THREAT DISPLAYS FOR FINAL APPROACH

A DISSERTATION

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FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

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May 2003

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality as a dissertation for the degree of Doctor of Philosophy.

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Abstract

During periods of good visibility, airports can conduct Closely Spaced Parallel Approaches (CSPA) and simultaneously operate parallel runways separated by more than 750 feet. When visibility degrades to Instrument Meteorological Conditions (IMC) and pilots must fly exclusively by the instruments, the runway separation required to operate parallel runways increases to 3400 feet or more. For many airports around the country and the world this means the second runway must be closed and the airport operates at half capacity. To alleviate the delays caused by this capacity reduction many airports worldwide are planning to expand and build new runways. The projected cost of the ten largest airport projects in the United States is $8 - 16 Billion. Perhaps a less expensive solution can be found with innovative technology rather than real estate?

This research presents the first ever design, implementation, and characterization of a synthetic vision display and the supporting flight system to attempt to achieve this solution. The display uses 3D graphics and an air-to-air datalink called Automatic Dependent Surveillance – Broadcast to present the pilot with the information necessary to aviate, navigate and monitor traffic. This thesis also documents the first series of flight experiments to test the applicability of synthetic vision displays to both runway incursion avoidance and CSPA. Finally, utilizing the results from the flight testing in a Monte Carlo analysis, the effect of deploying this display on minimum safe runway separation is calculated.

It has been found that the minimum safe runway separation for IMC operation can safely be reduced to 1900 feet. If, in addition, significant changes are made in Air Traffic Control procedures for longitudinal aircraft spacing, the analysis shows that the display system presented herein will allow for runway separation of 1400 feet with no new restrictions on aircraft size or crosswind. Furthermore, with certain restrictions on aircraft size and crosswind the runway spacing can be reduced to 750 feet. These results have tremendous implications for pilots, controllers and the public. They will also have large impacts on the financial and environmental costs of airport expansion projects

Acknowledgments

The completion of this doctorate has been the largest and most difficult endeavor of my life. Whether that says that my life has been unduly easy or that my thesis was unduly hard, I cannot say. What I can say is that I did not, nor do I now have, the strength to complete such an endeavor alone. Over the years I have called on the aid of family, friends and colleagues. Those kind souls have answered with more copious and more effective help that I could have imagined.

My mother and father have been my closest allies in this process. In addition to support and love they also assist me in the most direct of ways. Mom helps me stay awake during "all-nighters." Due to the time difference between Sydney and Stanford, Mom is arriving home from work as the clock strikes midnight in the lab. If requested, Mom is all too happy to ring me at 3am to wake me from a catnap. My father, along with my Uncle Ken, took on the formidable task of proofreading the first revisions of this manuscript. My step-mother has also been a staunch supporter of finishing the Ph.D.

Friends, dance partners, and colleagues have all offered help or have been willingly conscripted for flight tests. In no particular order, I owe my thanks and more than one six-pack to, Tony B., Frank V., Frank B., Keith, Andy, Mohamad, Skander, Maria, Sherm, Jonathan, Brenda, the San Diego Crew, Swingtime, Vintage, RadVin, Decadance, Ming, Sharon, Sasha, Lee, Wendy, Mieke, Ben and Sky Research, Rodney, Todd, Eric, Shau-Shin, Ryan & Monica, Aldo, Nancy & John & Sarah V. Chris & Andrew & Charlotte, Holt.

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The flight test and simulation pilots deserve my thanks for agreeing to fly my experiments as a favor to me:

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- Capt Michael Maya Charles, Federal Express,
- Ben Hovelman, Sky Research,
- Capt Al Bernard, United Airlines (ret.),
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This thesis is dedicated to those generous people who have shared their assistance, friendship and love with me over the last several years. I am increased by their gift and humbled by their affection.

May, 2003 San Carlos, CA Chad Jennings

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Acronyms Defined

Term	Definition	Chapter Defined
ADS-B	Automatic Dependence Surveillance - Broadcast	Chapter 3
AGL	Above Ground Level	Chapter 6
AILS	Airborne Information for Lateral Separation – NASA research program	Chapter 2
AMASS	Airport Movement Area Safety System – alerting logic for ASDE-3 Radar	Chapter 2
ANOVA	Analysis of Variance	Chapter 5
ASDE-3	Airport Surface Detection Equipment – surface radar at major airports	Chapter 2
CDTI	Cockpit Display of Traffic Information	Chapter 2
CSPA	Closely Spaced Parallel Approach	Chapter 1
FAA	Federal Aviation Administration	Chapter 1
FTE	Flight Technical Error	Chapter 3
GA	General Aviation	Chapter 1
GPS	Global Positioning System	Chapter 1
HITS	Highway-In-The-Sky	Chapter 2
IFR	Instrument Flight Rules	Chapter 2
IMC	Instrument Meteorological Conditions	Chapter 2
kts	knots (1 kt = 1 nautical / hour)	Chapter 2
MSL	Mean Sea Level	Chapter 5
MSRS	Minimum Safe Runway Spacing	Chapter 7
NAS	National Airspace	Chapter 2
nm	nautical miles	Chapter 2
NSE	Navigation Sensor Error	Chapter 3
NTSB	National Transportation Safety Board	Chapter 2
OTW	Out-the-Window	Chapter 6

P(LOS)	Probability of a Loss of Separation	Chapter 7
PFD	Primary Flight Display.- artificial horizon, shows roll and pitch of the aircraft	Chapter 2
PVT	Position/Velocity/Time	Chapter 4
RI	Runway Incursion	Chapter 2
RIM	Runway Incursion Monitor	Chapter 6
RIPS	Runway Incursion Prevention System	Chapter 2
RSP	Runway Safety Program	Chapter 2
SA	Situational Awareness	Chapter 2
SFO	San Francisco International Airport	Chapter 1
SJC	San Jose International Airport	Chapter 5
SV	Synthetic Vision	Chapter 1
SV PFD	Synthetic Vision Primary Flight Display	Chapter 3
TSE	Total System Error (TSE = NSE + FTE)	Chapter 3
UPS-AT	United Parcel Service – Aviation Technologies	Chapter 4
VFR	Visual Flight Rules	Chapter 2
VMC	Visual Meteorological Conditions	Chapter 2

Chapter 1

Introduction

1.1 Problem Statement

The airspace in the United States and around the world is primarily constrained by the landing capacity of the largest airports. In a Winter 2001 statement to Congress, John Carr, the President of the Air Traffic Controllers Association said, "We need a concrete solution." He estimated that fifty miles of new concrete runways around the United States would solve the congestion problem. Mr. Carr has probably correctly evaluated the situation but each mile of runway is an expensive proposition. Amid great furor, San Francisco proposes adding 4-5 miles of runway for $2-$10 billion dollars. Lambert Field in St. Louis is adding approximately two miles of runway at the expense $1.1 billion dollars and almost two thousand existing homes and lots of land. Figure 1.1 shows the Lambert Field real estate acquisition schedule. The color code marks when a particular track of land will be acquired by the airport.

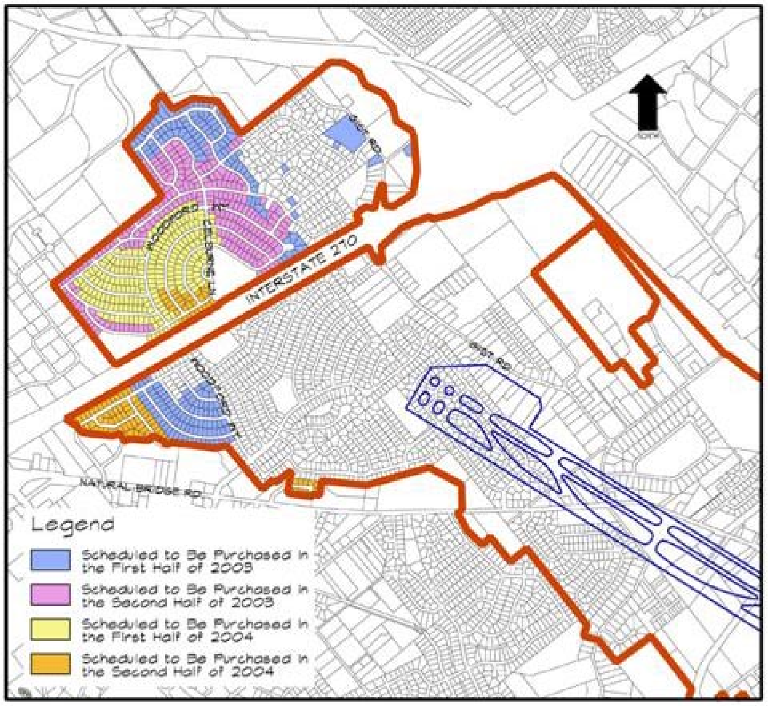


Figure 1.1 – Lambert Field Land Acquisition – 1,937 parcels of land (urban homes) acquired or to be acquired. The Mayor of St. Louis was among those forced to sell.

If you are a driver, an extra fifty miles of concrete does not sound like a big proposal. However if those miles are concrete runways at big-city airports the price tag skyrockets. In San Francisco and St. Louis, the aggregate costs exceed $1 billion per mile! That figure does not include environmental costs or unrest in the community.

A significant portion of that price tag is driven by the need to have at least 3400 feet between runway centerlines to do independent approaches when the visibility is too poor for the pilots to see adjacent aircraft. In this situation it is up to the air traffic controller to assure separation by using radar surveillance and radio communication. Obviously it takes more time for a controller to interpret radar screen data, discern a problem, and communicate that problem than it does for pilots to look out the window and respond. This delay in emergency alerting is what inflates the runway separation in low visibility. The runway separation requirement when the visibility is good is 750 feet [FAA99].

Thirty four of the major airports in the United States have runways separated by less than 3400 feet. When the fog or clouds come in and the visibility decreases, those airports are often forced to limit operations or entirely close one runway. In the worst cases this can exactly halve that airport's landing capacity. Communities served by those airports have a great interest in the problem as well. The current method of solving the problem is either by adding new runways to existing airports or by building entirely new airports. It is a big enough concern that the leadership of those communities are willing to move thousands of residents and pay billions of dollars. Table 1.1 shows the ten most expensive runway expansion projects in the United States [AIRPORT TECH].

Airport	Forecasted Completion	Forecasted Cost
Atlanta	2005	1B
Boston	2002	33M
Chicago	2008	2B
Cincinnati	2006	220M
Dallas/Ft Worth	2008	350M
San Francisco	2008	2.5-10B
Seattle	2006	733M
St. Louis	2006	1.1B
Wash. Dulles	2011	400M
Greensboro	2006	126M

Table 1.1 – Runway Expansion Projects in the United States

As Figure 1.2 shows, other nations have made this same realization and are addressing this constraint with thirty-three airport and runway expansion projects worldwide. North America alone owns almost half of these projects. From Table 1.1 it can be seen that the most expensive 10 projects have a total budget of $8-$16

Billion. If the low estimate average cost of 800M is applied to the thirty-three worldwide projects, then that reveals that the world is facing an airport expansion cost of approximately $26 Billion.

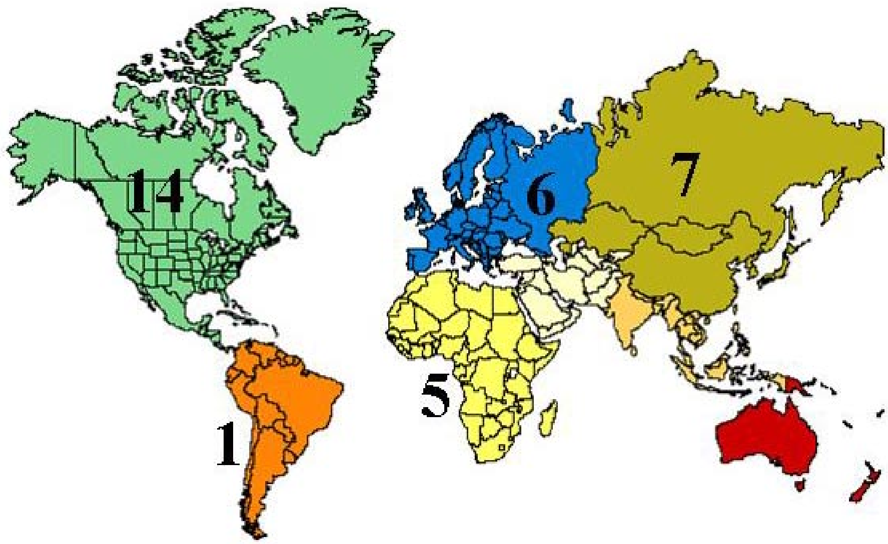


Figure 1.2 – 33 Runway Expansion Projects Being Planned or Underway Around the World [AIRPORT TECH]

This dissertation presents the application of technology, research and development to find another solution that requires fewer additional miles of runways. This new solution will hopefully be far less costly, both financially and environmentally.

1.2 New Solution

Simultaneous approaches to parallel runways separated by 750 ft can be flown in visual conditions [FAA99]. If a cockpit instrument can reproduce the critical elements of the visual with the same fidelity as the out-the-window view then perhaps pilots will be able to fly the same operations using that instrument as they can using the out-the-window scene. The goal of this research is to produce such an instrument.

The instrument presents the pilot with the information necessary to aviate (control) and navigate (guide) his/her aircraft while monitoring traffic on the parallel approach and on the runway. It does this by presenting the pilot with real-time information about his/her own aircraft and with real-time traffic position, heading, velocity, and roll angle.

1.2.1 Enabling Technologies

As stated above, the goal is to produce a cockpit display that reproduces the critical cues of the out-the-window scene. To do that, the display must understand the location and orientation of the vantage point from which to draw the out-the-window scene. In addition, the display must convey traffic data. The following technologies made it feasible to build a prototype display.

1.2.1.1 Global Positioning System (GPS)

GPS is a satellite-based navigation system operated by the U.S. Department of Defense. The system provides users worldwide with highly accurate position, velocity and time information. Currently, there are 27 satellites in Middle Earth Orbit ~22,000km above the earth in nearly circular orbits. Properly equipped users can measure the time of travel of a signal from a GPS satellite to calculate the range to that satellite. By using ranges from four or more satellites users can determine their 3D position and time offset.

The standard positioning service of GPS gives position accuracy of about ten meters. Using differential GPS, like the Local Area Augmentation System (LAAS) or the Wide Area Augmentation System (WAAS) increases that accuracy to less than two meters [Enge96]. WAAS is scheduled to be operational by August 2003.

1.2.1.2 Automatic Dependent Surveillance – Broadcast (ADS-B)

Once all the aircraft know their position using GPS or another position sensor it is necessary to communicate those data with neighboring aircraft. ADS-B is an air-to-air datalink to do exactly that. ADS-B broadcasts position, velocity, flight ID and other data at a nominal rate of 1Hz to any ADS-B receiver within range of the signals.

This technology is beginning to emerge in the aviation community. The Cargo Airlines Association, in conjunction with NASA, the Federal Aviation Administration (FAA), and academia orchestrated a pair of Operational Evaluations of ADS-B in July 1999 and 2000. [ADSB OpEval]. More than 20 aircraft were equipped with ADS-B and Cockpit Displays of Traffic Information. These aircraft then flew controlled scenarios common to Air Cargo Operations: departure spacing control, arrival spacing control, enhanced visual acquisition of traffic, ascending through low cloud layers, runway incursion mitigation. These OpEvals were designed to demonstrate the utility of ADS-B to the major air carriers in the United States.

The FAA's Capstone Project [CAPSTONE] has a similar mission to the OpEvals. Capstone is a strategic deployment of ADS-B technology for general aviation (GA) aircraft in Alaska. Currently, Capstone has outfitted some 200 light aircraft (less than 12,500 lb) aircraft with ADS-B. These aircraft are using ADS-B in their everyday operations.

1.2.1.3 Inertial Navigation System (INS)

Aircraft attitude information, roll, pitch and heading are essential to controlling the vehicle. Several technologies can provide high bandwidth and accurate attitude information. Inertial Navigation Systems integrate the output of highly accurate accelerometers and gyroscopes to calculate position and aircraft attitude. Although it was not used in the flight tests described later in this document, Stanford University has used GPS-only attitude sensors for this function [Hayward98]. Although Inertial Navigation Systems are an enabling technology they are not a new technology. All modern Civil Air Transport aircraft are equipped with an INS.

1.2.1.4 Synthetic Vision

GPS and ADS-B are methods to acquire and transmit data. Once that data exists in the electronics of the aircraft it is still necessary to transfer it clearly and quickly to the pilot's mind. As shown in Figure 1.3, the principle behind Synthetic Vision cockpit displays is to reproduce the out-the-window scene on a screen in the cockpit. The display system integrates position and velocity information from GPS and attitude information from an Inertial Navigation System (or other attitude sensor) with traffic data from a datalink such as ADS-B. The display then presents this information to the pilot along with information from terrain, runway and pathway databases. In this manner the Synthetic Vision Display system can generate a clear view of the out-the-window-scene regardless of the actual visibility conditions.

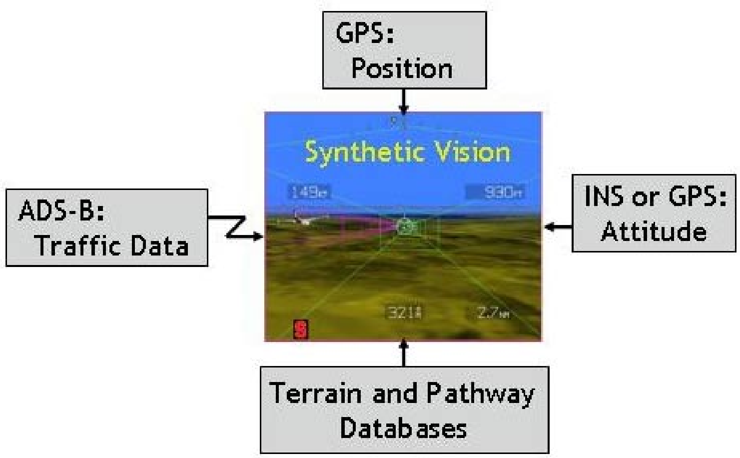


Figure 1.3 – Cartoon of Synthetic Vision CSPA Display System

1.3 Contributions

This effort was the first research program to apply Synthetic Vision methodology to Closely Spaced Parallel Approaches (CSPA) and Runway Incursion Mitigation. As will be seen in Chapter 3 this required new display designs and modifications to existing synthetic vision (SV) displays. In support of those designs, entirely new symbologies, the Roll Bug and Color Strips, were invented, developed and tested.

Similarly, the simulation studies and flight demonstrations following the display design marked the first time this type of display had been experimentally evaluated.

To ascertain how pilots would react to these novel cockpit interfaces the performance of the displays in CSPA and Runway Incursion scenarios were characterized in both human-in-the-loop simulations and flights.

Although it is not a research contribution the integration of the datalink was a significant engineering effort. It was necessary to reengineer of ADS-B data message to be suitable for CSPA operations. This involved a re-derivation of the datalink requirements then redesigning and reimplementing the datalink to suit the needs of the experiment.

Using the characterizations derived in simulation and in the aircraft it was possible to then analyze the effect of novel display systems if they were put into widespread use.

1.4 Roadmap of the Thesis

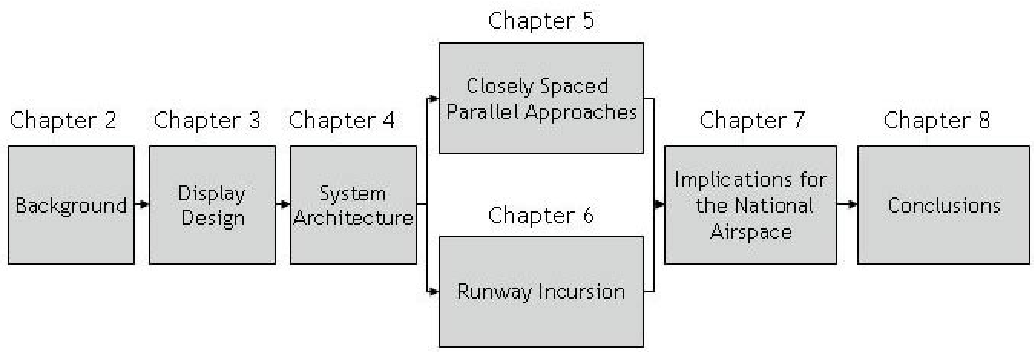


Figure 1.4 – Roadmap of the Thesis

Figure 1.4 shows the roadmap of the topics addressed in the thesis. Chapter 2 gives the reader background information dealing with Closely Spaced Parallel Approach operations and Runway Incursion Mitigation and Synthetic Vision. Chapter 2 also outlines the prior research in these areas. Chapter 3 details a task analysis of pilots on final approach and the display design generated to accommodate those tasks. The flight system necessary to achieve those displays is presented in Chapter 4. Chapter 5 reviews the characterization of the displays in human-in-the-loop simulations and flight tests as applied to Closely Spaced Parallel Approaches. The testing of the Runway Incursion Monitor is described in Chapter 6. Finally, the effect that these displays and display systems can have on the safe spacing of parallel runways is analyzed in Chapter 7. Chapter 8 holds a concise summary of the thesis.

Chapter 2

Background

This chapter outlines the current procedures, equipment and accidents surrounding Closely Spaced Parallel Approaches and Runway Incursions. Prior research in these areas and the relationship of this work to those prior efforts is described.

2.1 Current Procedures and current technology in the field

To land at an airport an aircraft must transition from en route flight to approach flight. For the pilot, this means that he or she must complete tasks such as contacting the approach air traffic controller, change course as per instructions, reduce speed, alert the passengers to buckle up and a host of other items. For the controllers, they must guide and direct all the aircraft to the airport such that the aircraft can align themselves with, and then land, on the runways. The geometrical pattern that is used to transition en route to landing is called the "Basic T".

2.1.1 Basic T

To minimize the over-the-ground speed at touchdown, pilots fly into the wind when landing. Airport designers orient runways such that they are parallel to the prevailing wind. This is what determines the orientation of the Basic T. The prevailing wind direction at Stanford University is roughly North West. To simplify the figures and the discussion in this chapter it is assumed that the wind comes mostly from the North. Figure 2.1 shows the properly aligned (and inverted) Basic T for the fictional Stanford University Airport, abbreviated SUA.

There are several points along the T whose coordinates serve as landmarks. BEARS and CARDI are Initial Approach Fixes (IAF). An aircraft arriving from the east would be routed first to CARDI and then to the Intermediate Fix (IF), ROBLE. ROBLE also serves as an IAF for aircraft arriving from the south. At ROBLE, the approaching aircraft turn northward toward the Final Approach Fix (FAF), OSTRA. MATEO is the Missed Approach Point (MAP), usually located at the runway threshold. If, at MATEO, the conditions are unacceptable the pilots will execute a missed approach and abort the landing. Pilots will then be instructed to hold at CARDI or BEARS and wait for the weather to improve. Or, they will be instructed to depart SUA and land at another airport. If, however, the conditions are acceptable, then the pilots will complete the landing at SUA [FAA99].

