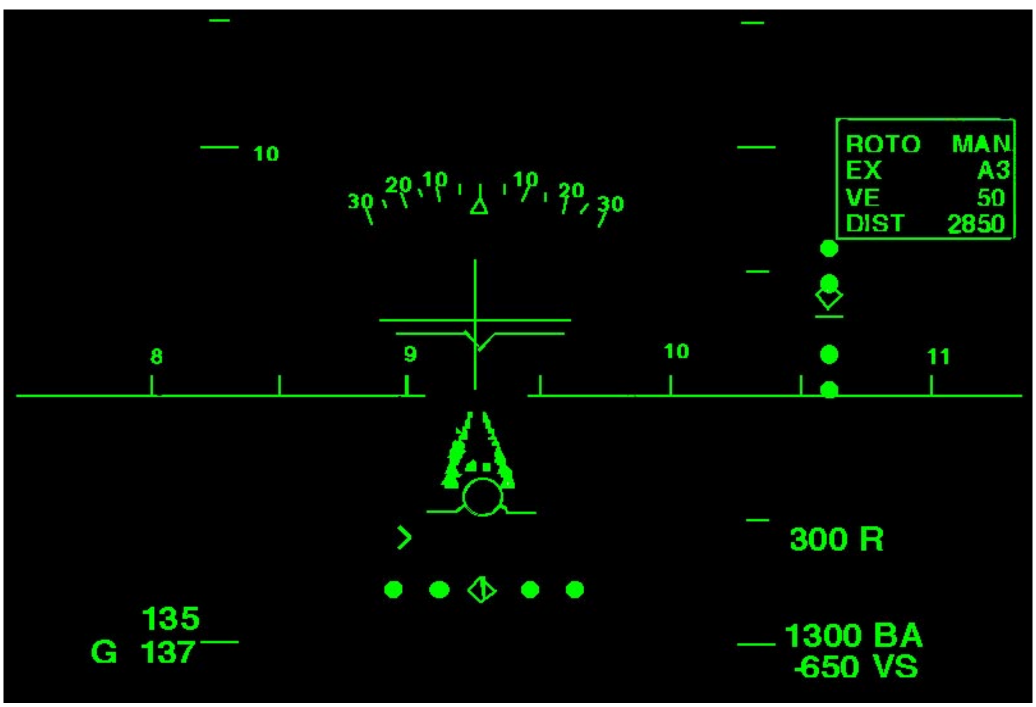
The purpose of the Roll Out and Turn Off Head-Up Display (ROTO HUD) is to increase runway throughput and reduce runway occupancy times. The ROTO HUD provides speed and turn guidance to assist pilots in exiting the runway quickly and safely in low visibility conditions.

DESCRIPTION OF THE ROTO HUD:

TWO ROTO MODES:

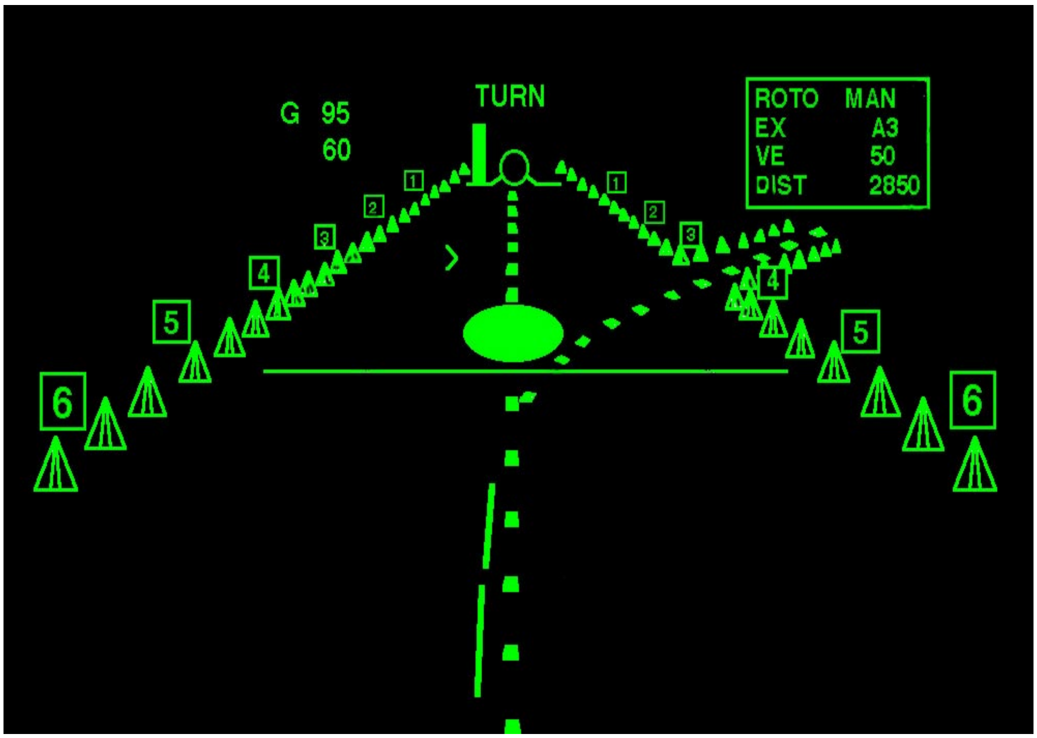
- <u>Automatic mode:</u> ROTO will automatically select the first turn-off that the aircraft can safely make without exceeding a nominal deceleration level (6.5 ft/sec). If the pilot cannot decelerate in time to make the turn off, ROTO will automatically switch to the next turn off.
- <u>Manual mode:</u> The pilot can select the desired exit using the ROTO runway selection control panel after a valid ILS frequency has been selected. If ROTO detects that the aircraft cannot decelerate to make the turn off, the turn symbology will not be displayed. The pilot will manually select the next desired exit.

In the air, ROTO symbology is added to standard HUD flight symbology. Once a valid ILS frequency has been selected, and the pilot has selected an operating mode (automatic or manual) a <u>ROTO box</u> appears in the upper right hand corner of the HUD to indicate the chosen runway exit, the acceptable turn off speed, and the nominal braking distance. <u>Virtual cones demarcate the edges of the runway and selected turn off</u>.



ROTO HUD: Airborne symbology

Immediately upon touchdown, the flight symbology transitions to the ROTO ground symbology, which provides current and predicted speed information. A ground speed error bar (on the left wing of the aircraft symbol) indicates whether the ground speed is too high or too low for the intended turnoff. As pilots approach the turnoff, guidance is provided to indicate when the pilot should begin the turn. The ellipse indicates where the aircraft will be when the desired exit speed is reached. The horizontal line across the runway indicates where the pilot should begin the turn. Two 2 second trend vectors provide information to aid pilots in positioning the aircraft on the exit centerline during the turnoff from the runway.



ROTO HUD: Ground Symbology

HOW TO USE THE ROTO HUD:
It is expected that most aircraft will be equipped with one head-up display centered over the left seat. Therefore only the Captain will have access to ROTO information. Upon touch down, the pilot follows the ROTO guidance to decelerate the aircraft to the nominal exit ground speed. The pilot s goal is to minimize the ground speed error bar while keeping it above the flight path symbol wing. As the aircraft approaches the turn off, the pilot lines up the ellipse on the turnoff line. If the ellipse is above the turn off line (as in the picture above), the aircraft will reach the desired speed too late. When the word TURN begins flashing the pilot commences the turn to exit the runway.

ATC-PILOT INTERACTION USING ROTO TECHNOLOGY

It is expected that pilots will always own the runway and maintain the right to choose their runway exit. However, it is envisioned that ATC could be equipped with tools that they could use to recommend an optimal turn-off to ensure efficient routing for all aircraft.

Taxiway Navigation and Situation Awareness (T-NASA)