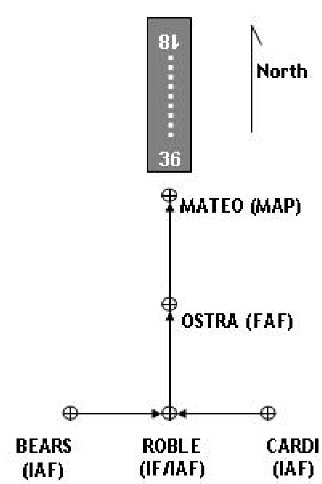


Figure 2.1 - Basic T at the fictional Stanford University Airport

There is a nomenclature to the legs of the T between the fixes. The bottom of the pattern between CARDI or BEARS and ROBLE is called the base beg. Generally the base beg is between 3 and 6 nautical miles (nm) long. Pilots “flying base” then turn to the final approach. The total final approach is generally 10-15 nm long. Although it is not pictured on this figure pilots inbound to CARDI or BEARS and flying southward are said to be on the downwind leg. If the wind is nominal then pilots flying this leg are actually flying downwind.

Figure 2.2 shows the most basic traffic pattern in use in aviation. It is used in good weather and in bad, from the smallest single seat aircraft to the largest, carrying hundreds of passengers. Figure 2.2 depitcts a “right handed” traffic pattern; thusly named because aircraft following this trajectory will always be making right turns. Although it is not depicted, there is a symmetric “left handed” traffic pattern. This pattern is also both an approach and departure pattern whereas the Basic T is solely for approach.

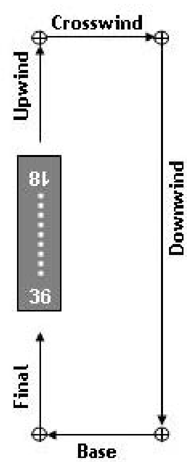
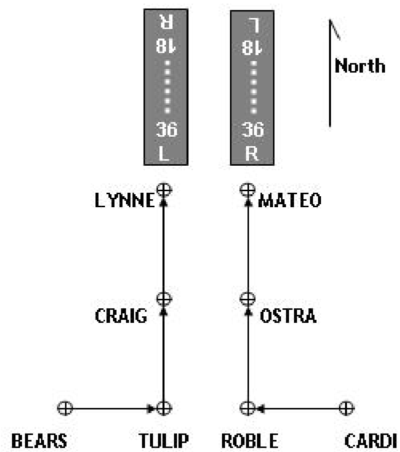


Figure 2.2 – Approach and Departure Traffic Pattern

Mixing the names of the fixes (Figure 2.1) and the names of the legs (Figure 2.2); yields the aviation vocabulary necessary to describe an approach. An example aircraft approaching SUA from the north east will be instructed to join the right downwind and proceed to CARDI, then turn right base to ROBLE and then turn to final for OSTRA and the airport. An aircraft approaching from the south will likely be given instructions to join final at ROBLE.

2.1.2 Modified T to Parallel Runways

Aircraft operating in both the right and left traffic patterns, is exactly analogous to two "base" roads merging onto a "final" highway. The analogy extends to the delays in merging caused when there is too much traffic. The solution, shown in Figure 2.3, is to add another lane of traffic, a parallel approach.



It should be noted that the Basic T and the Modified T are procedure templates. Large airports will customize these procedures to more exactly fit their operations.

Figure 2.3 – Modified T for Parallel Approaches[1]

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[1] Sources of the names of the Fixes:

CARDI – Stanford CARDInal
BEARS – Cal Bears
ROBLE – Roble Gym is home to Stanford Dance
OSTRA – The OSTRAnder ski hut in Yosemite
MATEO – I currently live in San Mateo
LYNNE – My mother
CRAIG – My Father
TULIP – I wrote this section in the Stanford University Bookstore. When I ran out of immediate family members, I noticed a coffee table book called Tulip sitting on the shelf to my right.

2.1.3 Visual versus Instrument Conditions and Flight Rules

The funneling of traffic onto the runways must take place in good and bad weather. Instrument/Visual Meteorological Conditions are the clear and concise metrics with which to measure the condition of the weather. Around major airports Visual Meteorological Conditions (VMC) are generally defined as visibility greater than three nautical miles, cloud ceilings greater than 1000 feet above ground level. Some airports choose to operate under more restrictive rules for certain operations. San Francisco International, for safety considerations in the event of a missed approach, requires 5 nm visibility and cloud ceilings above 2100 feet for VMC parallel approaches. Instrument Meteorological Conditions (IMC) are defined by any visibility and cloud conditions that are more restrictive than the locally established VMC [FAA99].

Along with those definitions of weather conditions are the definitions of the appropriate flight rules. Not surprisingly, Visual Flight Rules (VFR) are employed during Visual Meteorological Conditions and Instrument Flight Rules (IFR) must employed during IMC and for all flights above 18,000 feet. Commercial airlines often use IFR for all portions of all flights for increased safety.

2.1.3.1 Traffic Alert and Collision Avoidance System

One tool that is useful to pilots in both VMC and IMC for identifying proximate traffic is the Traffic Alert and Collision Avoidance System (TCAS). TCAS generates traffic advisories and resolution advisories based on the returns from a radar installed on the aircraft. Resolution and update period limitations of the radar have yielded TCAS of limited use in CSPA operations. Some pilots put the TCAS in training mode [Trotter03] while on final approach. In this mode the display of traffic still functions but the alarms are disabled because constant advisories are a nuisance. TCAS was designed to be useful in the en route and transition to approach phases of flight. While the applicability of TCAS for final approach is dubious, pilot reaction to having TCAS for en route has been exceptionally favorable.

Using Instrument Flight Rules, Visual Flight Rules or TCAS equipment doesn't affect the shape of the traffic patterns described in Figure 2.1, Figure 2.2, and Figure 2.3. It does affect the method of navigation during the final approach and the responsibility and requirements for aircraft separation.

2.1.4 Visual Approach

Navigation on final approach during VMC is a relatively simple task. The harder problem of finding the airport and aligning with the runway has already been solved by the time the pilot turns to the final approach. Now the pilot can visually track the runway or closer landmarks and make fine corrections in attitude and airspeed as they descend to touchdown.

During VMC, controllers are responsible for separation until a pilot declares, "Traffic in sight." When the controller acknowledges that statement, the legal responsibility for maintaining separation from that traffic transfers to the pilot. Once the pilots have visual contact with the traffic there is no mandatory separation to be maintained. It is now up to the judgment of the pilots to determine safe distances. Adjustments to that distance can be made as quickly as a pilot can see the other aircraft and take action. As such pilots conducting parallel approaches can land on runways separated by only 750 feet [FAA99].

2.1.5 Instrument approach procedures

When pilots cannot see out the windows the scenario above becomes much more complicated. Pilots must rely exclusively on instruments to control and navigate the aircraft and they must rely on instruments and air traffic controllers to maintain separation between aircraft. Because the controller is the information conduit between proximate aircraft it is necessary to increase the distance between aircraft during IMC. Depending on the fidelity of the radar available to the controller, parallel runways must now be spaced farther apart.

Precise navigation on final approach is most often accomplished by using an Instrument Landing System (ILS). On the ground the ILS is comprised of two radio frequency emitters called the localizer and glideslope. These provide lateral and vertical deviation from a constant gradient approach path leading to the runway. In the cockpit pilots refer to the "ILS needles" to track the approach path to the runway. A more complete treatment of the ILS and comparisons to GPS navigation is available in [Houck99].

There are three varieties of simultaneous approaches to runways in IMC, Independent Parallel, Dependent Parallel, and Independent Closely Spaced Parallel Approaches. All three use the ILS navigation but each has different requirements and responsibilities.

2.1.5.1 Independent Parallel Approaches

Independent parallel approaches are permitted to dual or triple runways with centerlines separated by more than 4300 feet. Between the runways, a 2000 foot wide No Transgression Zone (NTZ) is protected by two final approach controllers. Each controller monitors the traffic inbound for a particular runway. If an aircraft appears to be straying from its assigned final approach course, the controller for that approach should attempt to alert the wayward pilot to return to the localizer course. If this proves unsuccessful the controller informs both aircraft to break out of the current approach and perform a missed approach. The pilots will then fly to a predefined holding pattern and wait to be reintegrated into the traffic stream or to be rerouted to another airport.

The process of warning the endangered pilot takes several seconds. That delay, coupled with the inherent inaccuracies in the ILS and the standard approach radars must be accounted for when determining the requirements for runway spacing. It is for these reasons that the requisite runway spacing for independent parallel approaches is 4300 feet. [FAA99].

2.1.5.2 *Dependent Parallel Approaches*

Dependent parallel approaches can be conducted at airports with runways separated by 2500 feet or more. Controllers dedicated to each approach path are not required. A radar equipped tower controller affords aircraft a minimum of 1.5 nautical miles of diagonal separation (Figure 2.4).

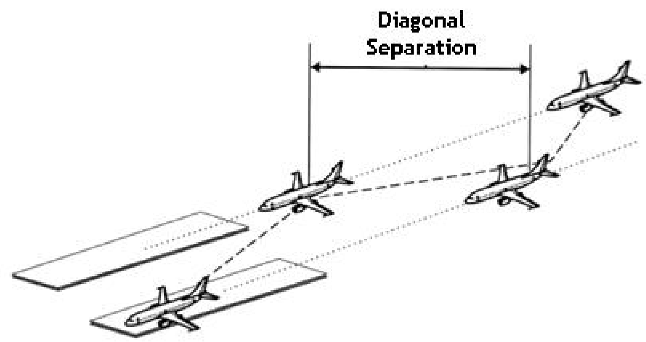

Figure 2.4 – Dependent Approaches (figure from http://www2.faa.gov/ATPUBS/AIM/Chap5/F0504016.GIF)

2.1.5.3 *Reduced Separation Parallel Approaches*

Reduced Separation Parallel Approaches can be conducted at facilities equipped with a Precision Runway Monitor (PRM) and with runways spaced between 3400 feet and 4300 feet. A Final Monitor Controller is required for each runway. As with independent approaches a 2000 foot wide no transgression zone (NTZ) is established between the approach courses and *"The Final Monitor Controller issues breakout instructions to any endangered aircraft on the adjacent approach course when an aircraft penetrates the NTZ."* [PRM Video] The procedures are similar to the independent approaches but the runways can be 900 feet closer.

The PRM radar has far superior accuracy and a faster update rate than standard approach radar (azimuthal accuracy = 0.057°, PRM update rate = 1Hz [Raytheon PRM]).

The PRM display in Figure 2.5 shows the final monitor controller's bird's-eye-view of the landing aircraft with an identifier tag specifying the flight (United Airlines flight 611), the intended runway (29Left) and the type of aircraft (Boeing 727). The display also shows the approach corridors, and the NTZ. A predictor has also been implemented to convey the short term intent of the aircraft.

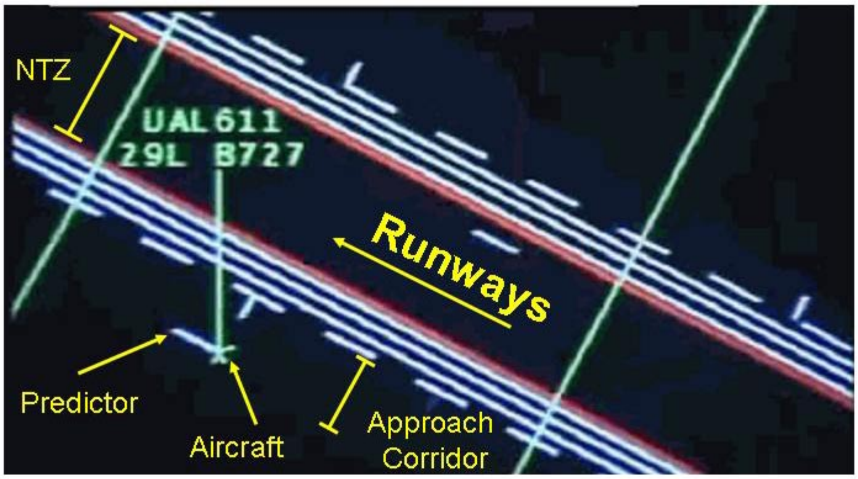

Figure 2.5 – Detail of Precision Runway Monitor Radar Display

This radar and display greatly reduces the time for a controller to detect a blunder and hence enables the reduction in requisite runway separation from 4300 to 3400 feet. Minneapolis/St. Paul and Sydney, Australia are two airports who have adopted this system. The fundamental shortcoming of the technology and ensuing procedures is that the controller has sole responsibility for separation and must detect and then convey the event of a transgression to the endangered aircraft. This communication loop is the significant driver that necessitates the 3400 foot spacing rather than the 750 foot spacing available during visual conditions when pilots can monitor neighboring traffic on their own.

2.1.6 Blunder on Final Approach

The act of a transgression during the final approach has been the subject of much debate in the parallel approach research community. A blunder, as it is called, first and foremost, is an extremely rare event. That can be seen both intuitively and empirically. Consider a parallel approach to the dual runways at Stanford University Airport. You, the reader, are the pilot of the aircraft on the right. You are currently at OSTRA and your parallel traffic is somewhere between TULIP and CRAIG. You know that there is an aircraft with pilots and passengers somewhere in the clouds to your left. If something were to go wrong with your aircraft you will do everything possible to turn away from the parallel traffic to avert any possibility of a collision. Intuitively, blunders toward parallel traffic are unlikely events.

Empirically: In the time since 1973 there have been roughly sixty million aircraft movements (take-off or landing) per year in the US [FAA03]. That totals approximately nine hundred million aircraft movements on the US airports in the last thirty years. In that period of time, this author is aware of only one accident resulting from a blunder on parallel approach. Empirically, an accident from a blunder is a very rare event.

Even though a blunder severe enough and ill timed enough to cause an accident is exceptionally unlikely, this is precisely the scenario that final monitor controllers watch for on their PRM display. This is also the scenario that drives the runway spacing requirements for parallel approaches. So, even though it does not occur in practice a blunder on parallel approach is frequently considered.

Over the years researchers have converged on a “standard blunder.” This trajectory is the input that researchers use in simulations to measure reaction times, miss distances after a blunder. The blunder profile includes first rolling toward the parallel traffic at less than 10 degrees/sec [Houck01] [Abbott01]. The maximum roll angle attained by the blunderer is assumed to be 30°. That roll angle is then held in coordinated flight until a heading change of 30° toward the parallel traffic is attained. Then, inexplicably, the blundering pilot recovers his/her aircraft and manages to level the wings but chooses to continue on the errant course. This is a totally contrived trajectory but it is a likely guess as to what a drastic and dangerous blunder on final approach would look like. This trajectory will be used as a baseline realizing that this "Standard Blunder" is not the worst possible that could ensue [Teo01].

2.1.7 Runway Incursions

For landing pilots the airborne blundering traffic is but one of the potential traffic threats to be considered. The other traffic threat (which is arguably more threatening) is that of a blunder on the runway, a runway incursion (RI). Runway incursions are formally defined as "any occurrence at an airport involving an aircraft, vehicle, person or object on the ground that creates a collision hazard or results in the loss of separation with an aircraft taking off, intending to take off, landing, or intending to land." [FAA01]. In lay terms a runway incursion occurs when an aircraft and another vehicle want to occupy the same runway at the same time.

2.1.7.1 In the tower

Like the landing and approach phase of flight with its traffic patterns and procedures the ground environment also has structure. Aircraft proceed from the gates to the runways and back via well defined taxiways. Controllers at major airports monitor the travels of aircraft on the ground visually and at the major airports in the US controllers use Airport Surface Detection Equipment (ASDE- 3) when visibility is poor [RANNOCH03]. The ASDE-3 is a 1 Hz radar mounted on the control tower. From this vantage point it can pinpoint aircraft within the aircraft movement area that are visible to the controllers. In this implementation controllers are presented with a map of the airport overlaid with "blips" that show the current position of aircraft. Another technology deployed at 13 of the major airports as of January 2002 is the Airport Movement Area Safety System (AMASS) [NTSB03]. AMASS is a system of warning logic to accompany the ASDE-3 radar. AMASS provides visual and aural warnings of potential ground conflicts by real-time analysis of the ASDE-3 data and the published airline schedules. There is a continuing debate between the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB) as to whether AMASS offers sufficient protection from runway incursions [NTSB03]

Using visual reference backed up by the ASDE-3 ground controllers issue clearances in accordance with maintaining safe separation between, taxiing, landing and departing aircraft.

2.1.7.2 In the cockpit

Ground controllers are not the only sets of eyes and ears tuned to this issue. Although it is not written into law, pilots adhere to standard operating procedures set down by their airline or personal experience. One Federal Express L-1011 Captain told me that he cross checks every runway crossing clearance that he is given. He and his first officer visually check for traffic and verbally state, "Clear left" or "Clear right" if it is safe to proceed.

In poor visibility much more faith must be placed in the ASDE-3 radar and the controller's judgment.

2.2 Accident Synopsis

Although accidents in the US are extremely rare it is useful to understand how a tragedy can develop. These accidents almost always result from a series of unrelated and seemingly innocuous elements. It is only in hindsight that the trajectory of the cause and the magnitude of the happenstance are clear.

2.2.1 Closely Spaced Parallel Approach

On 12 April, 1973 a NASA Convair and a US Navy P-3-C collided while on final approach for Moffett Federal Air Station in Mountain View, California. (Ironically, this airport was the venue for the Closely Spaced Parallel Approach Flight Tests described in

Chapter 5). The collision and ensuing crash killed 16 of the 17 people aboard both aircraft [VP NAVY].

It should be noted that the visibility was excellent and that these are both large aircraft. The P-3-C is a four engine aircraft and has a wingspan of 99 feet. The Convair when it is set up for passengers can carry 96-121 people and has a wingspan of 120 feet.

At the time of the collision the P-3 was practicing landings on Runway 32Left. Visibility was "excellent" and both aircraft were operating under Visual Flight Rules. The Convair was returning from a two hour research mission over Monterey Bay.

- 14:46 - The Convair called the Moffett Air Traffic Control Tower (Moffett Tower) and reported that they were 10 nautical miles south of the airfield and requested a straight in approach (a straight in approach is one in which the pilot does not fly a downwind or base leg. Essentially the final approach is extended as far as necessary, see Figure 2.2.) The controller at Moffett Tower put the Convair on the approach for Runway 32Right and instructs the Convair to advise when it was 7 nm from the airport. Moffett Tower advises the Convair that there are several aircraft in the traffic pattern for Runway 32Left.
- 14:48 – The P-3 turns from left downwind to left base. The Convair advises Moffett Tower that he is 7 nm from the airport.
- 14:49 – Convair advises Moffett Tower that the landing gear are down and locked. Moffett Tower responds with wind speed and direction and then mistakenly directs the Convair to land on Runway 32 Left. Convair acknowledges "32Left, thank you."
- 14:50 – Two transmissions, "Tower; you got that?" [source unclear] followed by a garbled transmission. Moffett Tower responded, "Go Around. Go Around. Weave." Controller then instructed all other aircraft to climb and maintain an altitude of 1500'. By this time the aircraft had already collided.
- The Convair descended on top of the P-3 and pushed its nose wheel through the P-3 fuselage just ahead of the vertical tail. The two aircraft fell entangled

onto the 12th tee of the Sunnyvale Municipal Golf Course less than 2 nautical miles from the runways.

- The controller at Moffett Tower returned to work months later after a stay in a psychological hospital and extensive retraining.

The root cause of the accident was the controller mistakenly switching the Convair from the Right to the Left runway. Moreover, despite the clear visibility and the large size of the aircraft involved, the pilots were unable to see and avoid the traffic. Some variety of cockpit instrument, such as TCAS or the displays presented herein, to cross check the controller's clearances could have averted the accident.

2.2.2 Runway Incursion

Although runway incursions do not drive the spacing requirements between runways they do claim lives every year at small and large airports alike. Milan, Italy 2002, Taipei, Taiwan 2000, Los Angeles 1991, Tenerife, Canary Islands 1977, stand as hallmarks as to why the National Transportation Safety Board has listed runway incursions as the number one 'Most Wanted Safety Issue' in aviation since September 1990 [NTSB03]. The real tragedy of these accidents is that while they collectively claimed 868 souls (183, 81, 22, and 583, respectively) they almost always result from some small, perhaps understandable, but ultimately avoidable mistake.

On 27 March 1977, Pan Am 1736 and KLM 4805, both Boeing 747's, collided on the runway at Tenerife, Canary Islands, Spain claiming 538 lives. Up until 11 September 2001 this was the most deadly aviation accident in history [TENERIFE]. Very much like 11 Sept, strange events on the day led to the accident.

Early in the day of 27 March a bomb exploded in the terminal building of Las Palmas Airport in the Canary Islands. The threat of a second explosion led controllers to route traffic to Los Rodeos Airport on nearby Tenerife Island. This resulted in an unusual overcrowding of Los Rodeos.

Both aircraft were on the ground at Los Rodeos prior to the collision. Both aircraft were making preparations to depart the airport. Visibility conditions were poor and worsening at the time of the collision.

- 17:05 – KLM is positioned for departure at the approach end of Runway 30.
- 17:05.41 – A slight forward movement due to opening of the throttle is observed on KLM. The co-pilot says, "Wait a minute, we don't have an ATC clearance." Captain replies, "No; I know that, go ahead – ask."
- 17:05.44 – KLM tells the Tower, "Ah, KLM four eight zero five is now ready for take-off, and we're waiting for our ATC clearance." From the cockpit tapes, this message was heard in the Pan Am cockpit.
- 17:06 – Tower gives KLM a departure clearance and the co-pilot read it back correctly. He also added the sentence, "We are now at take-off."
- 17:06.11 – the brakes of KLM released and the aircraft began its take-off roll.
- 17:06.18 – the Tower replied in the following way, "OK." Then about 2 seconds later added, "Stand by for take-off…I will call you."
- KLM continued its take-off roll.
- Simultaneously the Pan Am co-pilot said to the Tower, "and we are still taxiing down the runway." This communication caused a "shrill noise" in the KLM cockpit.
- 17:06.25 – Tower confirmed the Pan Am message, "Papa Alpha one seven three six, report runway clear. This was audible in the KLM cockpit.
- 17:06.29 – Pan Am replied, "OK, will report when we are clear. This reply was audible in the KLM cockpit.
- In the KLM cockpit the following sentences were spoken
- 17:06.32 (co-pilot) – Is he not clear then?
- 17:06.34 (captain) – What did you say?

- 17:06.34 (co-pilot) – Is he not clear, that Pan American?
- 17:06.35 (captain)– Oh, yes (emphatic)
- 17:06.47 the KLM captain utters an exclamation and the impact occurs shortly thereafter. The KLM aircraft was already pitched up with their nose wheel off the ground at the time of impact.

The root cause of this accident was the KLM captain initiating take-off and continuing the take-off without clearance. There were several contributing factors. The KLM Captain was anxious to take off because his crew was approaching the end of their legal duty time. Interrupting the flight to get a fresh crew would have caused significant inconvenience to the airline and the passengers. In addition the poor visibility conditions contributed to the KLM captain's uncertainty in the position of the Pan Am aircraft. The ambiguous statement by the KLM co-pilot, "We are now at take-off." was not interpreted by the Tower or Pan Am as an indication that KLM had begun their take-off roll. In addition, the Pan Am call, "We are still taxiing down the runway." could have been obscured in the KLM cockpit. Lastly, the unusual circumstances in the Las Palmas airport generated overcrowding at Los Rodeos.

2.2.3 Summary of Accidents

It is only in hindsight that the trajectory of the cause and the magnitude of the happenstance are clear. Such is the case with the two accidents described above.

CSPA – Moffett – controller makes a simple mistake and says right instead of left. The pilot then assumes that the controller meant the mistake and failed to crosscheck with the earlier warning that there were already several aircraft in the traffic pattern for the left. Then, both pilots didn't see the large and very proximate traffic. RI – Tenerife – a bomb in Las Palmas creates extensive rerouting and overcrowding at Los Rodeos. These stressors contributed to an experienced KLM Captain executing a take off without clearance.