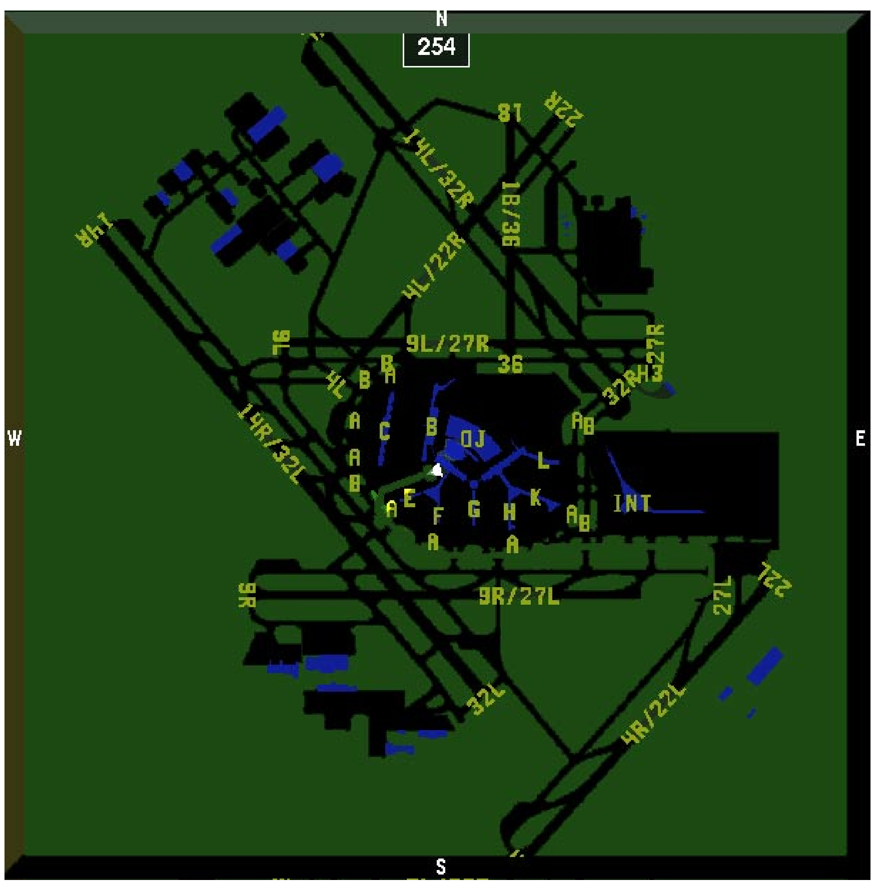
Purpose:

The Taxiway Navigation and Situation Awareness (T-NASA) display suite consists of three components: A panel mounted Taxi Map, a Taxi Head Up Display (HUD), and directional auditory alerts to warn pilots of approaching traffic and hold shorts. All components are designed to increase taxi speed, route navigation accuracy, and situation awareness in low visibility conditions.

DESCRIPTION OF T-NASA DISPLAYS

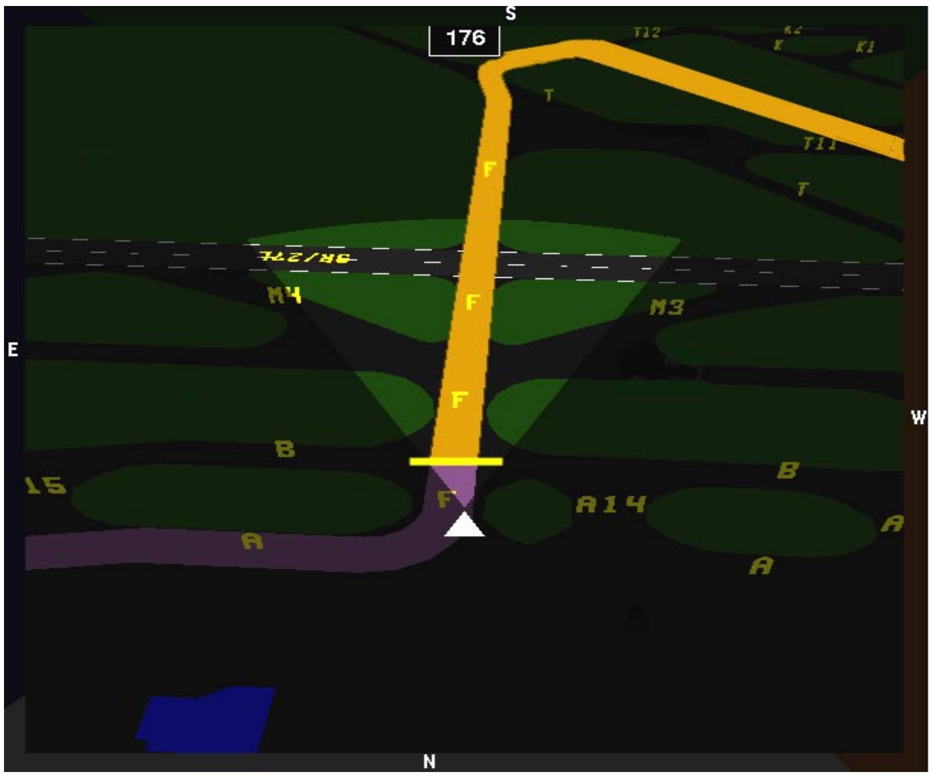
T-NASA Taxi Map

The **T-NASA Taxi Map Overview Mode** presents a north-up, fixed view of the entire airport surface, runway and concourse locations, much like a paper taxi chart. Pilots have found that this mode is best used to preview the airport layout while airborne — but it is also available on the ground to aid in planning a route before taxiing, and to view traffic sequences while holding short of runways.



T-NASA Overview Mode.

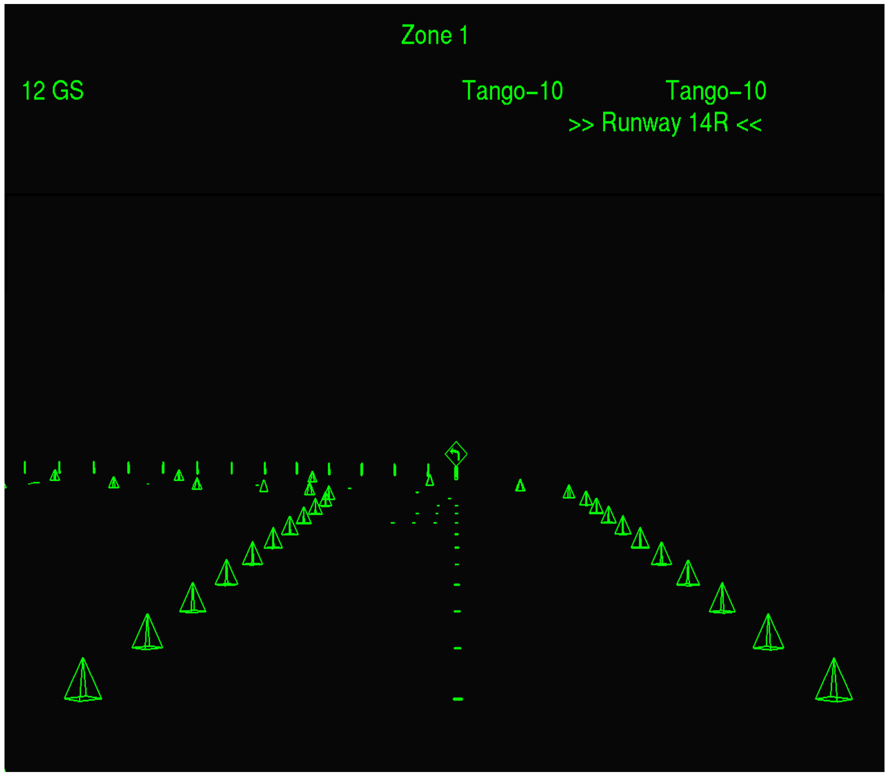
The **T-NASA Taxi Map Perspective Mode** presents a view of the airport from above and behind the ownship. Similar to the EHSI, the taxi map is oriented track-up so that it rotates around the fixed aircraft symbol. The cleared taxi route is presented via a magenta path. Hold short instructions issued by ground control are highlighted on the taxi map by a flashing yellow line, and the magenta path beyond the hold bar turns yellow. The position of the ownship and other aircraft are presented and updated in real time. Ground speed (upper left corner), compass heading (upper GS 13 d cardinal direction bars (surrounding moving frame) are provided. There are four els to choose from that show progressively greater detail.