It is possible to extract other examples of runway incursion from recent aviation history that share the same moral. These aged incidents were chosen over more recent accidents because they are particularly clear examples of the moral: A series of unrelated circumstances can combine and magnify into a dangerous situation. For this reason is it important to give pilots foolproof information on intuitive displays to cross-check instructions and to verify their situation.

2.3 Prior Art

First section of this chapter described current practices. Second section described some of the continuing accidents that occurred with those current practices. The current practices are very safe but there is obviously room for improvement, and the flying public and the professionals in aviation seek perfect safety records. For those reasons researchers have investigated methods and technologies to increase efficiency, throughput and safety. Of relevance to this discussion are the methods and technologies with Synthetic Vision and the operational areas of Closely Spaced Parallel Approaches and Runway Incursion Mitigation.

2.3.1 Synthetic Vision Research

Synthetic vision (SV) systems for aircraft have been the subject of discussion and research for 50 years. The concept of a Highway-In-The-Sky (HITS) originated with George Hoover and the Army-Navy Instrumentation Program in the 1950's [Barrows00]. Early work dealt with researching the appropriate symbology to control an aircraft in simulation [Grunwald84]. A decade later this research moved into small aircraft [Barrows95] [Theunissen97] [Alter98] [Jennings00] [Langley SV] [Sachs02] [Schnell02]. These efforts have shown that synthetic vision cockpit displays hold enormous benefits for all levels of aviation from General Aviation and Military Aviation to Civil Air Transport.

In particular these researchers have shown that synthetic vision and HITS can decrease a pilot's flying error (decrease the distance between where a plane should be at a particular time and where the plane is) while simultaneously decreasing the mental demands on the pilot and increasing the pilot's awareness of the state of the aircraft (Situational Awareness). All of these researchers have studied the approach and landing phase of flight. [Schnell02] has been particularly focused on evaluating the utility of SV displays integrated with a map display for approaches of a 757 operating as an air transport category aircraft. Flight test pilots preferred the SV display over the standard Electronic Flight Information System (EFIS). As a group, these researchers have discovered and studied the basic properties of synthetic vision displays for aviating (controlling and flying) and navigating a single aircraft for approach and landing.

2.3.2 Operational Research

2.3.2.1 Closely Spaced Parallel Approach Research

In response to the constrained landing capacity around the world NASA and Honeywell undertook a project called Airborne Information for Lateral Spacing (AILS). The goal of this effort was to develop a system that will enable CSPA operations at facilities with runways with centerline-to-centerline spacing of more than 2500 feet. AILS used the ADS-B air-to-air datalink and alerting algorithms to determine when the aircraft on the parallel approach was a threat [Elliott00] [Abbott02]. [Battiste02] conducted a detailed full mission simulation of the AILS system in and around the Seattle Tacoma International Airport. The AILS system is designed to mesh as seamlessly as possible with the current equipment and procedures found in the National Airspace (NAS). This means that the AILS cockpit displays are identical to standard displays with the addition of the AILS textual cautions and alerts. [Abbott02] concluded from questionnaires given to pilots immediately following flight tests that AILS was a "reasonable" system to implement and thus achieve IFR parallel approaches at 2500 foot runway spacings. This promising research has subsequently been abandoned by NASA.

Another research project aimed at CSPA is the effort surrounding the Paired Approach Concept put forth in [Stone98] and more deeply studied in [Bone01]. This concept strives to make procedural changes using ADS-B and Cockpit Displays of Traffic Information (CDTI) to increase the landing capacity of airports in IMC. Controllers pair like-speeded aircraft and deliver them to final approach with 1000 feet of vertical separation and within a certain longitudinal tolerance. The trail aircraft conducts the procedure by achieving and maintaining a defined longitudinal spacing to the final approach fix. The trailing aircraft is responsible to maintain longitudinal separation and therefore must execute a breakout maneuver if it cannot keep the requisite spacing. These efforts are aimed at increasing capacity by safely reducing minimums for CSPA Operations.

Houck conducted a series of flight tests wherein she verified that the roll angle of the traffic is a leading indicator for pilots to detect a blunder. In a separate experiment she quantified the Flight Technical Error of pilots flying with the Stanford University Synthetic Vision Display [Houck01]. Using a Monte Carlo simulation she calculated the probability of collisions during closely spaced runways versus certain parameters including; reaction time to blunders and ability to match the roll angle of the blundering aircraft.

Pritchett [Pritchett99] conducted a simulation study in which she added symbology to a conventional primary flight display (PFD) and navigation display to show the lateral, vertical, and longitudinal spacing of traffic on the parallel approach. To this author's knowledge this was the first attempt to put CSPA traffic on a civilian Primary Flight Display (shown below in Figure 2.6). This display was coupled with top down "bird's eye" displays.

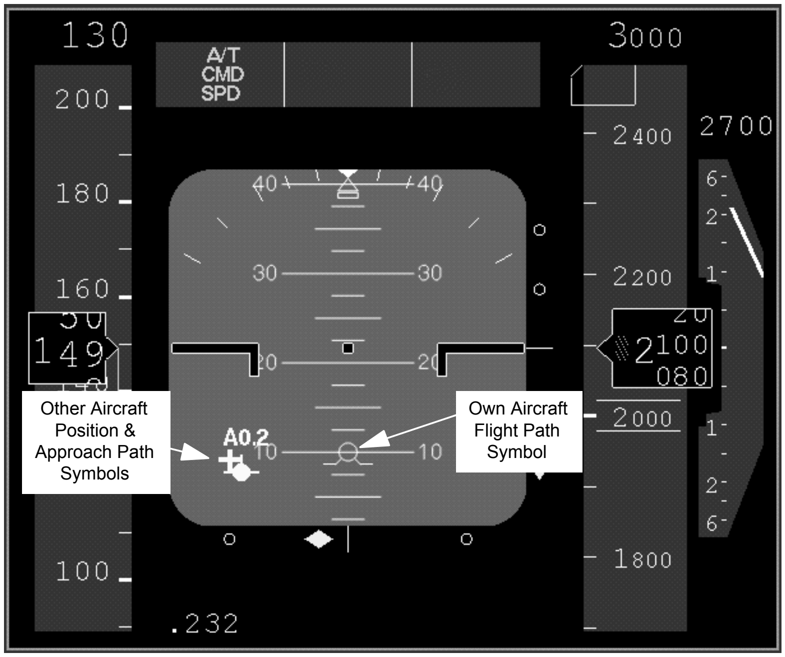

Figure 2.6 – Grey Scale Example of Primary Flight Display with parallel traffic indications (from [Pritchett99])

In a theoretical effort Teo [Teo03] analyzed CSPA operations using differential game theory. He developed a real-time algorithm to compute a region around traffic called the Danger Zone. If the parallel traffic, the evader in this example, penetrates this zone then a collision is possible if the blunderer does the worst possible thing given their aircraft dynamics. If the evader stays clear of the Danger Zone and a blunder occurs then it can be shown that there is a safe escape maneuver for any blunder. The method calculates, in real-time, what the worst case blunder is, rather than assuming a trajectory from an a priori set of blunders. Teo's code to calculate these regions was incorporated with the display code to generate the Color Bar symbology described in §3.5.4.1.

Teo then went on to calculate the minimum safe runway spacing assuming positive control on longitudinal spacing between aircraft. Teo found lateral runway separations of 750 feet can be safe if aircraft maintain more than 2000 feet longitudinal separation.

[Gazit96] compared the safe runway spacing achievable with standard and PRM radar surveillance and ILS navigation to the achievable safe runway spacing using GPS for surveillance and navigation. The combined rapid update rate and the increased accuracy of GPS for these functions yielded safe IFR parallel approach operations at runway spacings down to 2250 feet.

Without giving away the "ending of this movie", the independently derived results presented in Chapter 7 corroborate well with [Teo03] and [Gazit96a].

2.3.2.2 Runway Incursion

In response to the increase in runway incursions in the 1980's and the ensuing recommendations from the NTSB, the FAA began work on the Runway Incursion Prevention System (RIPS) under the Runway Safety Program. The Runway Safety Program is a multi-tiered effort using technology and education to address the danger from incursions. RIPS is the result of the technological development. The system serves controllers and both ground borne and airborne pilots by fusing multiple sources of surveillance data. Inductive loop sensors embedded in the runaway asphalt, ADS-B and ASDE radar data are all fed into prediction algorithms to identify losses of separation well in advance of a collision. To support this effort Mitre has developed a runway incursion alerting algorithm called Pathprox [Cassell00]. Pathprox assigns protected zones around aircraft and runways and uses current position and velocity of aircraft to predict conflicts. The alerts and warnings are given to both pilots and controllers. In the cockpit the displays are incremental changes from those currently in use. The alerts and warnings are displayed as text messages overlaid on the Primary Flight Display and the Map Display. Development of RIPS has generated scores of papers culminating in a successful flight test at Dallas/Ft. Worth in October 2000 [Jones01].

2.3.3 Mixing the Synthetic Vision and Operational Research

A logical next step is to combine these areas of research. Synthetic Vision has demonstrated its utility in cockpits of all levels of aviation. The current work addressing the operational concerns of CSPA and runway incursions has generated impressive systems utilizing the emerging GPS and ADS-B technologies but they have not taken advantage of the benefits afforded by Synthetic Vision. It is the goal of this research to design an SV display specifically for these two operational areas. Then in flight testing and human-in-the-loop simulations these displays will be characterized and, finally, their implication on the National Airspace will be studied.

Chapter 3
Display Design

> *[I flew] the standard SSC mission at zero dark thirty during our JTFEX. I was flying with our only non-NVG-qualified copilot, so we would do a classic LAMPS Mk III mission: flying into the blackness of the VACAPES to make sure the carrier was safe from the bad guys.*

The cryptic paragraph above describes the beginning of a night mission flown off an aircraft carrier. Even to pilots who are fluent in several dialects of aviation acronyms the details contained above are inaccessible, but the events of the story are clear enough. The story continues to describe the mission that goes from bad to worse amidst a continued flurry of unknown acronyms. It ends in what would have been a careless disaster but, happily and luckily, everyone lands safely with lessons learned. The primary lesson was:

> *When the weather is closing in… remember: aviate, navigate, communicate, and when all else fails, aviate some more - those priorities work and they will get you back to mother [Smith02].*

That quote harkens to a language every pilot speaks. From military fighter jocks to air transport captains to general aviation pilots, this mantra of Aviate, Navigate, and Communicate is ubiquitous. It is always recited in that order, the order of importance. Aviate: Fly the airplane. Navigate: determine where you are and set course to the desired point. Communicate: Talk to air traffic control or other pilots.

These displays are designed to serve the Aviate and Navigate functions on those last 5-10 miles of the flight, from the final approach fix to touchdown.

The ultimate goal is to safely conduct IFR CSPA operations to alleviate landing congestion and consequent delays. CSPA Operations with 750 foot runway separation are safely conducted in VFR Conditions now. If the critical elements of VFR flight necessary for aviating and navigating can be recreated on an IFR display then perhaps the IFR rules can be changed to resemble the VFR rules.

3.1 Design Philosophy

To generate the displays for CSPA Operations (hereafter, CSPA Display) a human-centered design methodology is used. To begin, investigators must complete a task analysis of pilots on final approach to understand exactly what information is necessary to complete those tasks. Then, once the requisite functionality is understood, displays can be tailored to the tasks at hand. The goal of this methodology is to assemble more than one display whose elements and symbologies are designed from the ground up and contain sufficiently rich cues to replicate the essential elements of the VFR scene and thus to enable to the pilot to safely execute a CSPA in instrument conditions..

3.2 Task analysis of pilots on final approach

The task analysis presented below is adapted from [Alter92] and [Trotter03]. It is meant to be a representative collection of the tasks that a pilot of a modern commercial airliner must complete between the final approach fix and touchdown.

Obviously, the details of this list will change from aircraft to aircraft but this listing captures the essential elements common to most civil air transport vehicles.

The list is presented roughly in chronological order. Most tasks are labeled as Aviate, Navigate or Communicate tasks. Aviate tasks are those inner loop tasks that deal with maintaining control of the aircraft such as monitoring the roll angle and roll out heading during a turn or managing airspeed. Navigate tasks involve choosing a destination and establishing a course to reach that point. Tracking that established course is an Aviate task. Communicate deals with the interaction between the pilot-in-command and everyone else, whether they are the co-pilot in the next seat or the controller on the ground. The items that extend beyond this three-tiered characterization are the ones that deal with managing the complex aircraft systems and are labeled as such.

Only the functions that are critical to controlling the aircraft and navigating the aircraft will be included on the display. Those items are indicated with a double asterisk (**).

3.2.1 Approach (From initial approach fix to just before airplane flare)

- *Control Flight Path* (Aviate/Communicate)
    - *Follow arrival procedures/vectors to final approach* (Aviate/Communicate)
        - *Continuously determine safety/efficiency of clearances* (Aviate)
        - *Monitor and interpret weather radar to avoid possible hazardous conditions during the approach and the missed approach area.* (Aviate)
        - *Monitor and interpret Ground Proximity Warning System to avoid possible obstacles and deviations from a stabilized approach path* (Aviate)
        - *Monitor and interpret TCAS to establish the approximate position of other traffic* (Aviate)
        - *Monitor and interpret caution and warning panel for the ongoing health of the aircraft* (Aviate)
        - *Request deviation if necessary* (Communicate)

            - *Mentally review the actions and drills for the approach and possible missed approach.* (Aviate)
    - *Slow to approach speed as per flight plan/ATC clearance* (Aviate/Navigate)
        - ***Plan deceleration to arrive at final approach fix at approach speed and configuration* (Navigate)
        - ***Limit airspeed as required* (Aviate)
    - ***Intercept final approach path*
        - *Anticipate interception* (Navigate)
            - *Determine lead point*
            - *Determine predicted turn radius*
        - *Execute turn* (Aviate)
        - *Verify approach path with instruments* (Navigate)
    - ***Track final approach path* (Navigate)
    - ***Follow appropriate glideslope* (Navigate)
    - ***Maintain approach speed* (Aviate)
    - ***Control airplane attitude (*Aviate)
        - *Maintain control of airplane*
            - *Wings level (avoid wingtip scrape)*
            - *Hold precise pitch control (avoid stall)*
            - *Optimize energy management*
- *Avoid Collisions* (Aviate)
    - *Avoid obstacles*
        - *Identify obstacles in flight path or potential flight path*
        - *Monitor time to maneuver*
            - *Determine obstacle clearance requirements*
        - *Modify path if necessary*
    - ***Monitor traffic*
        - *Parallel Traffic*
            - *Assess if traffic is within its specified location*
            - *Assess likelihood of blunder*
        - *Runway Traffic*
            - *Assess likelihood of incursion at all taxiway intersections.*
    - ***Maneuver abruptly if required*
- *Communicate/Follow Procedures* (Communicate)
    - *Receive pertinent information/clearances/requests from ATC (approach/tower)*

    - *Approach clearance*
    - *Landing clearance*
    - *Windshear alert*
    - *Runway condition*
  - *Acknowledge receipt of ATC clearances*
  - *Transmit requests to ATC*
  - *Uplink/downlink information as required*
  - *Tune landing navigation equipment (ILS/MLS) as required*
    - *Confirm receiving/correct station for approach*
  - *Determine whether weather conditions are above minimums at appropriate points in approach*
  - *Cabin crew as required*
  - *Passengers as required*
- *Manage Systems*
  - *Configure for approach*
    - *Extend flaps/other secondary flight control surfaces to approach position*
    - *Extend landing gear*
      - *Identify gear extension point*
      - *If safe at this point to extend gear*
    - *Arm autobrakes/groud spoilers/other automatic breaking systems*
    - *Configure external lights as required*

3.2.2 Landing (from flare to turn off runway)

- *Control Flight Path* (Aviate)
  - *At decision height, decide if VMC exists.*
    - *If visual then land*
    - *If still instrument conditions then conduct a missed approach*
- ***Ground Roll* (Aviate)
- ***Avoid Collisions* (Aviate)
- *Communicate/Follow Procedures* (Communicate)
- ***Plan Future Action* (Navigate)
- *Manage systems*

3.3 Necessary Data

As stated earlier, the goal of this display is to recreate the critical elements of the visual scene on final approach. Those critical elements must then be discovered. To accomplish that goal it is necessary to understand the important tasks and then, more precisely, which pieces of data are necessary to conduct those tasks. Starting with the ownship tasks; careful inspection of the aviate tasks in §3.2 reveals that they can be completed with the following ownship variables: roll, pitch, heading, airspeed, and altitude. The navigate tasks can all be completed if the pilot has an understanding of their heading, airspeed, and three-dimensional position with respect to the runway and the approach path (displayed position with respect to the approach path is called Flight Technical Error (FTE)).

Several researchers have empirically shown that a Synthetic Vision Primary Flight Display (SV PFD) can effectively display the data necessary to complete the ownship tasks in §3.2. Adding three dimensional location with respect to the runway, terrain and approach path completes a sufficient set to enable the navigate tasks. The union of these two sets of variables yields the SV displays that have been studied and developed and flown by several groups worldwide [Alter98] [Theunissen97] [Barrows99] [Sachs02]. The question now becomes: Which variables are essential to understand whether traffic, either airborne or ground-borne poses a threat? Or in more focused words: What information do pilots need in order to detect and avoid blunders on Closely Spaced Parallel Approach and runway incursions.

Significant research into Cockpit Displays of Traffic Information has determined that relevant traffic information for strategic traffic awareness includes relative horizontal position, relative altitude, flight identification, heading, airspeed, and intent [Johnson01]. Awareness of traffic during CSPA is a tactical effort and as such all of these data listed above may not be necessary. [Pritchett99] cites relative position (lateral, longitudinal, and vertical) and the nominal flight path as the essential information. [Houck01] conducted a series of flight tests wherein she verified that roll angle of the traffic is a leading indicator for pilots to detect a blunder. Thus, leveraging Houck's results and to improve the Compatibility of the display (see §3.4.1 for a definition of Compatibility) roll and heading were added to Pritchett's list.

When the positions of both aircraft and both approach pathways are shown in a common reference frame the relative positions and various technical errors become obvious. For instance, showing the position of the traffic and the approach pathway for the parallel runway one can immediately infer the Total System Error for the parallel traffic.

For runway traffic the location and heading of the traffic with respect to the runways are the paramount data.

Essential data – Aviate ownship: roll pitch, heading, airspeed, altitude. Navigate ownship, position with respect to pathway and runway, heading, nominal flight path. Monitor and avoid traffic: relative longitudinal, lateral position and relative altitude, roll, traffic's nominal flight path. Hereafter these variables will be referred to by their grouping, Aviate, Navigate, Traffic.

3.4 Designing Displays

Now that a clear and concise list of the tasks and the data necessary for the approach has been compiled we are ready to assemble the data into displays. There are some guidelines for this task that have come from the last six decades of designing cockpits.

3.4.1 Principles of display design

[Sanders93] and [Roscoe81] outline several general principles that codify good display design. Three of these have particular relevance here:

Principle of Pictorial Realism: "A display should present a spatial analog, or image, of the real world. [An image] in which the position of an object is convincingly seen in depth as well as up-down and left-right." [Roscoe81]

Principle of Movement Compatibility – defines the relationship between movement of the displays and controls and the response of the system being displayed or controlled. For example in a tracking task if the target moves left a display with good compatibility will depict the symbol moving to the left and the appropriate action will be to move the controlled object to the left.

Principle of Pursuit Presentation: generally it is advantageous to use pursuit displays as contrasted with compensatory displays for tracking (these terms are defined in the following section).

3.4.2 Pursuit versus Compensatory Displays

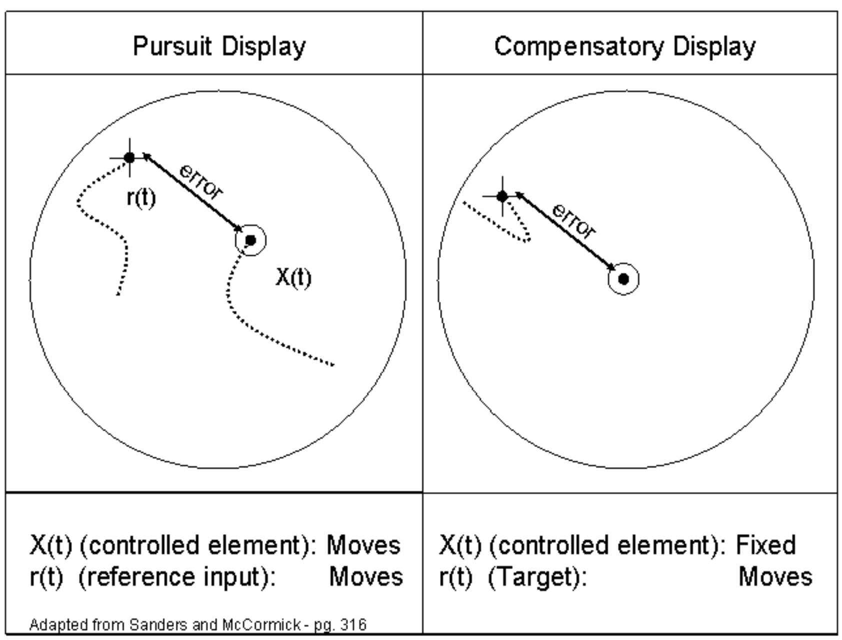

Figure 3.1 – Pursuit and Compensatory Display Example

There are two fundamental roles for a control system: Tracking and Regulating. A tracking control loop is designed such that the output, x(t), follows the input, r(t). A regulator is a special case where the input, r(t), is a constant. The prime function of a regulator is to reject disturbances. These control strategies apply to human-in-the-loop systems as well. Consider the two element task pictured in Figure 3.1. The operator must continually align the controlled element with the reference input and thus minimize the distance between the reference and controlled elements. This error when applied to aircraft tracking a trajectory is called Flight Technical Error (FTE). Figure 3.2 and Figure 3.3 show the block diagrams for the pursuit task and the compensatory task, respectively.

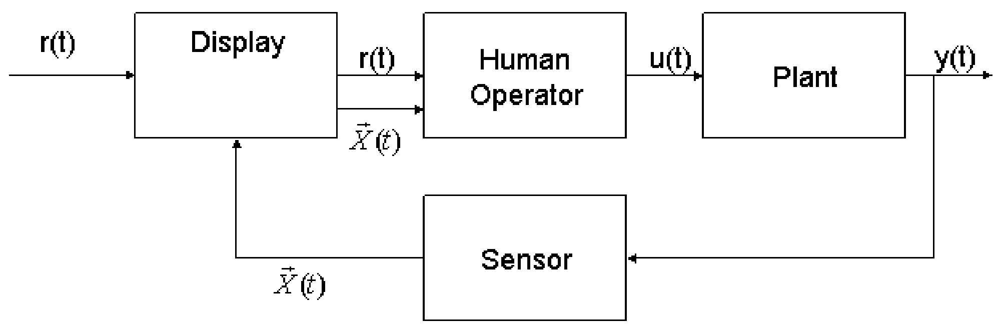

Figure 3.2 – Tracking Role for Operator – Pursuit Display

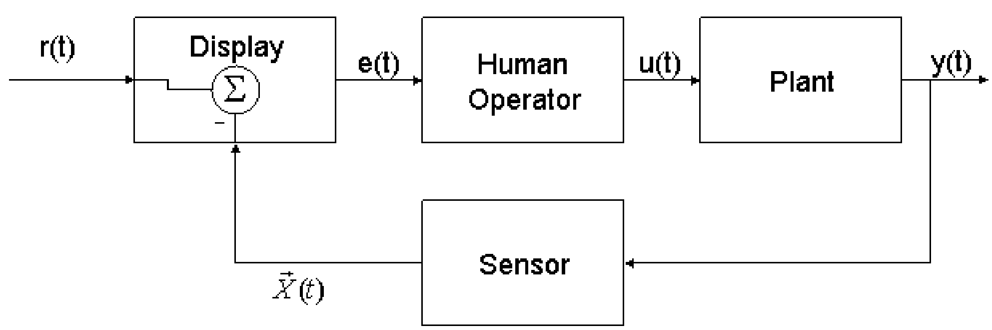

Figure 3.3 – Regulating Role for Operator – Compensatory Display

The difference to the human operator between these two models lies in the display that he/she is presented with and thus the control strategy that he/she is equipped to implement. In the tracking loop the inputs to the display are the states of the two elements, in this example the state is the (x,y) position. The display in the left panel Figure 3.1 shows the movement of both elements. The compensatory display shows only the error between the positions of the elements.

The advantages of compensatory displays is that they conserve space on an instrument panel as they do not have to save room for the range of possible values of the two elements, merely the difference between the two. Additionally, any common mode errors are automatically eliminated.

The Principle of Pursuit Displays results from the fact that pursuit displays outperform compensatory displays because pilots can discern between deviations that result from the behavior of the input and deviations that result from their own control inputs. In a compensatory display disturbances that affect only the controlled element are indistinguishable from those that affect only the reference input. Moreover, compensatory displays only offer information with which to minimize the error between the controlled element and the reference input. Conversely, with a pursuit display a pilot can perform more complicated control tasks such as, “stay to the left of center of the display and track the input if possible.” This type of complex task has an analog during approach, “stay inside the approach path and avoid the aircraft on parallel approach if necessary.”

When the controlled element is the only moving element the advantage of the pursuit display is diminished [Wickens84]. Such is precisely the case for the aviate and navigate tasks for landing an airplane on a runway. The approach path is constant and the pilot’s job is to follow that path as accurately as possible. Thus a compensatory display for these tasks is a reasonable choice especially if that choice affords other advantages. Tracking, or conversely, avoiding tracking is better done with a pursuit display so that the pilot can individually see his/her own progress along the approach *and* the progress of the parallel traffic. Thus, the track/avoid traffic task group is well-served with a pursuit display and the aviate and navigate task group is best served by a compensatory display.

3.5 Assembling the Displays

From the beginning we wanted to create displays that employed the human factors engineering fundamentals outlined in the previous two sections. With a nod toward convention, a map type display was first to be developed. Pilots are comfortable with this type of display and it does well in the overall representation of the approach. A map display where the map moves exactly with the motion of the pilot's own aircraft is compensatory. We also wanted to produce a pursuit-type display to explore the advantages afforded by that format.

It has been shown that SV PFD's in conjunction with moving map displays have excellent benefits for aviating and navigating tasks. Moreover, pilots report that workload is significantly reduced over standard IFR instrumentation [Barrows01] It is further speculated [RockwellSV00] that SV/Map combinations would also reduce initial training and recurrency training without degrading safety. For these reasons we will leverage the SV PFD work conducted at Stanford and around the world and augment the SV PFD with symbology and views that convey the traffic information.

3.5.1 Primary Flight Display

As suggested by [Poppen36] the correct display methodology for an aircraft attitude indicator is an exact analog of what would be viewed through the windscreen. He reasoned that the gyro horizon indicator should be like a symbolic "porthole" through which the pilot views an analog of the real horizon. Thus the horizon moves as it would if viewed from inside the aircraft. Displays where elements attached to the vehicle are stationary are called "inside-out". The SV PFD is implemented in this paradigm (moving horizon) as is the convention for standard PFD's. This complements the completion of the navigation tasks which are compensatory in nature since the approach path is stationary.

Figure 3.4 – SV PFD showing a blunder

The elements of the PFD are (from top left):

1. Longitudinal Spacing Indicator (LSI) in nautical miles
2. Ownship Bank Index
3. Roll Bug (Indicating roll of the traffic = 28°)
4. Airspeed (knots)
5. Artificial horizon
6. Altitude above mean sea level (feet)
7. Parallel Approach Path (magenta)
8. Image of the parallel traffic (shown just about to leave the parallel approach path)
9. Ownship Approach Path (green)
10. Corner Tic-Marks and Flight Path Vector [Grunwald80]
11. Brand Name
12. Magnetic Heading (degrees)
13. Distance to Touchdown (nautical miles)

Most of the information in this scene presents data pertaining to the ownship. Elements pertaining to the parallel traffic are the image of the traffic, the magenta pathway, the longitudinal spacing indicator and the roll bug. The image also displays current position, roll and heading of the traffic. The color convention for the pathways is green for the ownship pathway and magenta for the pathway for the parallel traffic (descriptions of the Longitudinal Spacing Indicator and the Roll Bug are included below).

Some of the traffic cues on the SV PFD are more precise than others. The azimuth and elevation to the traffic are well conveyed by the perspective display. Whether the other aircraft is above or below the ownship is also precisely shown by whether the image of the traffic is above or below the horizon. However, because the image of the traffic is drawn in perspective, distance cues (size of objects) are vague. This trait makes it difficult to ascertain if the traffic is just inside or just outside of its pathway. The careful observer of Figure 3.4 can discern that the traffic is indeed at the edge of the pathway and will soon be deviating further from the magenta pathway.

3.5.1.1 Roll and Relative Roll - Roll Bug

The Roll Bug (Figure 3.4, element 3) shows the roll of the traffic on the ownship roll indicator. Assume that you, the reader, are piloting the ownship. Aligning your roll indicator with the roll bug ensures that you will match the roll angle of the traffic. Moreover, if the traffic is on the left side then any time the roll bug is right of your own roll indicator then the traffic is rolled toward you. The roll bug turns red when the roll angle of the traffic exceeds 20 deg. Figure 3.4 shows that the traffic is rolled + 28 deg.

3.5.2 Traffic Variables

Introducing traffic to the SV PFD highlights the fundamental weaknesses of the display format. Those weaknesses are – weak longitudinal distance cues and the limited viewing frustum (also known as the keyhole effect). To ameliorate these weaknesses it is necessary to augment the SV PFD with some other symbology or a complementary display. Those augmentations must give sufficient cues for the pilot to detect and act on a blunder in the minimum time. The augmentations cannot conflict with the SV PFD's main function of providing aviate and navigate cues, nor can they conflict with any traffic cues shown on the SV PFD. Lastly, the augmentations must be the sole source of traffic information when the parallel traffic isn't in view of the SV PFD. As another design constraint, it is favorable not to implement text alerting messages. These messages are valuable as they offer clear and immediate interrupting cues. However they violate the principles of pictorial realism and movement compatibility. Using text messages is like playing your aces in poker. The longer you wait to use them the more valuable they become.

The next sub sections describe the pursuit format, Orthographic Display and the compensatory format, Map Display, and how these displays function to show the relevant data that was specified in §3.2.

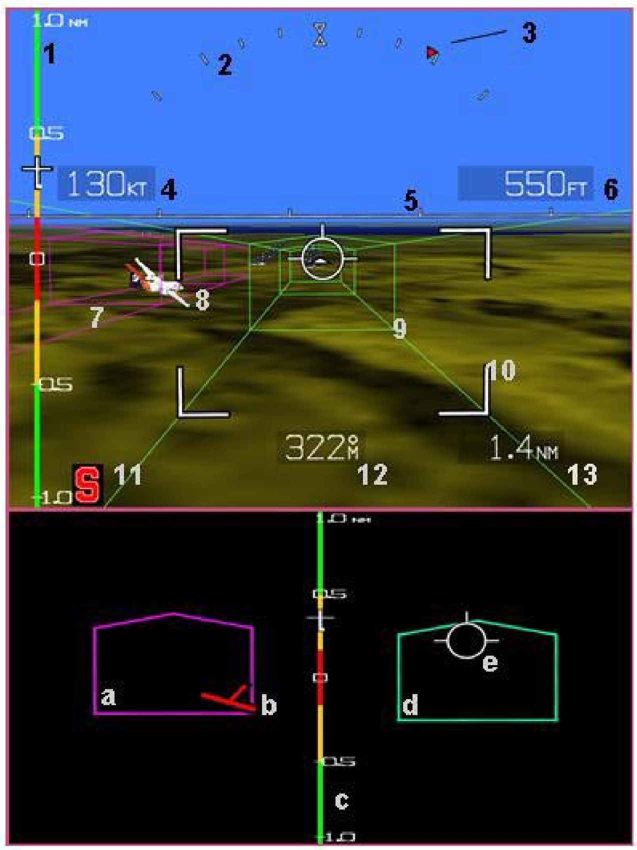

Figure 3.5 – SV PFD and Orthographic Display showing a Blunder

3.5.3 Orthographic Display

The lower portion of Figure 3.5 shows an orthographic projection of the aircraft and the current station of their respective pathways. The goal of this display is to efficiently show the pilots the lateral and vertical offsets between the aircraft and their approach pathways so that pilots can immediately ascertain if the traffic is blundering. Elements of the Orthographic Display (Figure 3.5, from left to right):

a) Traffic's Current Cross-Section of Parallel Approach Path (magenta)
b) Traffic Indicator (shows roll and Flight Technical Error)
c) Longitudinal Spacing Indicator (identical to the LSI in the PFD)
d) Ownship's current approach path cross-section (green)
e) Ownship indicator (shows roll and FTE)

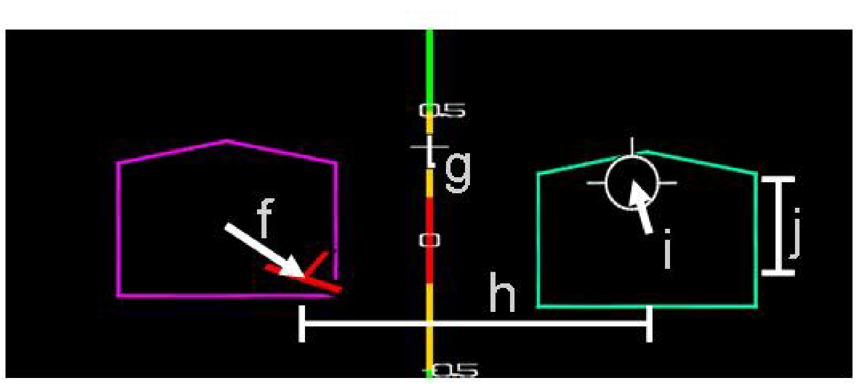

Figure 3.6 – Orthographic Display (detail)

Quantities Shown (Figure 3.6, left to right):

f) FTE of the traffic (vertical and horizontal) with respect to their current station along the pathway.
g) Longitudinal spacing between aircraft (Longitudinal Spacing Indicator, see below)
h) Lateral spacing between the aircraft.
i) Current FTE of the ownship with respect to its current station along the pathway
j) Shows the vertical spacing between the aircraft.

To understand the workings of this display define a coordinate system centered on the ownship's runway. The X axis lies along the runway heading, defining the longitudinal direction. The Y axis is 90° counterclockwise, defining the lateral direction. Z is up. The display is a pair of projections in the YZ plane, one for the traffic and one for the ownship. This presents information in the lateral (Y) and vertical (Z) directions without cluttering the display with information in the longitudinal (X) direction. Having the direction of the projection defined now leaves three important issues to resolve: Should the display be Inside-Out or Outside-In? Which point in our projection are all the symbols referenced to? (Where is the zero point?) What section of the pathway is to be drawn?

An Outside-In (from an outside vantage point looking in, the tunnels are stationary and the aircraft symbols move) display format referenced to the ownship pathway hoop was chosen because we wanted to show the condition of the approach regardless of the attitude or position of the ownship. For example, the horizontal and vertical distance between the aircraft symbols (Figure 3.4, elements b. and c., respectively) remain precise indications of the lateral and vertical (Figure 3.6, elements h. and j.) spacing between the aircraft even when the ownship rolls. Another benefit of this choice is that it draws a stark contrast between the behavior of the Inside-Out SV PFD and the Orthographic Display.

Since there is no longitudinal information inherent in this display, the portion of the approach pathway to be drawn must be chosen. To depict the FTE of the two aircraft it is important for the pilot to be able to compare the current aircraft position to the current stage of the approach path. The pathway hoop for the ownship drawn in the Orthographic Display is a vertical slice through the pathway at the current position XY position of the ownship and similarly for the traffic. It is important to note that this trait is what makes this display a pair of projections. In Figure 3.5 and Figure 3.6 the left side of the display is the projection for the traffic and its current pathway hoop and the right side is for the ownship.

As stated earlier, this display is a projection along the approach and there is virtually no longitudinal information shown. Therefore, the Longitudinal Spacing Indicator is included in the center of the display.

3.5.4 Map Display

Figure 3.7 shows the addition of a track-up moving map display centered on the ownship. The elements shown are as follows:

a) Parallel Approach Path (Magenta)
b) Ownship Approach Path (Green)
c) Danger Zone Contour (see §3.5.4.1)
d) Image of Traffic Aircraft
e) Danger Zone Indicator
f) Image of Ownship

Figure 3.7 – Map Display

Quantities shown:

- Current FTE of the other aircraft (horizontal only) with respect to their pathway.
- Current FTE of the ownship with respect to its pathway

- Lateral and Longitudinal spacing between the aircraft.
- The parallel and ownship pathways to the runways and the runways themselves

The pathways follow the same color convention. The symbols show the location, roll and heading of both aircraft. The white aircraft (a De Havilland Dash 8) is the traffic and the blue aircraft is the ownship. These symbols were chosen because the plan views of these aircraft are radically different and hence minimize the possibility of mistaking the traffic for the ownship or vice versa. To further distinguish the two, the color convention in use by the CDTI Research Team at NASA Ames has been employed (traffic is drawn in white and the ownship in light blue) [Johnson01]. The distances and bearings between the aircraft symbols, pathways, and runways are all drawn to proper scale. The smallest size that the aircraft symbols can take is limited so that they are always visible regardless of the level of zoom of the display.

3.5.4.1 Color Bars/Danger Zone

The yellow contour in Figure 3.7 shows the Danger Zone. [Teo01]. Assuming air transport aircraft dynamics, if you are outside the Danger Zone and the traffic blunders then there is a provably safe evasive maneuver if you begin within 2 seconds of the onset of the blunder. In short, you have two seconds to begin to move the aircraft to have a provably safe escape route. The entire contour is unnecessary for a pilot flying through the green pathway so the red Danger Zone Indicator shows the intersection of the 2 Second Danger Zone with the pathway. The yellow Danger Zone Indicator shows the intersection of an 8 Second Danger Zone with the pathway.

The procedure for flying with this symbology is: Stay out of the Danger Zone if possible. If you choose to fly within the yellow zone then you must begin an evasive maneuver in less than 8 seconds from the onset of the blunder: paying close attention to the actions of the traffic. If you must fly within the red zone then you must begin an evasive maneuver in less than 2 seconds from the onset of the blunder: paying very close attention to the actions of the traffic.

3.5.5 Map/Ortho Mixed Display

When testing the two previous displays on the simulator and in flight it became apparent that each had unique strengths and failings (described in the next chapter). The Mixed Display (Figure 3.8) is a first-cut attempt to combine the traits of the Orthographic and Map Displays.

Researchers understood early that the two display concepts, orthographic/pursuit and map/compensatory, have different strengths and weaknesses. These differences are explained and highlighted in Chapter 5. The mixed display is a first attempt to combine the traits of the Orthographic and Map Displays. As will be seen in the results of Chapter 5, the pilots appreciated the combination, but the specific implementation has problems. Notably up and ahead longitudinal spacing cues are both toward the top of the screen. Thus upward motion on the screen is ambiguous. If the Traffic Indicator moves up it means the traffic is climbing relative to the ownship. If the Longitudinal Spacing Indicator or the traffic representation on the map display moves up that means the traffic is now further ahead. This orthogonal conflict is a design flaw in the Mixed Display and as such the author is not proposing this display as the final iteration. However, based on the results contained in Chapter 5 it is likely that the final iteration will have elements and capabilities of both the Orthographic and Map Displays.

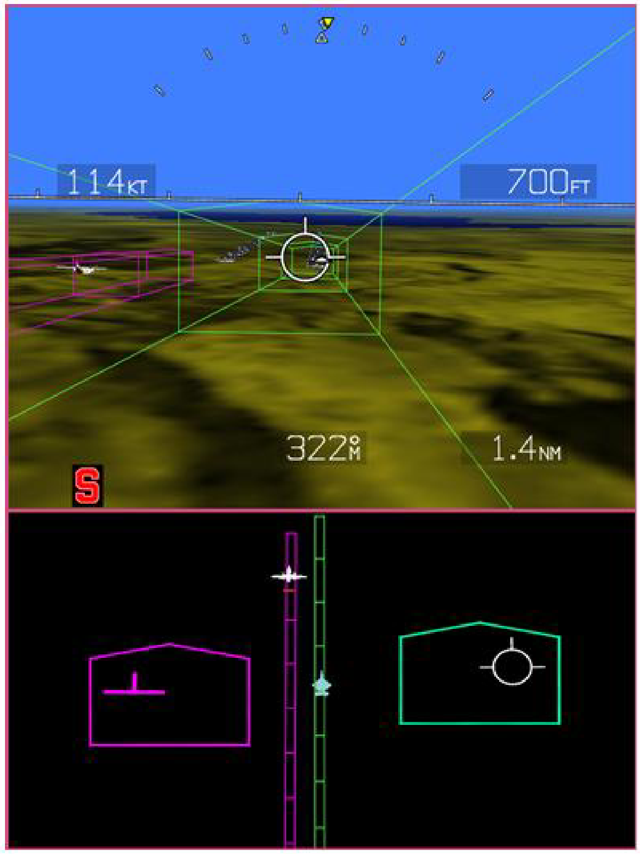

Figure 3.8 – Mixed Display

This completes the design of the CSPA display which shows the aviate, navigate and parallel traffic cues. The remaining traffic threats come from runway traffic.

3.6 Runway Incursion alerting symbology

Contrary to CSPA traffic information which often lies outside the field of view of an SV PFD, runway incursion information almost always occurs in the forward field of view. In addition, the onset of an incursion and the subsequent course of action are binary events. Either the traffic is dangerous or not and if it is the approaching aircraft must go around. There are some subtleties in assessing if the traffic is dangerous or not but those issues are separate from the presentation of the incursion information. For these reasons the display of the runway incursion information is more simple than the display of CSPA traffic information. Thus a simple symbology can be used to indicate when the runway is unsafe. In keeping with the principles of Pictorial Realism and Compatibility the strategy for including the runway incursion traffic alerting was to replicate the out-the-window view. In addition, it is advantageous to augment that image with a symbology that, while compelling, would make the minimum possible change to the display. In this method one has the greatest chance of preserving the benefits of SV found by [Alter98] [Barrows99] [Grunwald80] [Theunissen97] [Sachs02] while seamlessly adding the capability to communicate to pilots when a runway is unsafe for landing. This strategy allows this capability to be easily integrated in other SV applications. The strategy then became to take an element that is already central in the display and change it in a way that is obvious and clear to the pilot.

The first option was to change the color of the flight path vector but initial trials suggested that that cue was too far abstracted from the cause. Changing the color of the runway more directly relates to the current safety condition of the runway. This meets the original requirement of being a change to an existing element, but the runway is also central to the view and the destination. The interpretation of this symbology is simple: ‘If the runway is red, do not land.’

The geometry of showing runway traffic to approaching aircraft on a forward looking SV display is such that one can show all the traffic cues on the limited viewing frustum of the SV display. This is a unique traffic configuration for aviation and it is nicely applicable to depicting traffic on a forward looking synthetic vision display. As described earlier tasks such as showing traffic for CSPA meet with significant challenges to show traffic that is outside the frustum of the display.

3.6.1 Design of cue

3.6.1.1 2-space/crisp logic

A protected zone surrounds each runway. This zone is divided into three regions. Starting at the approach end (bottom in Figure 3.9 and Figure 3.10) the regions are: Short Final, Position & Hold, and Rollout. The exact dimensions of each region were tailored to the dimensions of the runways at Moffett Field and then adjusted based on empirical observations during the flight trials.

The logic that determines whether a caution or warning is issued follows these simple rules:

- When a vehicle shows intent to use or is using a runway all other vehicles are issued a caution on that runway.
- When two vehicles show intent to enter the same region, then issue warnings to both vehicles.
- Issue a warning if one vehicle shows intent to enter Position & Hold when another shows intent to enter Short Final on the same runway.

This concept of intent is designed to account for the velocity of a vehicle. A predicted point, $\vec{P}$, is the location of the vehicle in ΔT seconds based on the current position, $\vec{S}$, and the velocity, $\vec{V}$. The predicted point is simply expressed by (3.1).

$$\vec{P} = \vec{S} + \vec{V} * \Delta T \tag{3.1}$$

If the predicted point for a vehicle lies within a region then it is assumed that the vehicle has intent to enter that region. Another way to describe intent is to say that the size of the safety regions scale linearly with velocity. This technique is analogous to adding lead compensation in a control system. The sole benefit is to give a reasonable and predictable amount of extra time for a pilot to react to an advisory.

ΔT is sized to ensure that a vehicle crossing an active runway will continue to generate a caution on that runway until it is impossible for that vehicle to start braking and have any part of the vehicle lie within the runway boundaries when it halts. A rough estimate of this ΔT is the time it takes for a taxiing aircraft to brake to a full stop. Choosing reasonable numbers for a standard taxi speed of 20 kts and a maximum deceleration of ½ g yields a ΔT of 8 seconds.

The decision making aspect of the software is a decision matrix, $\bar{\bar{D}}$, where $\bar{\bar{D}} \in R^{mxn}$, and m, n = the number of possible locations for aircraft 1 and 2 respectively. The elements of $\bar{\bar{D}}$ are display options such as DisplayWarningOnLeftRunway() or DisplayCautionOnRightRunway(), etcetera. Thus, Dij is the display option appropriate for vehicle 1 being in the ith region while vehicle 2 is in the jth region. In this implementation it is straightforward to add dimensions to $\bar{\bar{D}}$ to account for more than two vehicles and it is trivial to add different display options.

A short example: In Figure 3.9 the green aircraft occupies the rollout region of the right runway, therefore a Caution is displayed on the right runway to all other aircraft. In Figure 3.10 that same aircraft is inside the Position & Hold region while the blue aircraft is in the Short Final region. This scenario is cause for a Warning on the left for the blue aircraft. Although it is not shown the green aircraft is issued a Warning Behind in this scenario.