Taxi Map: Perspective Mode

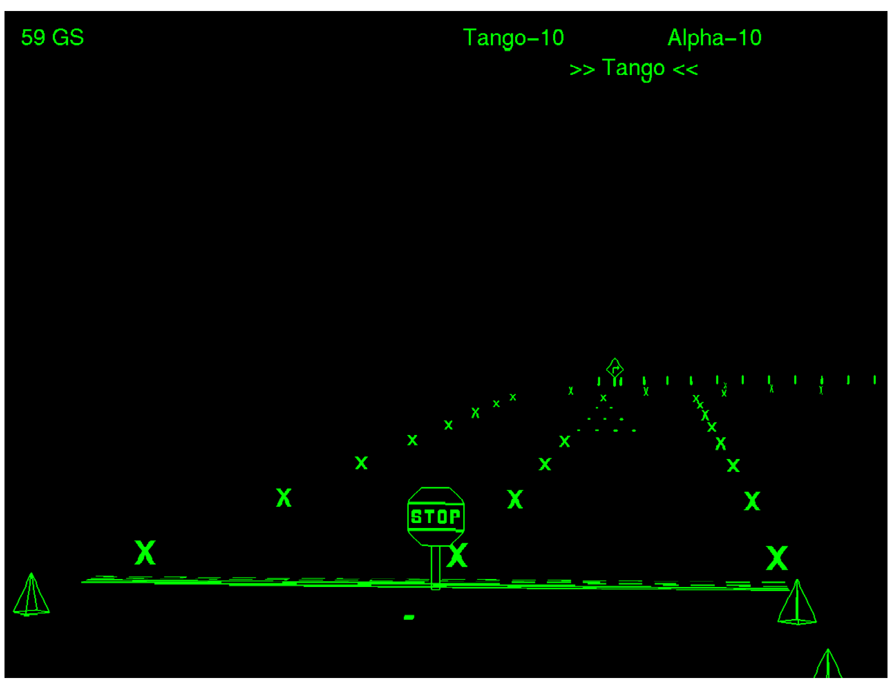
T-NASA TAXI HUD:

The **T-NASA Taxi HUD** displays the cleared taxi route in the form of a series of virtual "cones" located along both edges of the cleared taxiway and a series of small squares that overlay the taxiway centerline. Ground speed is displayed in a digital format in the upper left hand corner of the HUD. In the upper right portion of the HUD, the taxiway that the aircraft is currently on, as well as the taxiways that are coming up on the right and left are presented in text form. When approaching a turn, the taxi HUD presents a virtual turn sign, which indicates the angle of the upcoming turn.



Taxi HUD: Route symbology

When a hold short instruction is issued by ground control, the hold bar appears on the HUD and enhances the hold bar on the airport surface. A virtual stop sign appears on the HUD to reinforce the hold short command, and the edge cones beyond the hold convert to X s. After the hold has been removed by ground control, the X s revert back to cones.



Taxi HUD: Hold Symbology

How to use the T-NASA Displays:

It is expected that most aircraft will be equipped with one head-up display centered over the left seat. Therefore only the Captain will have access to the HUD information. However, both pilots will have their own taxi map located on the navigation displays (ND). Directional audio alerts will be provided through each pilots headphones. An audio alert from the right side will indicate that an aircraft is approaching from the right — a left auditory alert will indicate the threatening traffic is approaching from the left.

Pilots may preview the taxi map while airborne — the overview mode will display the airport surface layout, as well as runway and concourse location. At least initially, the taxi route will not be available while airborne.

At touch down, the taxi map perspective mode will automatically appear on the NAV display. The ROTO HUD will automatically transition to the T-NASA taxi HUD after turning off the runway.

ATC-Pilot Interaction

- Smart routing algorithms designed to increase productivity and efficiency for airport surface operations will determine taxi routes.
- In the Near Future:
  - After clearing the runway, pilots will call Ground Control (GC) for clearance.
  - GC will provide a taxi clearance by voice and send the clearance via datalink to the T-NASA taxi HUD and taxi map.
  - Pilots will acknowledge by voice and datalink response buttons on glare shield.
  - All hold and route amendment instructions will be provided by voice and will be datalinked to the taxi HUD and map in pending form until acknowledged by the flight crew.
- In the Distant Future:
  - The taxi clearance may be datalinked to the T-NASA taxi map while airborne or as exiting the runway.
  - Pilots will acknowledge the route using datalink response buttons on the glare shield.
  - At runway turnoff, pilots will continue taxiing, without talking to ground control (except for emergencies).
  - All hold and route amendment instructions will be datalinked directly to the cockpit accompanied by a datalink message tone, and will appear on the Taxi HUD and taxi map as pending changes until acknowledged by the flight crew.

APPENDIX B - SELECTED COCKPIT PHOTOS OF THE EMB-120 AIRCRAFT (SKYWEST CONFIGURATION)

EMB-120 Captain's Panel

EMB-120 First Officer's Panel

EMB-120 - Center Panel

EMB-120 View of Overhead Space at Captain s Station

EMB-120 Instrument Panel

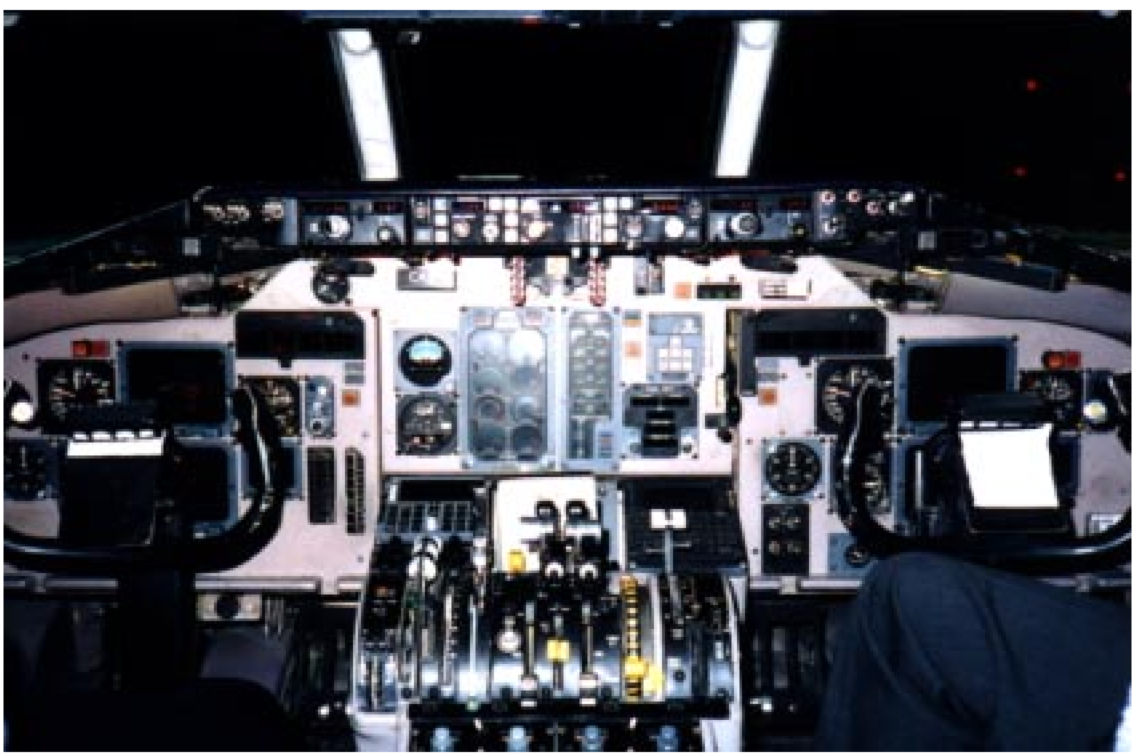
EMB-120 Partial Overhead Panel View

APPENDIX C - SELECTED COCKPIT PHOTOS OF THE MD-87 AIRCRAFT (ALASKA AIRLINES CONFIGURATION)