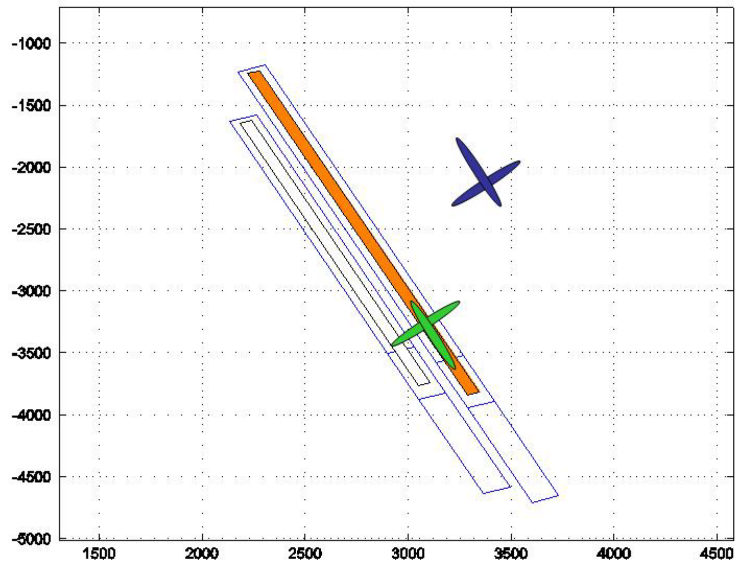

Figure 3.9 – Runway Incursion Logic – Caution on the Right

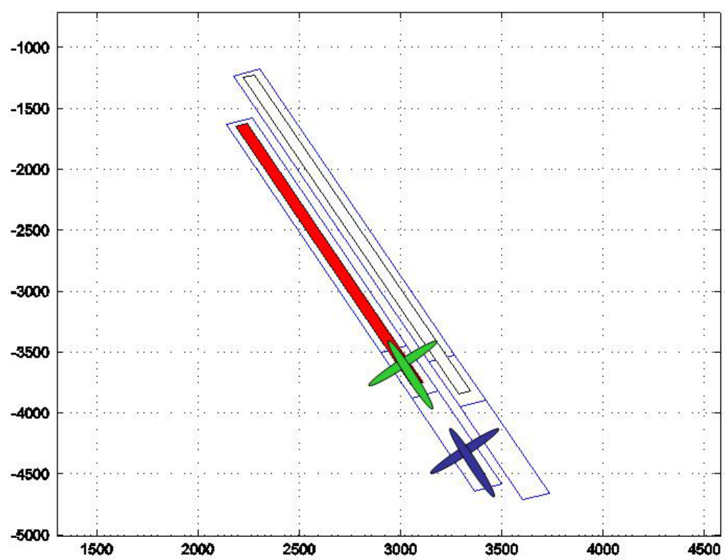

Figure 3.10 – Runway Incursion Logic – Warning on the Left

This symbology integrates seamlessly into any design that uses a SV PFD.

3.7 Examples and explanation of other ideas that weren't as good

Designing the displays presented above was an iterative process. Many more ideas were sketched and analyzed. In the end seven separate designs were coded and flown on the simulator at the WAAS lab. These seven were presented to pilots and display researchers in informal evaluations to get a "gut feeling" for these novel and perhaps even useful concepts. Of these seven the Orthographic, Map and Mixed displays were strongest designs. In the interest of brevity one of these designs is presented below as an example of the "other" things that were tried.

3.7.1 Auto Zooming

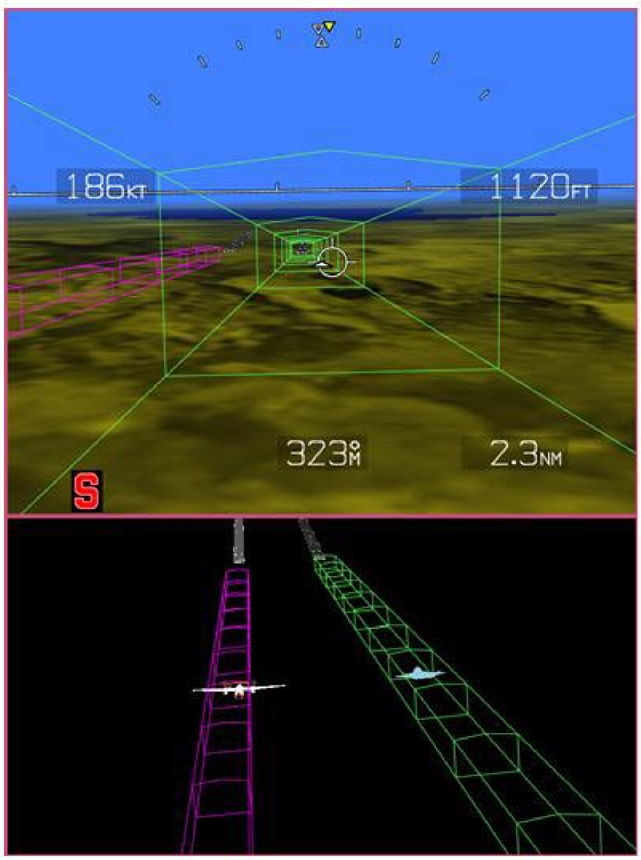

Figure 3.11 – Autozoom Display

Through experience with the map display the issue of scale becomes quickly obvious. The lateral spacing to be shown on the display needs to be accurate at the level of tens of feet. The longitudinal spacing needs to be accurate to 100ds of feet and has a range of thousands to tens of thousands of feet. As such with linear-linear scaling (lat, long) it is impossible to convey both variables at the necessary fidelity and over the necessary range. Some non-linear mappings however might prove useful. One such mapping was dubbed AutoZooming. Here the point of view follows the two aircraft and continually adjusts its zoom and range to always include both aircraft in the scene. The benefit is that you can always see both aircraft and they are always as large as they can be and yet still have them in view. The drawback is that the vantage point mixes lateral, longitudinal and altitude cues. In a video game this representation is quite adequate but it can get very disorienting and in a situation where the player/pilot only has one life, this mixing of cues was not suitable. As such this was not included in the experiment described in Chapter 5.

3.8 Filtering to account for variable datalink update rate.

In addition to designing how the various data are drawn it is sometimes necessary to filter incoming data into a format conducive for display on a smoothly updating display. During the flight testing described in Chapters 5 and 6 it was discovered that outages in the datalink were frequent occurrences. As such the information available to the display computer regarding the traffic was often unavailable. This condition required the implemention of some simple filtering schemes to see if the outages could be managed. It was discovered that the filtering scheme for one variable might not be the best for another.

A first order hold on the outages works well to smooth out position and heading. Roll however is better left as a zero order hold. Roll rates are high enough and the range of reasonable roll angles are small enough that a perfectly common roll rate followed by a data outage of 2 seconds or more can produce absolutely nonphysical behavior of the traffic, 720 degree barrel rolls for example. Obviously it is possible for an aircraft to have a high roll rate at one epoch during the approach. Being knocked around by a spot of turbulence or an overzealous pilot course correction could generate such a rate. However, within a short time the pilot or autopilot will null that roll rate when they have rolled back from 20°to 0°. If there is an outage in that epoch then that high roll rate will persist too long and the plane will appear to roll uncontrollably. Roll is unique among the aircraft states in this respect. No other state has such a small dynamic range and such a large dynamic range in its first derivative. Pilot 4 from the experiment in Chapter 5 commented on exactly this (paraphrase), 'I like the zero order hold on roll and the first order hold on everything else.'

3.9 Summary

The SV PFD is an open, but narrow, window on the world. The other displays are necessary to give information on what is happening outside the field of view of the SV PFD. The Orthographic Display is more abstract yet more precise than the Map Display; especially when a pilot is trying to evaluate whether or not the traffic is within its pathway. Conversely the Map Display gives less precise information but it can be zoomed out to give a comprehensive image of the entire approach. The Mixed Display is an unsubtle attempt to combine the capabilities of these two concepts. It presents some immediate issues in that it combines a vertical projection with a horizontal projection on the same piece of glass.

These displays are meant for use between the initial approach fix through touchdown. Previous experiments have shown that the Synthetic Vision and Cockpit Display of Traffic Information displays are also useful in other phases of flight such as en route or on a missed approach. Thus, although the result of this design effort is focused on final approach alone, these designs will be useful to other phases of flight.

The human centered design process yielded displays to provide all necessary aviate, navigate and traffic cues from the final approach fix to touchdown. For the aviate and navigation functions the SV PFD has proven itself as a valuable but limited format. Both compensatory and pursuit augmentations, Map and Orthographic displays were designed to give pilots traffic information. The next chapter describes the system needed to power these displays. Subsequently, the performance and operational benefits of these displays will be ascertained in Chapters 5, 6, and 7.

Chapter 4

System Architecture

A primary tenet of this research is to test the displays designed in Chapter 3 in flight. To accomplish this, a system of sensors, computers and interfaces to fuel the displays with the requisite data must be constructed. Much work has been done at Stanford and around the world to investigate data requirements and build these systems [Barrows00] [Theunissen97] [Theunissen01] [LangleySVReqt]. The hardware system presented in this chapter is an integration of the SV and ADS-B system partially developed by Barrows and Houck at Stanford University. This chapter presents the hardware and software systems that were developed to support the data needs of the displays presented in Chapter 3.

4.1 Prototype System

The displays in Chapter 3 require the following information.

- Ownship Position & Velocity
- Ownship Roll, Pitch, Yaw
- Traffic Position & Velocity
- Roll of the Traffic

The ownship system must be able to display the requisite data and the traffic system must be able to transmit its requisite data. Outlined below are the component specific requirements that flow down from those listed above. Much of the safety-of-life GPS literature (WAAS and LAAS) deal with studying methods to increase integrity and continuity. These particular traits are not critical to a proof-of-concept research program, and as such, are not addressed here.

4.1.1 Ownship

4.1.1.1 GPS – accuracy – datarate

For the purposes of our flight testing the accuracy afforded by WAAS, 7.7 m 95%, [Barrows00] was sufficient to show the proof of concept of the displays. Other researchers at NASA Langley and Rockwell Collins [LangleySVReqt] have also determined through flight testing that WAAS level accuracy is sufficient for SV systems.

Through flight testing, researchers at Stanford University [Barrows00] and NASA Langley [LangleySVReqt] have observed that a display refresh rate of 10Hz yields a usable display. For this reason a GPS position/velocity/time (PVT) solution rate of 10Hz was used.

4.1.1.2 Attitude – accuracy – datarate

Prototype requirement for a useable research SV system is 1 deg in roll pitch and heading accuracy [Barrows00].

To make the display appear smooth, a higher datarate is desired in roll and pitch than in position. 10Hz is stipulated in [Barrows01]. In a study described in [King93]; he found that pilots suffered no loss in performance when the sensor latency was varied from 70 to 300 ms. Pilots in that study did, however, have to work much harder to maintain their performance at data latencies greater than 100ms. This is further corroboration that 10Hz is an acceptable minimum datarate for attitude information to support SV Systems.

4.1.1.3 Display Computer

The display computer must support the 10Hz refresh rate and have sufficient memory to hold the terrain, pathway, and runway databases.

4.1.1.4 LCD Display

For flight testing the display had to be sunlight-readable. It had to be as large as possible and still fit in the physical confines of the cockpit and in case of emergency the display also had to be immediately stowable.

4.1.2 Traffic

4.1.2.1 GPS – accuracy – datarate

Since there is no SV display in the parallel flight test traffic, the flight tests only require the same accuracy as the minimum resolution of the datalink message. This is approximately 15m for the ADS-B Basic Message [UPSAT ICD].

The data will ultimately only move at the datarate of ADS-B so the requirement for the GPS sensor is that it be faster than 1Hz. It is an interesting question to understand the effects of data latency on reaction times for pilots flying the display. These latencies will almost always be driven by the datalink rather than the sensors. Since the ADS-B hardware is not easily configurable to higher datarates it is left to the human-in-the-loop simulations (Chapter 5) to discern the effect of datalink latency.

4.1.2.2 Attitude – accuracy – datarate

Only the roll and heading of the traffic are needed. Pitch is unnecessary because pitch doesn't cue a pilot to look for a blunder [Houck01] or a runway incursion. For roll accuracy the requirement isn't very stringent because pilots need to see the onset and progress of a blunder. Thus, roll accuracy to 1 degree is perfectly suitable for the experiments.

Heading errors of a few degrees are barely visible on the display. Thus the errors inherent in calculating heading from the arctangent of east and north velocity are imperceptible. Velocity errors from WAAS are small, on the order of centimeters per second and crab angle generally less than 10 degrees (8.2 deg for a 20kt crosswind and 140kt airspeed). Moreover small (10°) changes in heading aren't strong indicators of lateral movement [Houck02]. Thus heading need only be accurate to a few degrees.

The rate of attitude data need only be greater than that of the ADS-B datalink.

4.1.2.3 DataLink

At the start of the project it seemed as if the fastest method to develop an air-to-air datalink was to adapt an existing datalink. ADS-B from United Parcel Service/Aviation Technologies (UPS/AT) fits this bill well. It is currently being evaluated by several groups around the country and it is generally accepted that some variation of ADS-B today will evolve into the standard air-to-air datalink in the NAS. Despite the fact that the display requirements of including the roll of the parallel traffic are not supported with the current ADS-B specifications it was thought to be more expedient to adapt ADS-B rather than develop a unique one-off datalink. Another project using this same system required that the wind speed and direction be encoded into the datalink. The requirements for the datalink were to implement 3 distinct modes, each highlighting either position (ADS-B Basic Message), roll, or wind. Together, these modes encode roll to 1 deg and position to better than 18.5m, windspeed to less than 5 kts and wind direction to one degree.

The nominal datarate as published in the [ADS-B MASPS] is stipulated at 1 Hz. The MASPS also place restrictions on the minimum datarate as a function of the operation being flown. For example, for 95% of the time during a simultaneous approach to runways separated by 1000 feet, the maximum allowable time between updates is 1.5 seconds. A complete listing of these requirements can be found in Table 5.1 – ADS-B Update Period Requirements for Simultaneous Approach.

4.2 Implementation

In the FAA implementation of ADS-B, two datalink formats will be used. For air carrier (major airlines) and private/commercial operators of high performance aircraft ADS-B will be carried on the transponder frequency of 1090 MHz. For the typical general aviation user the Universal Access Transceiver (UAT) at 966 MHz will be used [FAA02]. The system implemented in this flight test uses the UAT.

Figure 4.1 – Flight Test Aircraft

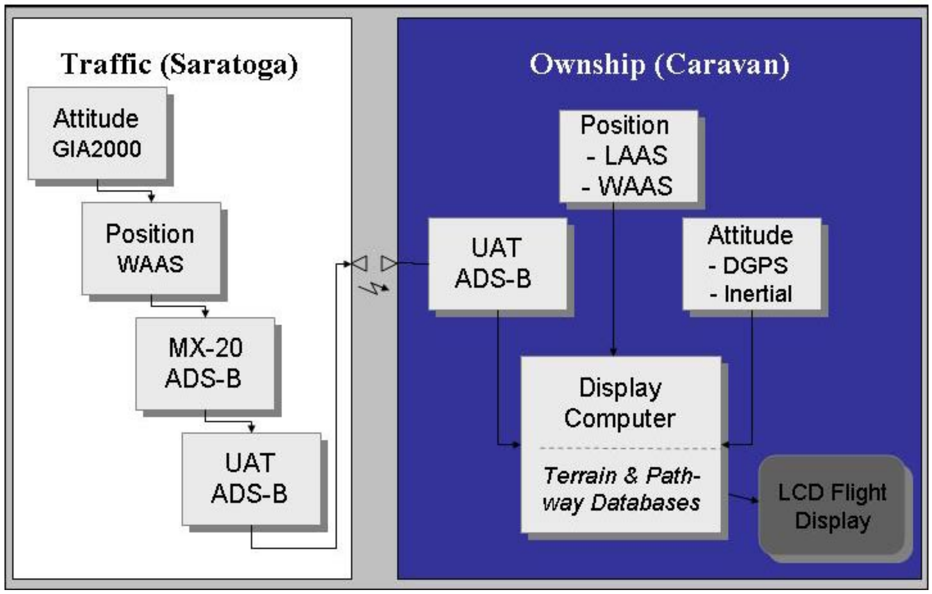

Figure 4.2 – Flight System Block Diagram

The aircraft used in the flight tests are shown in Figure 4.1. A Piper Saratoga (brown and white) served as the traffic and a Cessna Caravan served as the ownship (blue with red and yellow stripes). The block diagram for the system flown is shown in Figure 4.2. In both figures the data travels from left to right, from the traffic to the ownship. In Figure 4.2 all the instruments in the traffic are contained in the white box and all the instruments in ownship are shown in the blue box. The traffic system is designed solely to transmit aircraft data to the ownship. The Sequoia Instruments GIA 2000 reports roll to the WAAS computer. The WAAS computer calculates a position/velocity/time (PVT) solution for the aircraft and then packs the position, and roll and wind data, into the message stream into the MX-20. The MX-20 then packs the data to the UAT for transmission out over the ADS-B datalink to all listening aircraft. The system in the Saratoga contains no pilot displays and although ADS-B is bidirectional we have implemented it as a unidirectional datalink.

The ownship system is a centralized design with all sensors sending data to the display computer through RS-232 serial connections. The display computer then assembles those data along with the terrain, pathway, and runway databases into the imagery presented on the LCD Flight Display.

4.2.1 Ownship

4.2.1.1 GPS – accuracy - datarate

Only recently have commercial WAAS receivers with faster than 1 Hz Position Velocity Time (PVT) solutions become available. Stanford University, through its research with the FAA over the last several years, has developed inhouse WAAS algorithms using the Novatel Millennium receivers. Using the SU receiver system allows us to generate WAAS corrected Position Velocity Time solutions at rates up to 10Hz. For this reason the GPS receiver of choice was the Stanford WAAS algorithm with a Novatel Millennium OEM 3 receiver. For the CSPA and Runway Incursion flight tests the SU algorithms utilized WAAS corrections broadcast on the Raytheon Signal In Space.

4.2.1.2 Attitude – accuracy – datarate

Honeywell HG1150 Inertial Navigation System (INS) reported roll, pitch and heading at a datarate of 50Hz. This is a commercial grade INS whose capabilities far exceed the requirements stipulated in Section 4.1.1.2.

4.2.1.3 Display Computer

We flew a Pentium III 850 MHz rack mounted PC from the Industrial Computer Source. The computer was equipped with a Gforce3 graphics card from nVidia and extra serial ports for communication with future sensors. With this display hardware we could maintain a maximum framerate of 36 Hz.

4.2.1.4 Cockpit Display

The cockpit display is a 10.4" Nav2000 from JP Instruments. The retractable mount for the display was designed and built by Terry Blanch at the NASA Ames Model Shop. Figure 4.3 shows the location of the display in front of and between the pilots.

Figure 4.3 – Cockpit Display Installed in the Caravan

4.2.2 Traffic

4.2.2.1 GPS – accuracy – datarate

We used the same GPS system in the traffic as that described in §4.2.1.1. The only difference between the two systems is that the SU algorithm in the traffic was run on a single board embedded computer and produced a PVT solution at 4Hz.

4.2.2.2 Attitude – accuracy - datarate

A GIA 2000 from Sequoia Instruments, Inc. (assets purchased by Garmin International in November 2001) recorded roll angle and serially transferred that data to the WAAS box which then packed it up to the MX-20. GIA2000 is capable of reporting aircraft attitude at 50 Hz. to a resolution of 5.5×10^{-3} °.

4.2.2.3 WAAS

The WAAS computer is an embedded processor running Linux. The computer was coded to calculate WAAS GPS solutions, read the roll or wind data from the GIA2000 and then, depending on the mode of transmission, pack the attitude or wind data into the appropriate format for the current ADS-B datalink mode.

4.2.2.4 Datalink

United Parcel Service – Aviation Technologies (UPS-AT) provided their off-the-shelf ADS-B system. The MX-20 and the UAT were not ideally suited to the research tasks at hand, so significant modifications had to be made to support the requirements stipulated in §4.1.2.3. These roll and wind data had to be added to an already full ADS-B message. The method for stuffing this extra data into the message stream was to overwrite slowly changing digits with the new data. A simplified example, if latitude and longitude are encoded as:

$$\lambda = \lambda_1\lambda_2^{\circ}\ \lambda_3\lambda_4.\lambda_5\lambda_6' \tag{4.1}$$

$$\varphi = \varphi_1\ \varphi_2^{\circ}\ \varphi_3\varphi_4.\varphi_5\varphi_6' \tag{4.2}$$

then one can send two digits of roll information by rewriting Eqn (4.1) and Eqn (4.2) with the following substitutions,

$$\lambda = \lambda_1\lambda_2^{\mathbf{o}}\ \mathbf{R_1}\lambda_4.\lambda_5\lambda_6' \tag{4.3}$$

$$\varphi = \varphi_1\varphi_2^{\circ}\ \mathrm{R_2}\varphi_4.\varphi_5\varphi_6' \tag{4.4}$$

The altitude buffer was also used to stuff added data. This technique has an obvious drawback that the operational workspace of the flight test is now limited by which digits in latitude, longitude and altitude were overwritten. In the example above we cannot cross between λ = 32° 22.99' and 32° 23.00 without incurring errors. This highlights the tradeoff we encountered between the workspace and the amount and variety of information transmitted. It would have been preferable to overwrite λ_1 with R_1. That would yield a 10° workspace. For reasons specific to the MX-20, that approach was impractical.

Three modes were developed for the ADS-B transmissions to support the research goals of the flight tests. For details of the resolutions and ranges of each of the variables in each of the modes see Table 4.1 – ADS-B Modification Modes.

Position Mode: This mode is native to the MX-20 software and the UAT from UPS-AT. The information transmitted in Position Mode is almost identical to the Basic ADS-B. Because of the encoding process in the MX-20 the resolution of Latitude and Longitude is larger than that of Basic ADS-B. Despite this degraded position resolution, this mode presents the benefit of having no practical limitations on the range of the transmitted parameters.

Roll Mode: The requirements for Roll Mode were to include the roll angle and more precise position information in the ADS-B message. This is the mode to be used when conducting simulated CSPA. Roll data was written into part of the altitude buffer. Then the ones digit in latitude/longitude was overwritten with thousands of minutes of latitude/longitude.

Wind Mode: The requirement was to transmit the wind speed and wind direction at the location of the traffic to the ownship to assist in the visualization of wake vortices on the SV Display [Holforty01]. The method to include this data was identical to Roll Mode.

Resolution/[Range]				
	Basic ADS-B	Position Mode	Roll Mode	Wind Mode
Latitude	18.5m/[-90°,+90°]	18.5m/[-90°,+90°]	2.5m/[-δ1°,+δ1°]	2.5m/[-δ1°,+δ1°]
Longitude	14.7m/[-80°,+180°]	14.7m/[-180°, +180°]	2.5m/[-δ1°,+δ1°]	2.5m/[-δ1°,+δ1°]
Altitude	25ft/[-103ft,105ft]	25ft/[-103ft, 105ft]	30ft/[0ft,990ft]	25ft/ 0ft,990ft]
Roll	---------------	---------------	1°/[-180°, 180°]	---------------
Wind Speed	---------------	---------------	---------------	1kt/[0kt,+59 kt]
Wind Direction	---------------	---------------	---------------	1°/[0°,+360°]

Table 4.1 – ADS-B Modification Modes

4.2.3 Hardware Summary

Table 4.2 shows a comparison between the published or known instrument update rates and those evident on the cockpit display. Naturally the filtering of the datalink channel is evident on all the sensors on the traffic.

	Component	Instrument Update Rate [Hz]	Update Rate on the Cockpit Display [Hz]
Ownship	Display Refresh	36	36
	WAAS GPS	10	10
	Honeywell INS	50	36
ADS-B	ADS-B	1	≤ 1
Traffic	WAAS GPS	4	≤ 1
	GIA-2000	50	≤ 1

Table 4.2 – System Components and Refresh Rates

4.3 Software Design

4.3.1 Modular Design

Whereas the SV system hardware is architected in a centralized mode with each peripheral sensor communicating with the single data fusion/display computer the software is architected in various modules of functionality. These modules are further categorized in layers, the hardware layer, the processing layer, and the graphics layer. Each layer operates and modifies a different level of data. The hardware layer reads the data stream from the sensors and converts it into variables with useful engineering units. The hardware layer also manages the low-level timing of data flow from the sensors. The processing layer consists of modules that perform various calculations on the incoming data specific to a particular feature or capability of the display. For example the runway incursion alerting logic and the danger zone calculations take place in this layer. Lastly the graphics layer utilizes data from the hardware layer and the results from the processing layer to draw the symbology on the screen.

4.3.2 Separation of layers

4.3.2.1 Hardware Layer

The primary component of the hardware layer are the packet readers that are written specifically for each sensor. Input/Output modules like ADSBIO.c,.h and GPSIO.c,.h hold the code to read and decode the serial packets from the ADS-B transceiver and the GPS receiver, respectively. All of the packet readers are implemented as finite state machines. This architecture provides the robust decoding of packets such that if the data stream is simply interrupted and then resumed a packet can be successfully decoded. Moreover if a portion of the incoming data packet is missing for some reason the decoding software can discard the incomplete information and read the next set of data. The primary reason that this implementation works well is that the code need not read a complete packet in one pass. The code can come to read a portion of the ADS-B packet, get interrupted and perform another task, and then return and complete the reading of the ADS-B packet. In a system where any hang-ups or delays in the execution of the code are instantly noticeable by the user it is essential that the code be able to identify and seamlessly contend with mistakes or gaps in the data stream.

4.3.2.2 Processing Layer

Although the computations are much more complicated in the processing layer the task is conceptually simpler:

- if(new data)
- perform calculations
- else
- skip calculations

This feature enables the program to skip costly calculations if no data is present, thus speeding the execution of the program.

4.3.2.3 Graphics Layer

This layer consists of modules such as CSPA_graphics.c,.h. These modules contain functions that specify the drawing instructions for each piece of symbology, i.e. place the traffic indicator at these coordinates, orient the traffic indicator at this angle, color the traffic indicator red. All of these functions are called once per frame. If there is new data then the position or orientation of the graphic is updated. If not then the graphic is redrawn in the same location.

4.3.3 Open GVS

In our implementation all of these layers execute under the framework of the Open GVS scenegraph from Quantum3D Corp. OpenGVS is a high level graphics toolbox that allows for the importing of terrain databases and for simplified generation of high level commands such as PlaceOwnship(X,Y,Z), PlaceTraffic(X,Y,Z), DrawRunway(X,Y,Z,Length,Width), etc.

4.4 Chapter Summary

This system is very much a prototype. During its design and implementation considerable thought went into the proper system engineering to generate a reliable system that is reliable for a research system. This thesis involves building a large and complicated system such that it works when it needs to and doesn't waste time when the engines are running. In the future these systems will have to be made ultra reliable such that their robustness can be relied not just to protect a testing schedule time but to protect lives.

Chapter 5

Closely Spaced Parallel Approaches

This chapter describes the application of Synthetic Vision to Closely Spaced Parallel Approaches. The first errand of this task was to conduct human-in-the-loop simulations to study pilot reaction time and pilot preferences for the three displays. This experiment is described in §5.1. The natural dual aircraft dynamics are required to measure a pilot's ability to control the longitudinal spacing between aircraft on approach for parallel runways. §5.2 holds the documentation of those flight trials. These system characteristics will be used in Chapter 7 to assess how these displays and the technology that supports them could affect the minimum safe distance between parallel runways.

5.1 Human-in-the-Loop CSPA Simulation

5.1.1 Objective & Hypothesis

The chief goal of the experiment is to rigorously evaluate the ability of the Orthographic and Map Displays to convey situational awareness of the traffic on parallel approach. To do this both objective and subjective data were collected. Pilot reaction time to a path deviation of the traffic is the pertinent metric of the performance of the displays. It was expected that pilots would prefer the Map

Display because it is a more familiar format. However, it was also expected that reaction times would be smaller with the Orthographic Display because it presents a more detailed image of exactly when the blunder begins. To gather the subjective data pilots completed multiple surveys during the experiment that queried their opinions concerning the clarity and efficiency of the displays. The surveys also posed questions to evaluate specific symbologies and to ascertain the self-perceived workload during an approach. Lastly the particular relationship between the update rate of the ADS-B datalink and the reaction time to a blunder was investigated.

5.1.2 Design of Experiment

The experiment was a full factorial design on a part task simulator. We used multiple subjects with wide varieties of experiences within aviation, including military fighter pilots, active line pilots from commercial aviation, and general aviation pilots.

A total of ten human-in-the-loop simulations were flown. First three pilots were full simulation tests to polish the logistics and the operations of the experiment. As such they saw the same displays and they flew mostly the same trials but the experimental process was not identical to the last seven pilots. Hence only the subjective data from these three pilots has been included in the analysis to produce the results in §5.1.3. The objective and subjective data from the remaining seven pilots were used in the analysis.

5.1.2.1 Independent Variables

Display – Since the chief goal of the experiment is to measure the effect of the method of information display on the reaction time to the blunder, the Map Display and Orthographic Display were tested. Since it is expected that some aspects of each display will be preferred over the other the Mixed Display will be introduced to the pilots but it will not be used in the full complement of scenarios in the experiment.

ADS-B Data Rate – 0.14 to 10Hz. The [ADS-B MASPS] stipulate the ADS-B update requirements for several categories of operations. The ADS-B rates tested in the experiment were chosen to directly overlay the rates outlined for simultaneous approach outlined in Table 5.1 below. The overlap is not perfect because the MASPS stipulate that a 7 second update period is only acceptable 1% of the time for runways separated by more than 2500 feet. Since it was not practicable to arrange for the 7s outage at the onset of the blunder in this simulation we applied a 0.14 Hz (T = 7s) ADS-B datalink for the entire approach. This approximation has the effect that it will make the reaction times longer at low datarates. Hence, the results will be conservative.

Level of Integrity of Update Period	Required Update Period, T (seconds)
Nominal - 95th percentile	$T \le 1.5$s for 1000' runway separation $T \le 3.0$s for 2500' runway separation (1s desired)
99th Percentile	$T \le 3.0$s for 1000' runway separation $T \le 7.0$s for 2500' runway separation (1s desired)

Table 5.1 – ADS-B Update Period Requirements for Simultaneous Approach [ADSB MASPS]

5.1.2.2 Action of parallel aircraft

In each trail the traffic started at 5 nautical miles on a 45 degree base at 150 to 170 knots (See Figure 5.1). The tunnel for the traffic had the same dimensions as the ownship tunnel of 100 meters wide by 60 meters tall. Following that turn to final both tunnels were straight in, the traffic to Runway 32Left and the ownship to Runway 32Right. The straight segments were four nautical miles long for the left runway and five nautical miles long for the right. As per current parallel approach procedures the tunnels were separated by 1000 feet vertically at the point where the tunnel for 32L finishes its turn from base to final.

The traffic was preprogrammed to fly four distinct behaviors:

- No Blunder – the traffic will make a normal approach for the left runway. At no time does the center of mass of the traffic leave the confines of the tunnel.
- Blunder – at some point after getting stabilized on the final approach the traffic will bank right 30 degrees and turn 45 degrees in heading, (see §**2.1.6** for the justification).
- Missed Localizer – the traffic will not execute the left turn from base to final and will fly directly under the approach path for the right runway.
- Surprise – to attempt to assess how pilots would react to an unexpected situation the traffic was programmed to fly an unbriefed and unexpected route depicted in Figure 5.1. The traffic started 2000 feet above ground level at the midpoint of Runway 32L. It then proceeded to fly toward the ownship at an almost opposite heading. If the ownship pilot takes no corrective action and flies his approach as instructed, the traffic would generate an almost perfectly aligned head-on collision. To approximate the rarity of such a scenario this action was flown only once during the experiment.

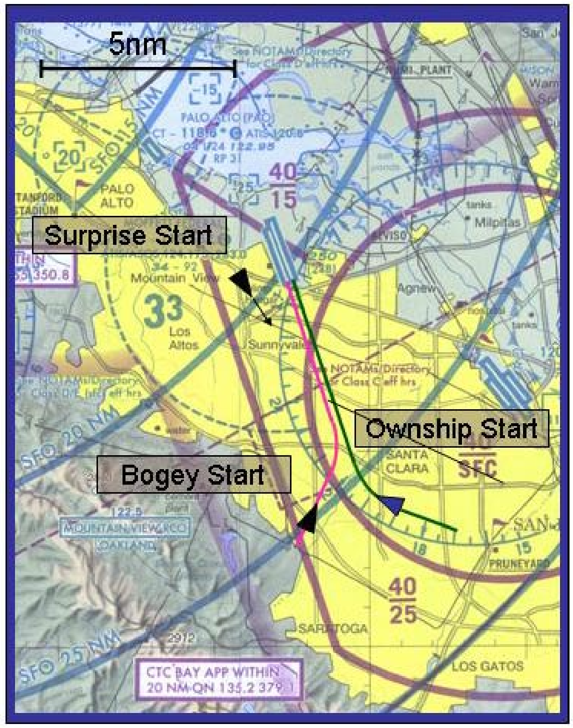

Figure 5.1 – Parallel Tunnel (Magenta) and Ownship Tunnels

The blundering aircraft trajectory, position, attitude and rates, were prerecorded. It is imperative that the pilots not be able to identify the blunder trajectories by a particular movement at the beginning of the trajectory. To mitigate this, two steps were taken. First, simulated turbulence was added to make the actions of the traffic less predictable. Second, with the exception of the Surprise action, multiple versions of each trajectory were recorded and selected randomly at the beginning of a trial. As a result the behavior of the traffic was somewhat unpredictable and pilots had to watch the traffic for continued trends in roll and position to correctly discern a blunder rather than anticipate the motion.

The parameters of the traffic approaches and the choices for the actions were designed to overlay current procedures and current mistake patterns as closely as possible. The tunnel approaches were designed based on the ILS approach plates for

Moffett Field, CA and for San Francisco International Airport. Controllers from both facilities were interviewed to ascertain procedures and common practices that were not captured on the published plates. Pilots from industry were similarly contacted to assess what the most common parallel traffic threats were. The Missed Localizer scenario was added, after interviewing an L-1011 pilot who described a Cessna Caravan missing its localizer and underflying his aircraft. (Note: Upon my request this pilot generously volunteered to come to Stanford University and fly my experiment.)

5.1.2.3 Dependent Variables

- Reaction Time to Blunder – a blunder is defined to begin at the instant the center of the mass (center of the symbology and 3D image) of the traffic crosses the edge of the tunnel. The stopwatch on the reaction time to blunder is stopped when the pilot presses the appointed button on the joystick.
- Workload – after several approaches pilots were given the NASA Task Loading Index (TLX) survey to assess their perceived workload. The TLX is described in detail in [TLX].
- Subjective reactions and evaluation of situational awareness – at multiple points during the experiment, pilots were asked to complete detailed surveys. Each survey was designed to probe the pilots' preferences as to which display was most useful and why, and which symbology was most useful.

5.1.2.4 Number of Runs

Each pilot flew 24 approaches in the experiment:

- 2 for acclimation
- 18 standard approaches (2 Displays x 3 ADS-B Frequencies x 3 repetitions, one in each scenario)
- 1 Surprise scenario
- 3 demo approaches with the Mixed Display

Each pilot took between two and a half to four hours to complete the experiment .

5.1.2.5 Pilots

Pilots with a wide range of aviation experience flew the experiment:

Pilots were divided into three groups:

- Testing – three pilots flew for final testing of the experiment process. Their quantitative data is excluded because the process for these three pilots was not identical to the following seven pilots.
- Data 1– five pilots who flew high ADS-B datarates of 1, 3 and 10 Hz;
- Data 2– two pilots who flew low ADS-B datarates of 0.14, 0.33, 0.66 and 1 Hz.

Obviously, Data 1 pilots flew the high datarate trials while Data 2 pilots flew the low datarate trials. For direct comparison both groups flew trials at 1 Hz.

Pilot	Total Hours	Experience	Type Aircraft Flown	Group
1	250	GA	Cessna 152, 172	Testing
2	2,500	GA	Cessna 172, 206, 337, Boeing 747 Sim, C17 Sim	Testing
3	1,130	GA	Piper Dakota, Cirrus SR-22	Testing
6	30,000	Military & Commercial	DC-6,7,8,10, Convair, Boeing 727, 737	Data 1
7	5,100	Military	T-34, FA-18, A-7, F-14, Learjet, MD-80, Boeing 747	Data 1
8	2,500	Military	T-38, F-16	Data 1
9	12,000	Military	T-38, C-141, DC-8, Boeing 727	Data 1
10	not available	GA & Commercial	Cessna Skywagon, DC-10, Robinson 22, 44	Data 1
4	4,500	GA & Commercial	Cessna 208, Jetstream 31 Piper Saratoga, Boeing 747 Simulator	Data 2
5	2,000	GA flight instructor	Cessna, Piper, Mooney, Bonanza, Dutchess, Apache	Data 2

Table 5.2 –Pilot Data

5.1.2.6 Instructions to Pilots and Experiment Scenario

Several days before coming to the simulator, pilots were given an information packet designed to familiarize them with the goals and mission of the experiment, the operation and meaning of the displays, and the required tasks of the pilots. The text below is an excerpt from the document that summarizes the instructions to the pilots as well as the experiment scenario. Note that "bogey" refers to the traffic on the parallel approach.

> *In almost all the trials there will be a bogey aircraft on the parallel approach. It is your job to fly your aircraft to Runway 32R while maintaining sufficient awareness of the traffic to avoid a blunder or some other mishap should one occur. To keep things interesting the bogey is flying with simulated moderate turbulence (you have smooth skies). In addition the*

bogey will not fly the same path every time, rather, it will do one of the following: No Blunder – the bogey will make a "normal" approach for 32L; Blunder – at some point after getting stabilized on the final approach the bogey will turn right and fly through your approach path; missed localizer – the bogey aircraft will completely miss the localizer.

If you detect a blunder or some other unsafe situation your priorities are to keep your aircraft safe and perform an appropriate evasive maneuver if necessary. If, however, you can safely complete your approach then do so. So that I can accurately measure your reaction time to a blunder you are also required to signal when you first notice the blunder by pressing the blunder button on the joystick. A blunder is defined to begin the instant the center of the bogey leaves the magenta tunnel.

You will be presented with each display under slightly different conditions. The experimenter will vary the action of the bogey and also the update rate of the bogey aircraft (the number of times per second new data comes through the simulated data link). Your reaction time and your perceived workload will be recorded.

In addition to the raw physical parameters of your reactions, I am interested in the experience you have in flying the approaches. To ascertain this data you will be presented with two types of questionnaires throughout the experiment. One is designed to query you regarding your opinions and reactions to the displays and the other is designed to measure the workload that you feel.

Task Loading Index (TLX) instructions

Because workload may be caused by many different factors, I would like you to evaluate several of them individually rather than lumping them into a single global evaluation of overall workload. TLX is comprised of six rating *scales defined in Table 5.3. It was developed by NASA as a procedure for recording and evaluating your perception of the experiences during the experiment. To record your ratings of the parameters please use the scales shown in Figure 5.2.*

Title	Endpoints	Descriptions
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Table 5.3 – TLX Parameter Definitions

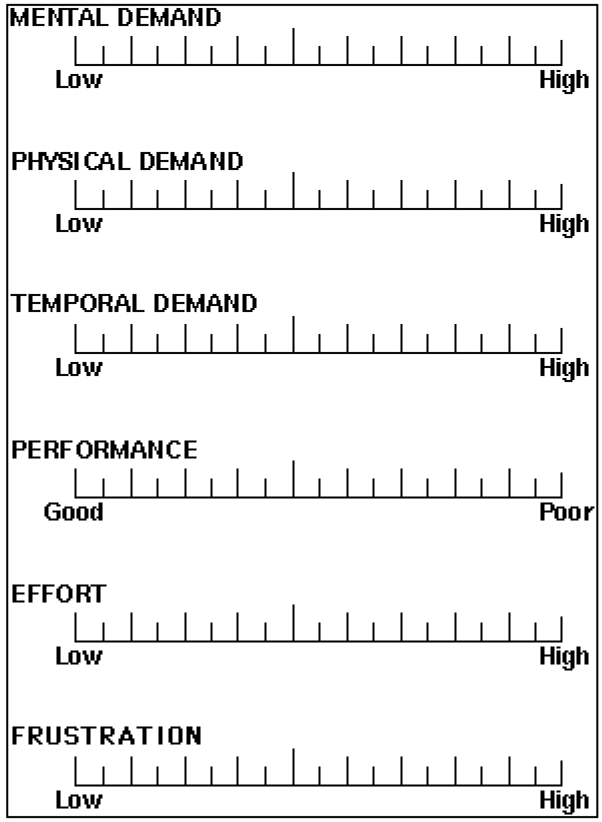

Figure 5.2 – TLX Parameter Rating Scale

5.1.2.7 Summary of Design

Just to reiterate, the key elements of the experiment design are:

- Minimize Predictability
  - Full factorial randomized progression of conditions
- Minimize pilot cueing and anticipation of events
  - Several Traffic Flight Paths
  - Simulated Turbulence for Traffic
- 10 Pilots
  - 3 Testing – Subjective data only

- 5 Data 1 – 1 Hz to 10 Hz ADS-B update rate.
- 2 Data 2 = 0.14 Hz to 1 Hz ADS-B update rate.

- Key results:
  - Display Evaluation
  - The Reaction Time dependence on ADS-B update rate
  - Performance results will be fed into the Monte Carlo study to assess the potential benefit of the best display system to the National Airspace System.

5.1.3 Results and Discussion

5.1.3.1 Display Evaluation

The first task of the experiment is to discern which of the display concepts is superior for maintaining situational awareness of the traffic and ultimately yields lower ownship pilot reaction times to blunders or missed localizer scenarios.

As edification for the reader, Figure 5.3, Figure 5.4 and Figure 5.5 show each display during a Blunder (on the left) and Missed Localizer scenario. These images are included to give the reader examples of the imagery the pilots used to generate the results reported below.

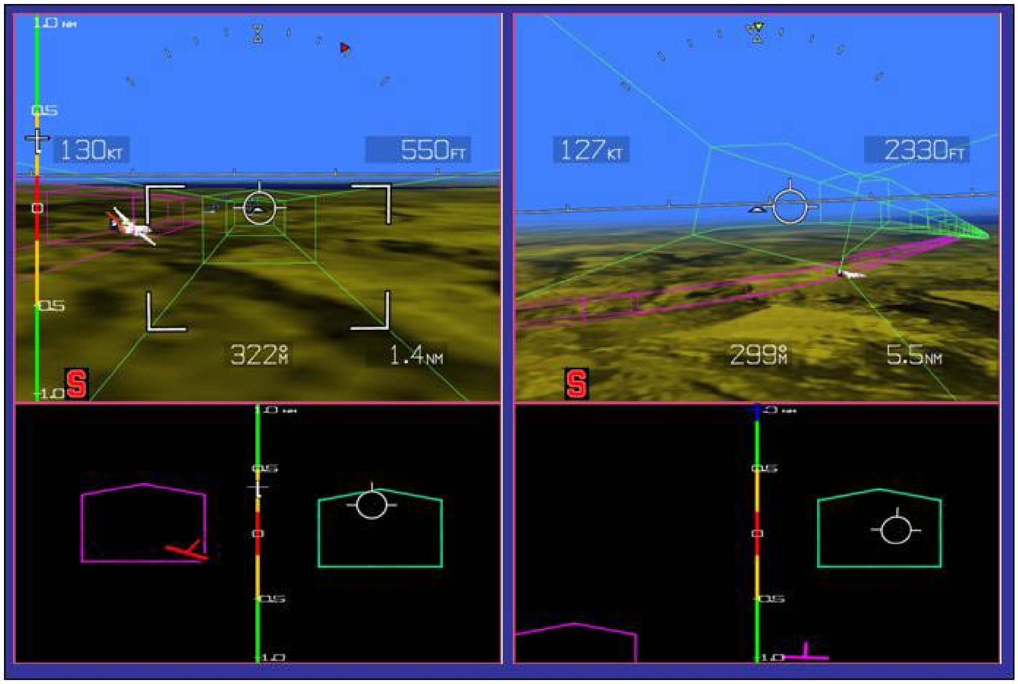

Figure 5.3 – Orthographic Display showing a Blunder and Missed Localizer

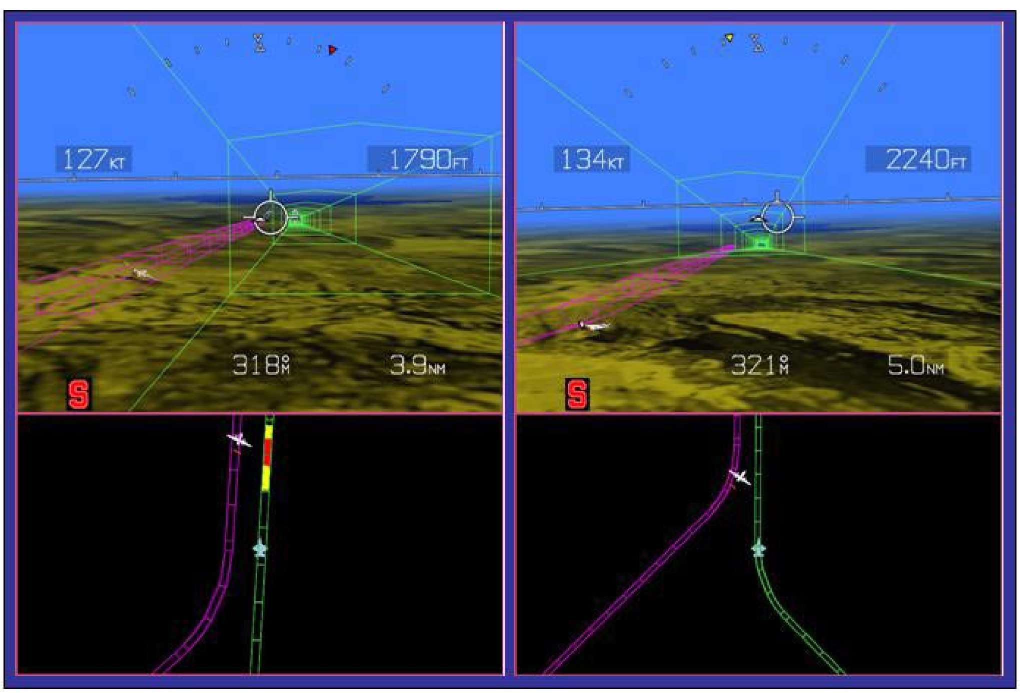

Figure 5.4 – Map Display showing a Blunder and Missed Localizer

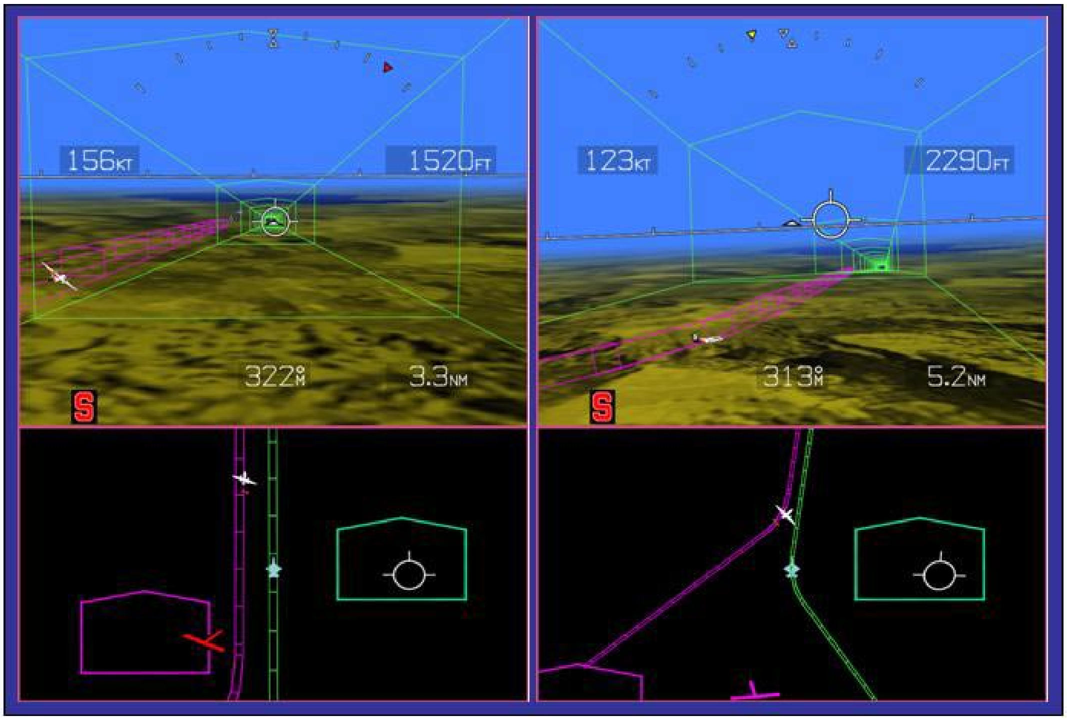

Figure 5.5 – Mixed Display showing a Blunder and Missed Localizer

ANOVA (analysis of variance) testing revealed that pilots responded significantly faster to blunders when using the Orthographic Display as opposed to the Map Display. Specific ANOVA results, as explained in Appendix A, are $F(1,61)=6.3$, $p<0.014$, which confirms that the results are statistically significant. Figure 5.6 shows the reaction time distributions (See Appendix A for an explanation of the structure of these plots). The statistics for the Map Display are μ = 1.4 seconds 95% = 4.4 seconds. For the Orthographic Display they are μ = 0.4 seconds and 95% = 3.7 seconds.