MD-87 Captain's Panel

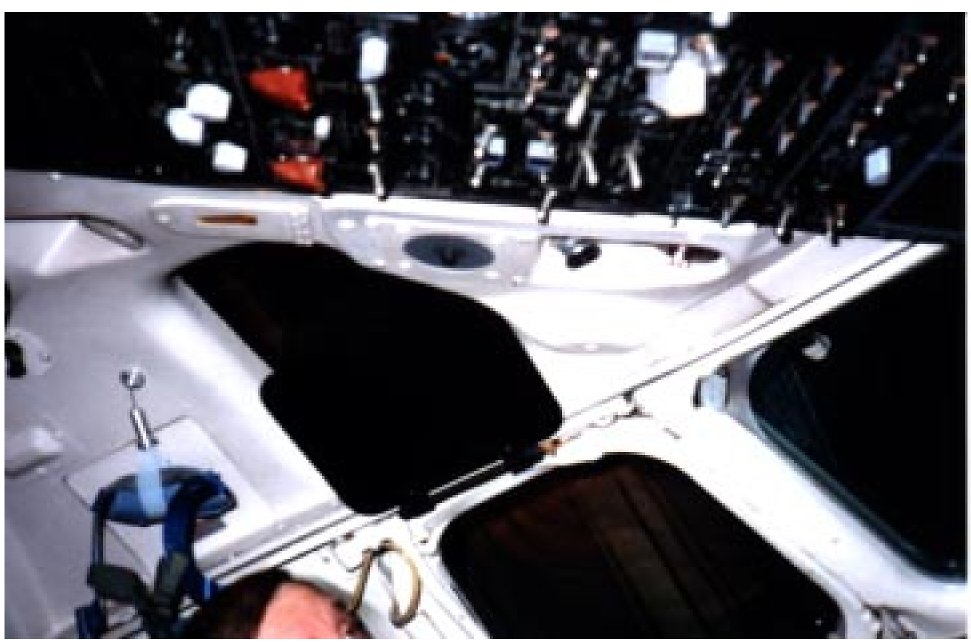
MD-87 First Officer's Panel

MD-87 Left-Center Panel



MD-87 Center Panel

MD-87 View of Overhead Area of Captain s Station



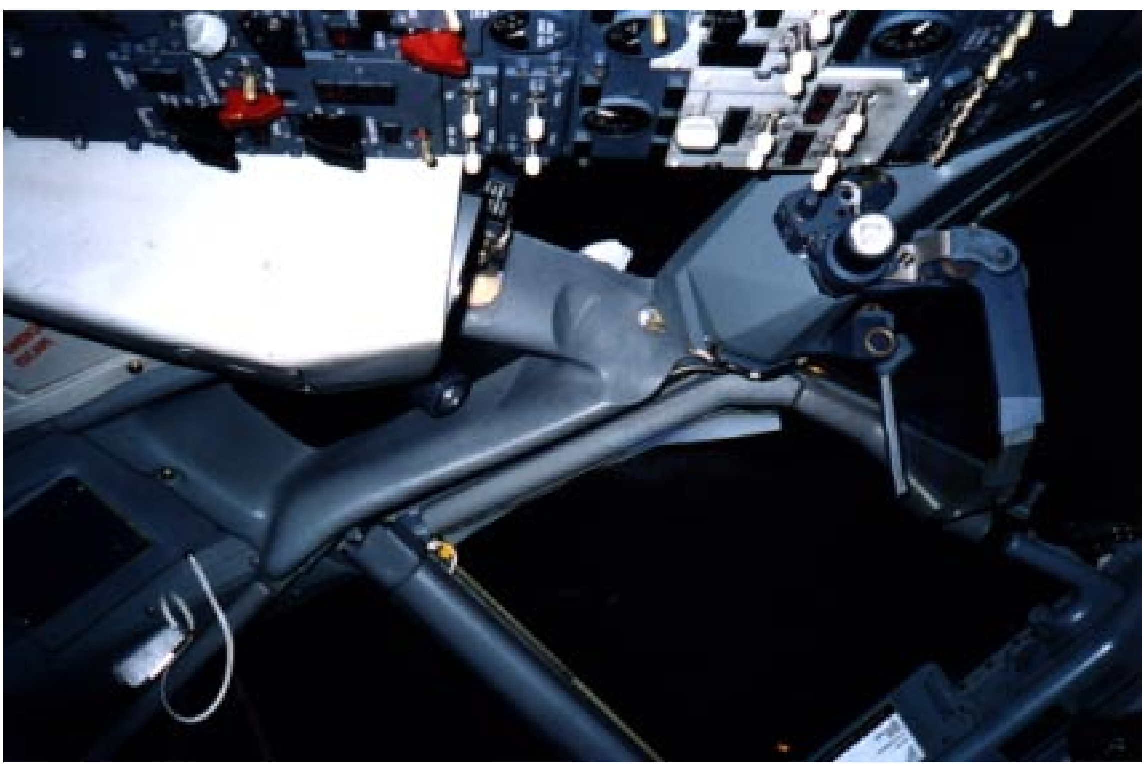
MD-87 . Another View of Overhead Area of Captain s Station

APPENDIX D - SELECTED COCKPIT PHOTOS OF THE B737-400 AIRCRAFT (ALASKA AIRLINES CONFIGURATION)

B737-400 - Captain's Panel

B737-400 First Officer's Panel

B737-400 - Center Panel



B737-400 View of HUD and Projector at Captain s Station

B737-400 HUD Combiner

APPENDIX E - SELECTED COCKPIT PHOTOS OF THE B747-400 AIRCRAFT (CATHAY PACIFIC CONFIGURATION)

B747-400 - Captain's Panel

B74

7-400 First Officer's Panel

B747-400 Full Panel and Pedestal

B747-400 Full Pedestal View

B747-400 View of Overhead Panel at Captain s Station

B747-400 View of Overhead Panel from behind Captain s Seat

APPENDIX F - SELECTED COCKPIT PHOTOS OF THE B747-200(F) AIRCRAFT (CATHAY PACIFIC AIRWAYS FREIGHTER CONFIGURATION)

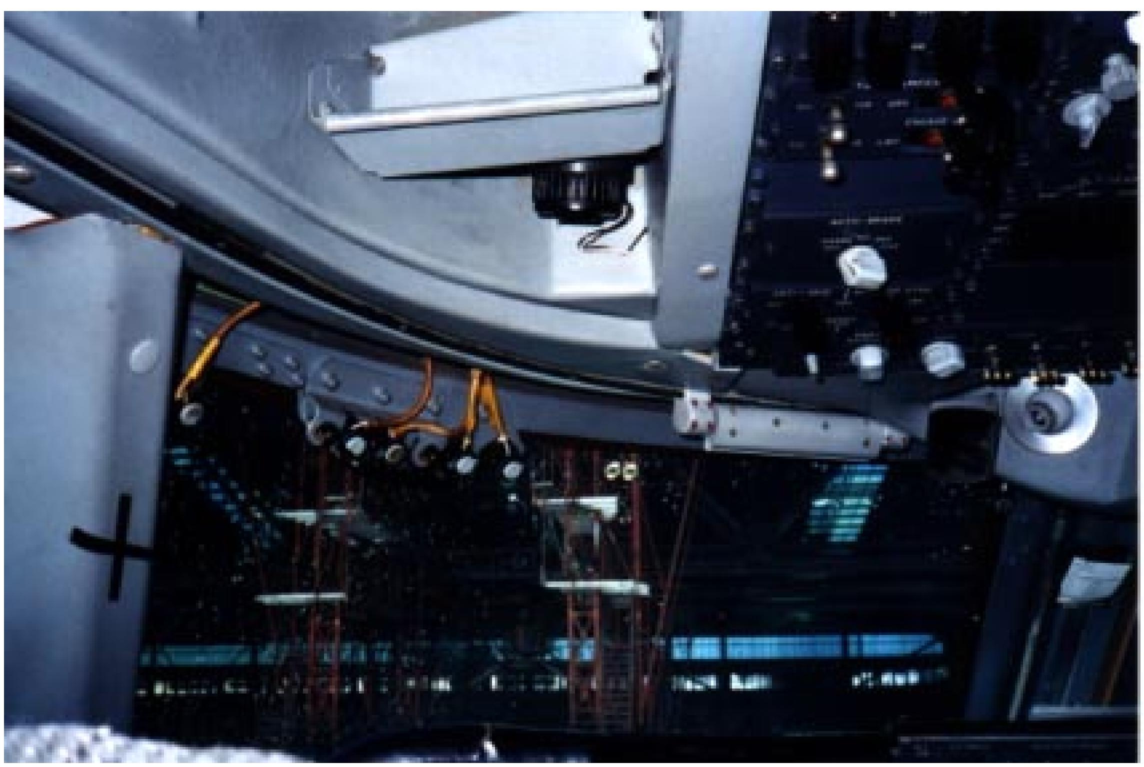
B747-200 - Captain's Panel

B747-200 First Officer's Panel

B747-200 - Center Panel

B747-200 — Full Pedestal

B747-200 View 1 of Overhead Captain s Station



B747-200 View 2 of Overhead Captain s Station

B747-200 View 3 of Overhead Captain s Station