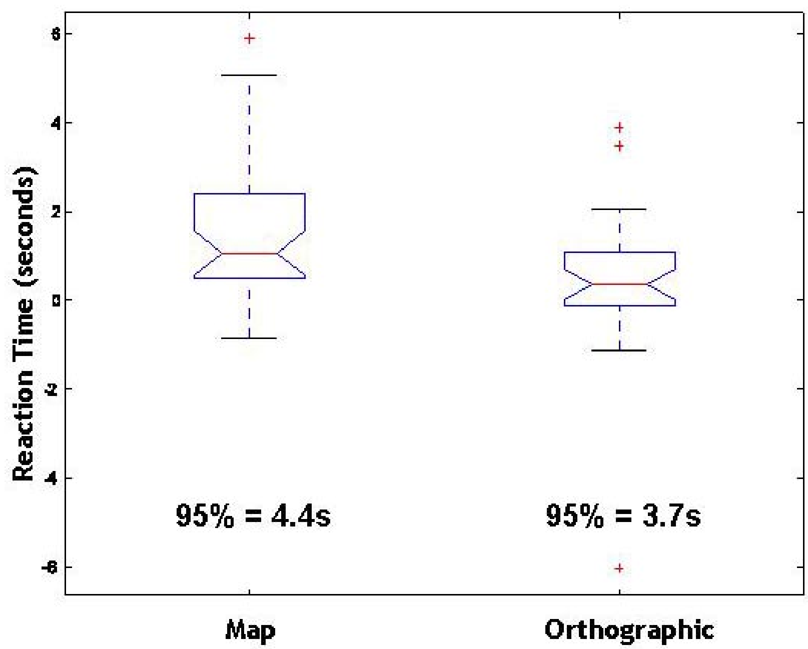

Figure 5.6 – Effect of Display on Reaction Time to a Blunder

Although the Orthographic Display is faster it isn't so by a great margin, Calculating 95% confidence intervals based on the distributions shown above yield 95% reaction times of 4.4 seconds for the Map Display and 3.7 seconds for the Orthographic Display. The Orthographic Display is only 15% faster 95% of the time. Thus, the objective results did not reveal a decisive winner. The self-perceived TLX results are also inconclusive.

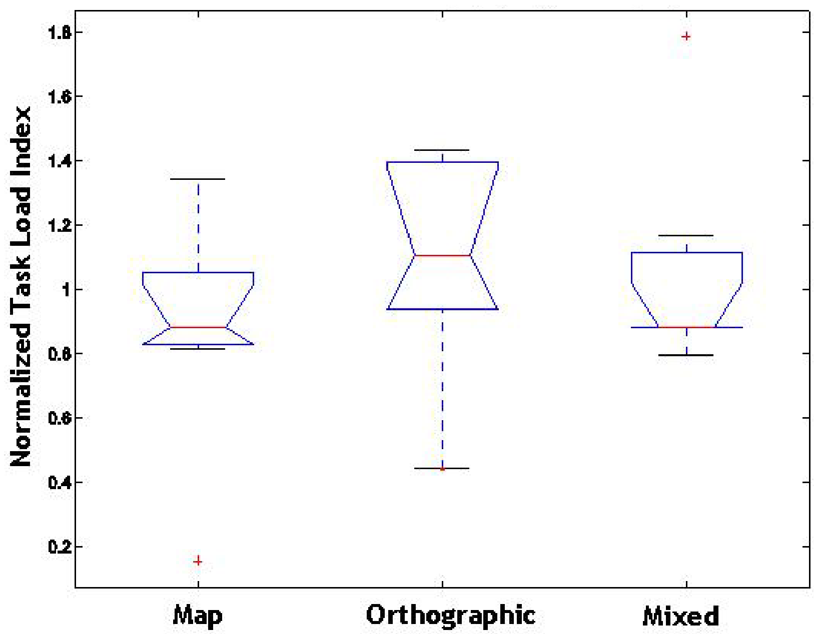

Figure 5.7 – Normalized Task Loading Index (TLX) versus Display

Figure 5.7 shows the normalized workload scores. Workload scores were assembled for each condition and then divided by the mean score to normalize each distribution to its mean. In this way all the TLX scores are relative to each other. The differences are not statistically significant signifying that we could not measure any appreciable difference in workload between the three displays; however, the data does begin to suggest that there is an increased workload for the Orthographic Display.

The display concepts are essentially tied at this point in the evaluation. The pilot surveys, however, show a preference. The surveys queried the pilots to reveal the pilots' preferences as to which display was most useful and why. To assess which display the pilots preferred they responded to the following statement, "If I were choosing the components of this system I would choose: Orthographic Display, Map Display, Mixed Display."

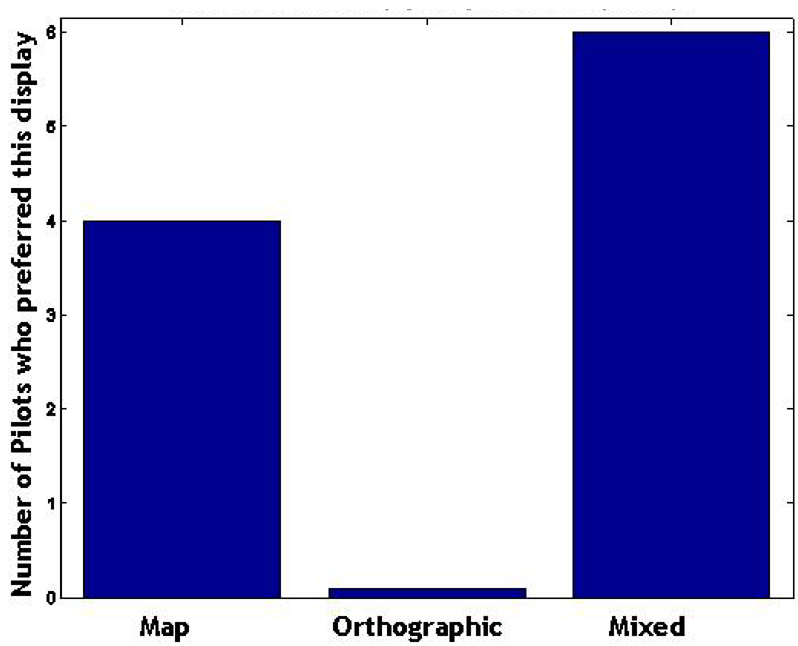

Figure 5.8 – Which display did the pilots prefer?

Figure 5.8 makes it plain that the map view information is essential. None of the pilots favored the Orthographic Display. Four Pilots chose the Map Display and six chose the Mixed Display. To illuminate why pilots chose as they did they were asked to give brief descriptions of the strengths and weaknesses of the displays. Those results are summarized in Table 5.4 below.

Display	Strength	Weakness
Orthographic		
1	excellent guidance for approach	longitudinal spacing is not as easy to pick up and interpret
2	quick, intuitive understanding of traffic relative to his tunnel	not as effective when image of traffic is not fully on screen
3	roll intent is much clearer	poor information on acquiring the localizer
4		Learning curve to understand
5		No missed approach guidance
Map		
1	feels natural, very intuitive, less learning required	not as sensitive [as the orthographic display]
2	lateral spacing info is instantaneous and available constantly	not as good for relative altitude of the traffic
3	blunder recognition very good and obvious	No roll information – roll bug is useful but takes a little time to get it in the cross check
4	long distance obvious and intuitive, good spacing tool	poor resolution on lateral position
5	situation awareness is good everywhere (final and joining final)	
6	missed approach guidance is available	
Mixed		
1	best of the three	need more time to get familiar with the display
2	got all the necessary information together	Too much clutter: overlapping portions of the displays
3	excellent guidance for approach	too much information
4	good situational awareness for both aircraft	not a good combination of the two displays
5	quick to see movement of traffic relative to tunnel	[I am] bothered by changing parameters (up/down and ahead behind) of display
6	gives all desired info for both acquisition and on final	requires most interpretation and learning to "get"
7	effectively combines the strengths of both map and ortho	

Table 5.4 – Pilot Evaluation of Strengths and Weaknesses of the Displays

From the survey results it is clear that pilots agreed that the Orthographic Display offered a precise depiction of the ownship and traffic roll and position within the tunnel. However, Map Display was simply more comfortable and afforded a larger and more intuitive view of the approach. Pilot 7 summarized the views of many, "I think I could fly a more precise approach with the Orthographic Display. Not that the Map Display is unsafe but the Orthographic Display is more precise. But, I like the Map Display."

Eight of ten pilots agreed that the combination of the precision of the Orthographic Display and the global view of the map on the Mixed Display was an improvement over the Map alone. Two of the four who chose the Map felt that the Mixed Display was good in concept, but this particular implementation was too cluttered. The two remaining dissenters felt that the Orthographic information on the map display was superfluous. After having seen only the Orthographic and Map displays Pilot 8 recognized their complementary capabilities and suggested that "features of each to be combined for a more intuitive display." Then, after flying the Mixed Display at the end of the experiment he wrote, "[I] like the combination of views." The majority of the pilots suggested that something like the Mixed Display would be the way to combine the strengths of each. The strength of that statement is that between the two displays the pilots felt that all the pertinent information had been conveyed. Restated, they felt that the 'right' display would be some uncluttered, timely combination of the elements and information already contained in the other two. This result allows researchers to significantly narrow the scope of future efforts.

Those pilots who chose the Map Display in Figure 5.8 all made some comment that they appreciated the goal of the Mixed Display but felt it was too cluttered. To alleviate the clutter one pilot suggested only bringing the hoops onto the Mixed Display after both aircraft had established themselves within the straight final approach tunnel as a method of "presenting the data only when we need it."

They also felt that the Orthographic Display was trying to give precise information when it wasn't necessary. Specifically they noted the poor depiction of the missed localizer scenario (Figure 5.3, right panel) with the imagery of the traffic and parallel tunnel just barely visible on the screen when the traffic deviated from the tunnel. Obviously, this display isn't equipped to show this type of scenario. The Orthographic display was designed for flying final not joining final and the capabilities of this display are not easily stretched to other situations as this example plainly shows. This is a natural strength of the map display. With no clever devices or nonlinear effects just zooming out one can see all of an approach, whereas a similar change is much harder and less intuitive on the ortho display. Still, features could have been added to the Orthographic display to make it better in this situation such as latching the hoops and indicator to the edge of the screen and changing the color when the parallel tunnel and aircraft were outside the frustum of the orthographic projection.

5.1.3.2 Reaction Time dependence on ADS-B datarate

Intuition suggests that reaction time should be a strong function of ADS-B datarate. Low datarates have longer lag between updates and hence more time elapses between an action by the traffic and when that action gets reported to the pilot. Given that reasoning, the results in Figure 5.9 are quite surprising. Figure 5.9 shows the distributions of reaction times for each ADS-B datarate tested (1, 3, 10 Hz) with the Data 1 group (see §5.1.2.5). ANOVA analysis revealed no significant difference between the 3 distributions, but if a trend can be inferred from the plot it seems that the reaction time actually *increases* as the datarate increases. This is opposite to the result that intuition implies. It is likely that the reaction time data for 10Hz is artificially high. The experiment was a randomized full factorial design. Inspection revealed that the 10 Hz run with the orthographic display was the very first run after the two acclimation runs. Figure 5.10 shows the same data for 1 and 3 Hz as Figure 5.9 but instead of using the data from the first run for the 10Hz (10Hz, Orthographic display) data from the last run 10Hz, Mixed Display, was used. It is suspected that pilots' skill at detecting blunders with the display increased as the experiment progressed. Although analytical attempts to verify this claim have been unsuccessful several pilots reported that their comfort level with the displays increased through the experiment. The trend in Figure 5.10 stilll does not match the expected results. These plots suggest that there is not much to be gained from using high datarate datalinks in CSPA operations.

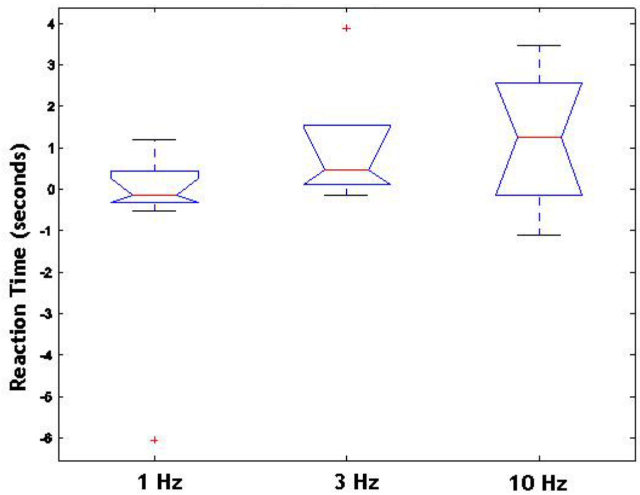

Figure 5.9 – Reaction Time as a Function of ADS-B Datarate

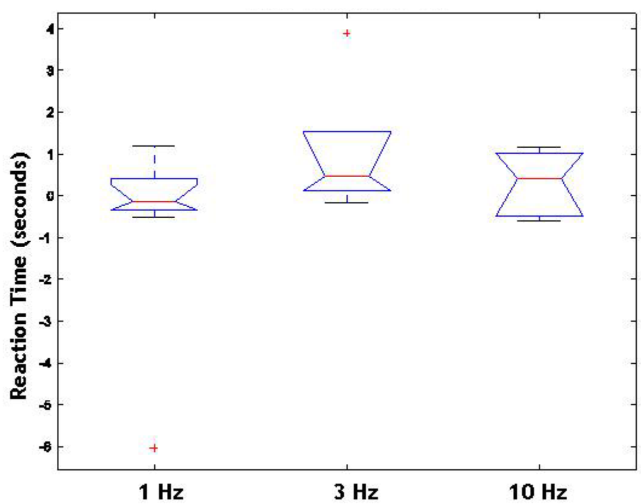

Figure 5.10 – Reaction Time versus ADS-B Datarate Using the Final Runs in the Experiment

To reveal more detail on the low frequency behavior of this relationship two additional pilots (Data 2) flew the experiment at ADS-B datarates of 0.14, 0.33, and 1Hz. As stated earlier these frequencies were chosen to overlap the requirements as set out in the ADS-B MASPS and summarized in Table 5.1.

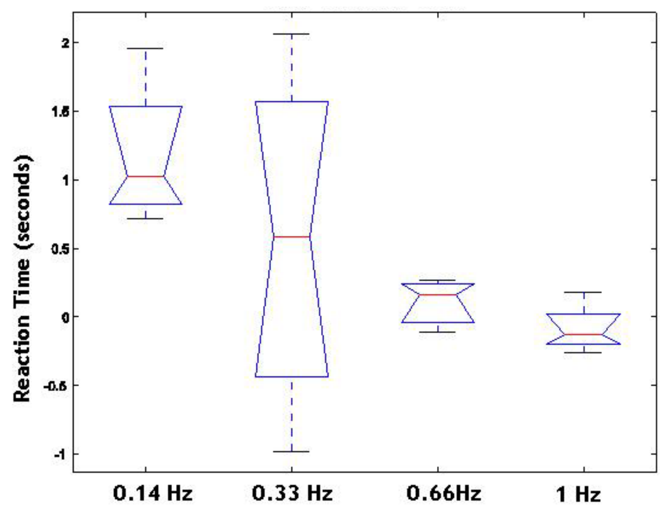

Figure 5.11 – Low Frequency Reaction Time versus ADS-B Datarate

Even at these ridiculously slow datarates with time between updates of 7, 3 and 1 second (from left to right) the difference between these distributions are not significantly significant, though now they do hint at the expected trend. The reason the ANOVA failed to decipher a difference is because the 0.33 Hz distribution is so wide. If the ANOVA is repeated for just 0.14, 0.66, and 1 Hz a difference with $F(2,8) = 13.6$ and $p < 0.002$ is found. This confirms that reaction time performance does degrade if the datalink suffers significant outages despite the pilots' best efforts. Even so the magnitude of this effect is surprisingly small. A 6 second increase in the length of an outage from 1 second to 7 seconds (0.14 Hz) only generated a 1-1.5 second increase in the reaction time.

It is likely that if the pilots were shown these plots that they would not be nearly as surprised as the researchers were. When asked at the end of the experiment to evaluate the following statement, "Increasing the update rate of the traffic increased my situational awareness of the traffic." Pilots neither agreed nor disagreed. On a scale of 1 to 5 with 1 being 'Strong Agree' 3 being 'Neutral' and 5 being 'Strong Disagree' the mean score was 2.9, Neutral.

It should be noted that the Data 2 pilots were faster than the pilots in Data 1. Comparison can be drawn between the 1Hz trials flown by both sets of pilots shown in Figure 5.12. Although the ANOVA statistics are insufficient to claim a significant difference it is obvious that the Data 2 pilots reacted to traffic deviation in a much more narrow window of reaction times than the Data 1 pilots. It should be noted that the Data 2 pilots were the youngest pilots to fly the experiment.

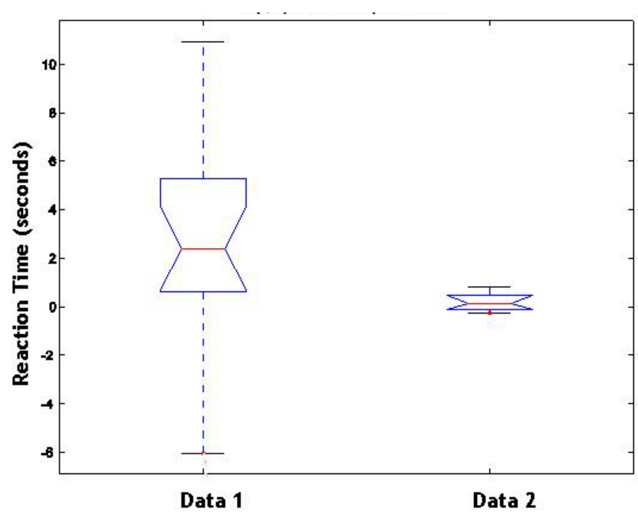

Figure 5.12 – Comparison Between Data 1 and Data 2

To the limits that the experiment tested, this data suggests that a 1 Hz datalink is adequate to achieve minimum reaction times to simulated blunders. Moreover, because of the first order interpolation in the display software and the judgment of the pilots, the human-in-the-loop system reaction times are robust to the currently allowable ADS-B data outages. Thus, more stringent continuity requirements for ADS-B will not significantly affect the achievable reaction time to a blunder.

The pilots are able to use the derivative information provided, east and north velocity and heading rate, along with the first order filter implemented in the display to extrapolate the traffic's position between ADS-B updates. This was obvious from the negative reactions times in the data and, additionally from comments made by pilots while flying the experiment indicating that they had sufficient information to anticipate what the traffic was about do to. Comments addressed to the traffic that preceded the blunder, "Don't do that." and "Oh, he's about to come around." (Pilot 8 and Pilot 3, respectively) indicated that pilots could anticipate the blunder.

5.1.3.3 Observations

While conducting the experiment the experimentor had opportunity to make observations on behaviors or trends that seemed interesting that did not necessarily fit into the rest of the experiment or were not addressed in the surveys. While developing the experiment one curiosity was: If, given the opportunity, would pilots adjust their final approach speed to maintain optimal spacing behind the traffic. The speeds were chosen so that the ownship would enter the final approach with the traffic just off the left side of the PFD and with the ownship just touching the rear limit of the yellow color strip. Moreover, pilots were instructed to fly the approach at 150 kts but the stall speed was placarded at 135kts. So, by design the pilots were not briefed that they could adjust the final approach speed but their simulated aircraft had room to slow down. Only, 2 of 10 pilots actually did slow down to increase the longitudinal spacing to put the image of the traffic on the PFD or to stay completely clear of the color strip. If the pilots had been briefed on this procedure then it is likely that more would have modulated speed to stay outside of the danger zones or to keep the image of the traffic on the PFD.

5.1.4 And the winner is…

The primary goal of this experiment was to evaluate the two displays (Map and Orthographic) to select an overall favorite, one that had superior reaction time characteristics and that found the most favor with the pilots. The outcome was that while the Orthographic Display yielded reaction times to blunders that were 15%

faster than the Map Display, the pilots unambiguously prefer the map format for monitoring traffic. Given that preference, most of the pilots advocated the benefit afforded by the precision of the Orthographic Display and suggested that some variety of the Mixed Display should be the ultimate solution. The Mixed Display has some internal inconsistencies (see Chapter 3) hence the eventual display for CSPA will be a new iteration of the Mixed Display that has the global view of the map and the precise view of the orthographic integrated into a consistent display or perhaps a series of displays. In the end the characterization of single display must be chosen to be included in the Monte Carlo analysis in Chapter 7. Since the quality of global situational awareness afforded by the map format was ubiquitously preferred the Map Display is selected as the winner in this race.

5.2 Flight Testing of the CSPA Display

5.2.1 Objective of Test

The primary objective of the flight testing was to conduct the first-ever proof of concept for using synthetic vision for CSPA operations. In particular the test focused on the following questions:

- Does the image of the traffic on the display faithfully represent the position of the traffic?
- Is the system capable of painting an image in a timely enough manner to be useful to a pilot who is both flying an approach and monitoring traffic on the parallel approach?
- Does the image of the traffic increase the pilots' situational awareness of the traffic?

In addition to an end-to-end test of the system we wanted to begin to investigate how this display would perform during CSPA operations.

- Can the pilot with the display fly an approach while maintaining a commanded longitudinal spacing between the traffic and the ownship? (station-keeping)
- What does a blunder look like on the display?

5.2.2 Description of the Demonstration

To answer these questions a series of 18 approaches was flown in December 02- January 03 using the system and aircraft desribed in Chapter 4. The ownship is shown in Figure 5.13. Each approach was either a station-keeping approach or a simulated blunder. Station-keeping approaches started 8nm from the touchdown point. The pilot flying the ownship was instructed to maintain a specific distance ahead or behind the traffic aircraft while the safety pilot monitored the situation. The planned final approach speed of the traffic aircraft was known to the ownship pilot prior to starting the approach. Station-keeping approaches were flown both eyes out and eyes in. In this way a comparison could be drawn between the station-keeping error whether the pilot controlling the ownship was using the display or using the out-the-window scene.

Figure 5.13 – Cessna Caravan as the Ownship

5.2.2.1 Pilots

Three pilots flew the 18 approaches. Pilots #3, #4 (see Table 5.2) and one who did not fly the experiment described in §5.1 flew this experiment. The pilots flew the displays for a total of 5.8 hours.

5.2.2.2 Safety considerations

For safety reasons the blunder approaches were carefully orchestrated. These approaches also started 8 nm from the touchdown point and progressed identically to a station keeping approach. The ownship would always be ordered to follow the traffic at a longitudinal spacing of 0.5 nm or 1.0 nm. At 2.6 nm the pilot and safety pilot confirmed that they had visual contact with the traffic. If both pilots did not have visual contact the blunder portion of the approach was aborted and both aircraft would turn 180° and return to their respective start points. If both ownship pilots had the traffic in sight and they confirmed that they were at least 0.5 nm behind then at 1 nm the traffic would announce that it was about to blunder, wait for confirmation from the ownship, and then roll to 30° and blunder from 32L to 32R, or vice versa.

5.2.2.3 Flight Test Workspace

Figure 5.14 shows a portion of the San Francisco Terminal Area Chart around Moffett Federal Airfield. San Jose International Airport (SJC) is visible at the right side of the image. The magenta and green lines show the location and extent of the approach tunnels for Runways 32L and 32R that were used for this experiment. The purple circle around SJC shows the extent of the SJC airspace that extends from the ground to 4,000 feet above ground level (AGL). Our approach tunnels obviously intersect this airspace. Although this is standard practice for Moffett Federal Airfield, the experimenters from Stanford appreciate the efforts of the Moffett Control Tower to safely accommodate an experiment of this nature within airspace that is well used.

As described in §4.2.2.4 the implementation details of including roll, precise position, and wind data in an already full data stream generated geographic boundaries on where these ADS-B Modes would function properly. The Position Mode is equivalent to the basic ADS-B service and functions properly anywhere on the globe. Items in that data stream, specifically the tens of minutes digit in latitude and longitude and the tens digit in altitude were overwritten to include roll and wind data. The operational bounding box of roll and wind mode was 10 minutes on a side and 1000 feet tall which is approximately 10 nm x 8 nm x 1000 feet (Figure 5.14). This added complications and more then one moment of panic for the flight engineer (me) when the traffic inadvertently flew beyond the southern confine of the bounding box during the downwind leg of the approach. As the traffic approached the border of the box its latitude was decreasing toward 37° 20.00’. At the border of the box the actual position of the traffic becomes 37° 19.99’. But because the tens of minutes digit has been replaced with roll data the image of the traffic doesn't make the same transition. The image of the traffic was instantly transported to 37° 29.99', 10 nm due north! The solution was to fly the majority of the experiment in Position Mode until we were inside the box centered at the airfield. Once both airplanes were below 1000 feet and thus within 3.2nm of the airport we could switch to Roll Mode for the remainder of the approach. It was fortunate that Moffett Field is roughly in the middle of this workspace. San Jose International, for example, is too close to the 37° 20' line of latitude. An approach in Roll Mode into this airport would experience the "teleportation" at about 0.5 nm from touchdown.

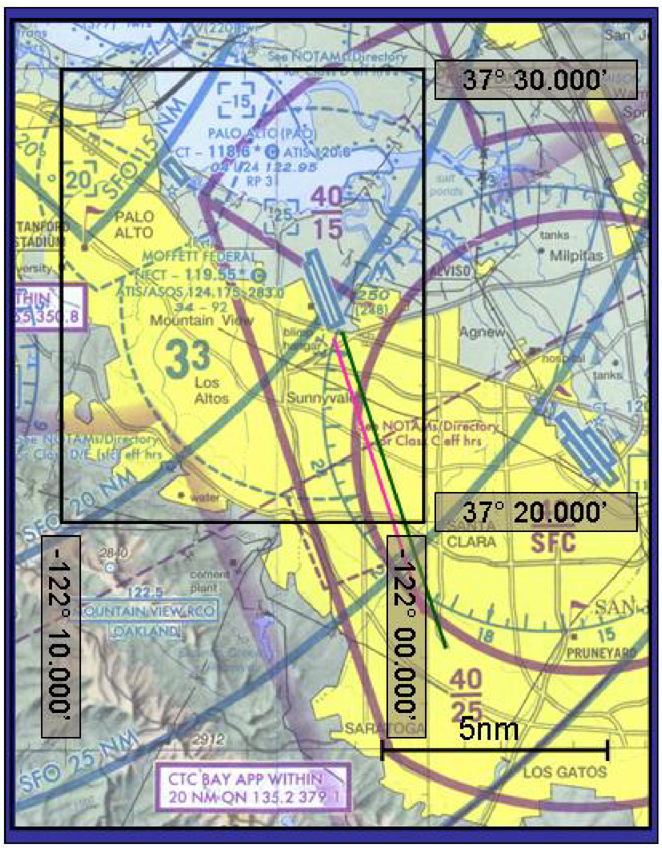

Figure 5.14 – Experiment Workspace at Moffett Field, CA

5.2.3 Results and Discussion

5.2.3.1 Subjective

Following each flight the pilots were asked to rate their responses to the six statements listed in Figure 5.15. Responses for each pilot were recorded on a scale of 1 to 5 where a score of 1 indicated "Strongly Agree" (green); 3 indicated "Agree" (yellow) and 5 indicated "Strongly Disagree" (Red)

	Statement	Pilot 1	Pilot 2	Pilot 3
1	The image on the display **faithfully represented the position** of the traffic.	2	2	2
2	The image on the display **faithfully represented the roll angle** of the traffic.	Always eyes out in Roll Mode	2	2.5
3	The display **improved my situational awareness** of the traffic when I was eyes out	1	2	2
4	The display **improved my situational awareness** of the traffic when I was eyes in.	Always eyes out.	2	2
5	The orthographic view was clear and easy to understand	1	Never used this display.	1
6	The map view was clear and easy to understand	2	2	1
	Time flying traffic display	3.9 hrs	1.4 hrs	0.5 hrs

1 — Strong Agree; 3 — Agree; 5 — Strong Disagree

Figure 5.15 – Subjective Results for CSPA Flight Demonstration

The statements are all positive assessments of the display. Therefore, the more low scores, green and blue, (blue represents a score of 2, between Strong Agree and Agree) the stronger the endorsement of the prototype display system. The statements were constructed to asses the objectives of the proof of concept outlined earlier in §5.1.2. The pilots found that the display did its job and increased their situational awareness of the traffic whether or not they were eyes in or eyes out. This data from the pilots suggests that it is feasible to produce a display system that can reliably show traffic on an SV PFD such that the image reliably represents the true position of the traffic.

5.2.3.2 Longitudinal spacing

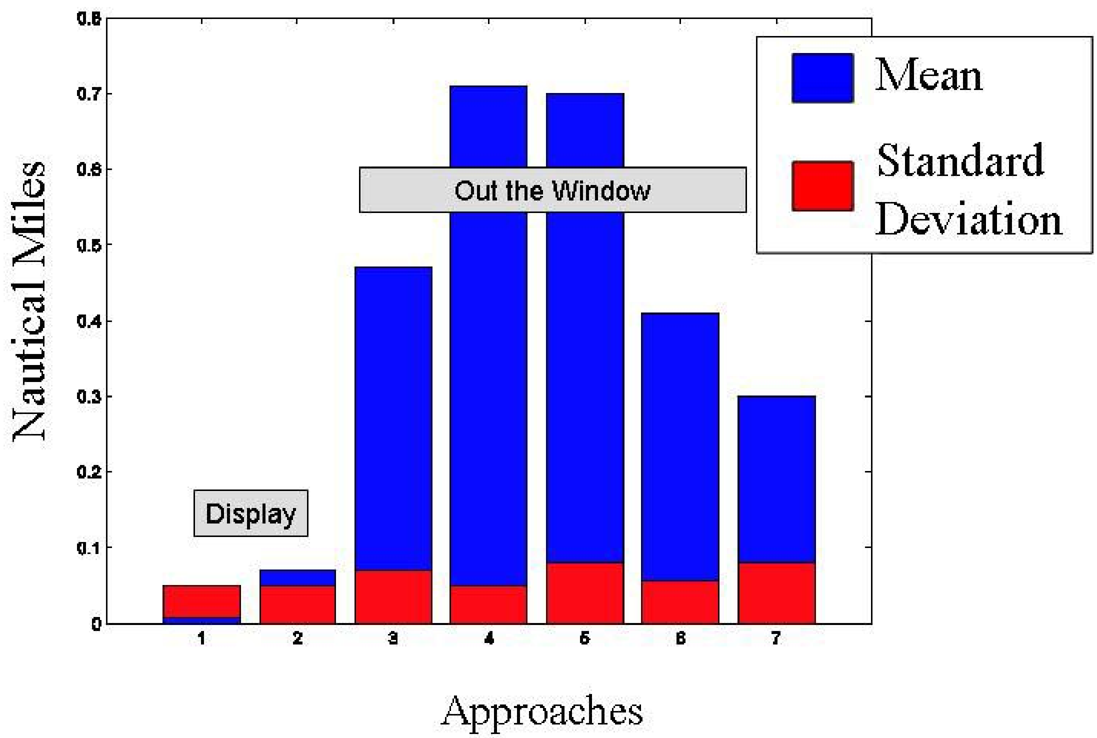

Figure 5.16 – Longitudinal Spacing Error versus Display or Out-the-Window

Figure 5.16 shows the mean error in longitudinal spacing for seven station keeping approaches. Approaches 1 and 2 were conducted with the pilot using only the CSPA Display. Approaches 3-7 were conducted with the pilot looking out-the-window. The maximum mean error for Approaches 1 and 2 is 0.07nm (425feet) and the mean error for Approaches 3 through 7 is 0.5nm (3038 feet).

The station keeping results are promising given that longitudinal spacing errors were substantially lower when pilots used the display rather than using the out the window scene. This shows that using the display affords almost a factor of 10 reduction in the error in longitudinal spacing. Pilots are able to control the mean error in longitudinal position relative to the parallel traffic to within 425 feet.

The standard deviations for both cases are roughly the same however. Perturbations around the estimate are roughly equivalent for approaches using the display and those using the out the window scene. These statistics generate a 95% confidence interval on longitudinal station keeping performance of of 0.168 nm or 1020 feet.

5.2.3.3 Recorded ADS-B Datalink Continuity

Over the 5.8 hours of flight time with the displays and datalink running an average ADS-B update rate of 0.5 Hz was recorded. This obviously does not comply with the specifications set out in the ADS-B MASPS and summarized in Table 5.1. This discrepancy could be partially explained because of an error in initialization of the UAT that presumably caused half of the messages to be dropped. Although this fact may be responsible for some of the missed message it is not the main cause. The outages were surprisingly bursty and menacingly severe. At distances of less than 1nm several dropouts of more than 15 seconds were experienced. The longest dropout at this range lasted 45 seconds. Preliminary analysis has revealed that this dropout is not a function of relative elevation and azimuth from the ownship to the traffic. Nor are the dropouts correlated with distance between the aircraft. The dropouts do seem to happen in the same portion of the approach. Since both airplanes were flying very repeatable trajectories it is speculated that the ADS-B encountered some attenuation due to the structure of the aircraft. It is also possible that destructive multipath interference from the wave bouncing off the ground caused some signal loss or that some direct interference from an unknown localized source in Silicon Valley contributed to the problem. However, although the datarate was studied in detail none of these potential causes have been verified. The conclusion to be drawn is that some extra precautions must be taken to ensure that ADS-B will function reliably during CSPA operations. The resolution of this issue is left for future research.

5.2.4 Summary of Flight Test Results

The goals of this flight test were to test fly a proof-of-concept of traffic on a Synthetic Vision Primary Flight Display (SV PFD) and to collect data on station-keeping performance using that display. Both goals were successfully met. The flight testing yielded a prototype SV system with a well conceived architecture (Chapter 4). The pilot responses indicated that it is feasible to convey detailed situational awareness of parallel traffic using synthetic displays and, furthermore, that using these displays allows for a significant improvement in the achievable station keeping accuracy. Figure 5.17 (a proud moment) shows the display running as the pilots perform the final approach of the flight testing.

Figure 5.17 – Map Display During the Flight Tests

5.3 Conclusions

The data presented here is too small a sample from which to draw conclusions regarding global acceptability of these displays. What can be inferred from the pilot responses is the system functioned well enough to prove that the concept of reproducing the out-the-window scene is feasible even when parallel traffic is included. If this reproduction is timely enough then it is reasonable to expect pilots to respond to blunders depicted on the display in a similar manner to blunders detected by looking out the window. If this is the case then and with the establishment from §5.1 that 4.4 seconds is the reaction time to a blunder using the Map Display and from §5.2 that pilots can maintain a commanded longitudinal spacing to within 1000 feet it then becomes possible to reevaluate the requisite runway spacing to conduct independent parallel approaches in IMC. Chapter 7 describes the analysis to investigate exactly that issue. Chapter 6 investigates the utility of adding runway incursion alerting to these displays. It is the overall goal of this research project to produce a display and supporting system to give approaching pilots all essential information to aviate, navigate to the runway, and monitor the potentially threatening traffic.

Chapter 6

Runway Incursion

The critical question when alerting a pilot to a hazardous situation is one of timeliness. This chapter describes the two series of flight tests designed first to test the runway incursion alerting software, §6.1, and then to compare the reaction times of pilots using the display to the reaction times of pilots using the out-the-window (OTW) scene, §6.2. §6.3 then combine the results from the previous experiments to answer the question of whether the algorithm and the display alert the pilots with sufficient time to execute the appropriate evasive maneuver.

6.1 Runway Incursion Flight Test 1 – Simulation and Verification (Aug '99)

6.1.1 Objective of test

As a first step to an eventual runway incursion flight test we endeavored to test the runway incursion software incrementally. The goal was to verify that the runway incursion alerting logic described in Chapter 3 would function as expected during flight. A second, but no less important, goal was to see if the pilots would reliably react to the traffic imagery on the screen. To do this they must understand the action and the potential hazard that the image represents and then take appropriate action.

To simplify the experiment we simulated the incurring vehicle. Hence, in this flight test the only real vehicle is the ownship. This allowed us to eliminate the broadcast system entirely (Figure 4.2) and focus on the functionality of the display software and on the pilot reactions.

6.1.2 Flight Test

We flew 6 approaches to runway 32L at Moffett Federal Airfield, Moffett, CA. On each approach the Virtual Aircraft (VAC) was commanded to taxi from hold short to position and hold. Pilots were instructed to fly level when the runway turned from grey (no alert) to yellow (caution) or red (alert). Simulated incursions were timed so that all transitions from no alert to caution and/or to warning cues were tested.

6.1.3 Results

The results are anecdotal in nature. The software performed as predicted and it was adequate to the task of translating vehicle positions and velocities into alerting cues for the pilots. Additionally, the pilots were able to discern the actions of the aircraft from the imagery on the screen while they flew their approach. This successful test set the stage for the formal analysis described in the following section.

6.2 Runway Incursion Flight Test 2 – Experiment (April 2001)

After the successful testing of the runway incursion monitor algorithm we replaced the simulated ground vehicle with a Ford Windstar Van courtesy of Prof. Chris Gerdes Vehicle Dynamics Lab and Visteon Inc. Into that van we loaded the system described in Chapter 4 and shown in the white rectangle in Figure 4.2. The flight test had two primary objectives:

- Complete a proof-of-concept flight of the display system.
- Conduct an experiment to establish a conservative baseline comparison between reaction times to runway incursions when pilots use the out-the-window (OTW) scene and when they use the display.

6.2.1 Venue

Moffett Federal Airfield was an exceptional location to conduct these flight tests. Moffett has two parallel runways 32L/14R (8,125' x 200') and 32R/14L. (9,200' x 200'). In addition the traffic volume at the airfield is relatively low during certain periods of each day. We were able to conduct these research operations with superb support and cooperation from Moffett Air Traffic Control and Moffett Flight Operations.

Figure 6.1 shows a map of the airfield. The Caravan approached on 32R (upper runway in Figure 6.1) and the van incurred either at Taxiway AA at the threshold or at Taxiway Bravo, 6,500 feet down the runway.

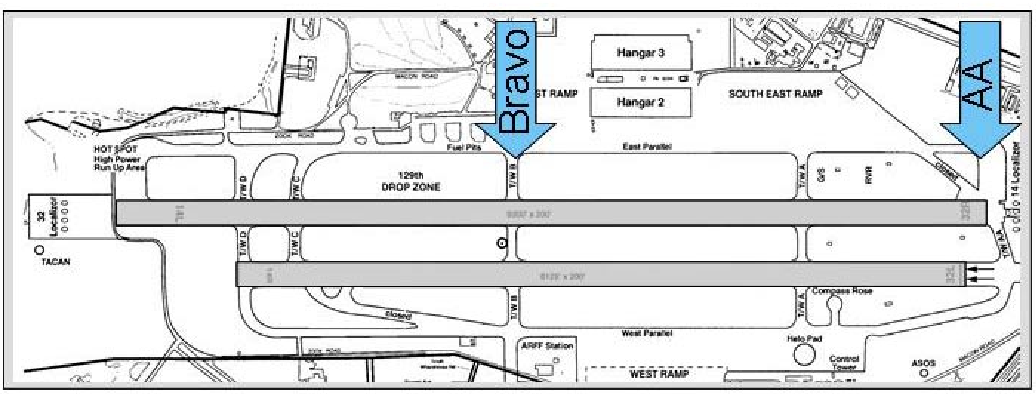

Figure 6.1 – Incursion Locations at Moffett Federal Airfield

6.2.2 Design of experiment

The experiment was a full factorial design with two independent variables and two dependent variables. The goal was to collect statistically significant data showing the effect of using the display on reaction time to a blunder. To do this we flew several pilots and repeated approaches in the various conditions. To attempt to lessen the cueing of the pilots to the van's incursions we flew 27% of the approaches without incursions.

6.2.2.1 Independent Variables

- Visual Cue, Out-the-Window vs. Display - The comparison between these two factors is the crux of the experiment.
- Pilot Task, pilot flying or observing – We also want to ascertain if there is any effect from to the increased workload of flying the airplane.

Figure 6.2 shows the combinations of the independent variables across all the pilots.

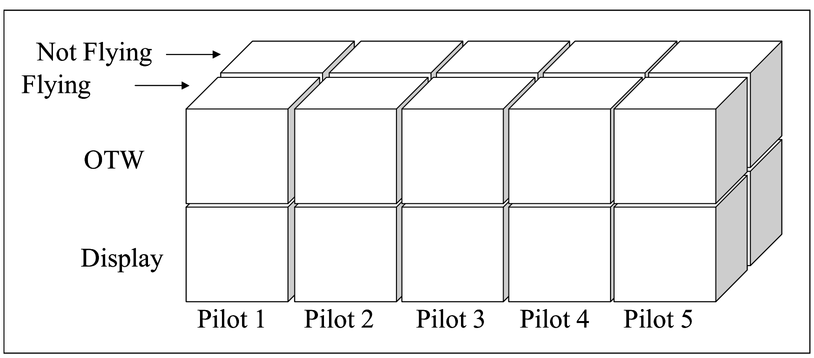

Figure 6.2 – Experiment Matrix

6.2.2.2 Dependent Variables

Reaction Time (RT): GPS time of each event in the experiment was recorded. The dependent variables in this experiment are the reaction times recorded by the pilots' button presses. With these data we can derive the central figure of merit for this experiment.

$$display\_advantage = RT_{OTW} - RT_{DISPLAY}$$

RT, reaction time, is the number of seconds between the instants when incursion began and when the pilots signaled that they saw the incursion. Display_advantage is the difference between the reaction time of the OTW and display pilots; if this number is positive then the pilot looking at the display saw the incursion first, hence there is an advantage to having the display. If this number is negative then this implies that the display causes that pilot to be at a disadvantage when compared to a VFR pilot.

6.2.2.3 Corner Cases

Corner cases are scenarios that are outside the primary objectives of the experiment but are nonetheless worth investigating with a greatly reduced number of approaches. Corner cases were chosen to replicate more realistic scenarios of dangerous runway incursions.

- Pseudo IFR Approaches. To simulate low visibility conditions we endeavored to make the van less visible by extinguishing all interior and exterior lights and flying the experiment at night.
- Bravo Approaches. To simulate a more common runway incursion incident scenario we conducted incursions at Taxiway Bravo, some 6,500 feet down the runway.

6.2.3 Flight Operations

To coordinate several people and two vehicles to study a potentially dangerous scenario it was essential to establish some standard flight operations. Meanwhile precautions must be taken so as not to cue the pilots to the incursion.

6.2.3.1 Downwind

The flight test engineer in the aircraft instructs the pilots as to who will be looking at the display (Display Pilot) and who will be looking out the window (OTW Pilot). The flight test engineer also instructs the pilots who will be flying the aircraft on this approach and who will be monitoring altitudes.

6.2.3.2 Final Approach – With Incursion.

On a frequency inaudible to the cockpit crew, the flight test engineer instructs the van to incur when the aircraft is 1 nautical mile from touchdown. For the OTW pilot the incursion started when the van had progressed far enough that it would be impossible for it to stop without entering the runway. This criteria coincides exactly with the methodology behind the design of the Runway Incursion Monitor (RIM) software (§3.6). At the speed of incursion this translated to the pilots pushing the button when the van was two vanlengths from the edge of the runway. The criteria for the display pilot was much simpler. They were instructed to press their button whenever the runway changed from grey to yellow or red.(see Chapter 3 §3.6. for a full description of the algorithm to change the colors of the runway).

6.2.3.3 Low Approach – Without Incursion

Pilots executed the approach as per normal procedures. If the van did not incur then they were to maintain 75 feet above ground level (AGL) until they flew past the van. At that point they could initiate their go-around.

6.2.3.4 Low Approach – With Incursion

Pilots were instructed to maintain 75 feet above the runway. They were also told not to indicate that they had seen the incursion in any way except by pressing their button. We did not want to cue the tardy pilot to an event by the actions of the early pilot. From their station the flight test engineer could ascertain whether the pilots had or had not seen the incursion and could appropriately direct the pilots to go around.

Figure 6.3 – Simulated Runway Incursion

When the ownship was 1 nautical mile from the touchdown point the van was commanded to incur. 1 nm was chosen for several reasons. First, at this distance the van should be plainly visible to both the OTW pilot and the display pilot. Any failure to see the van here would be a result of some factor other than visibility, workload, etc. Another reason was to limit the length of the final approach. With an incursion at 1nm the pilots could fly a 2nm final. This kept the overall time per approach to about 4 minutes. Any effort to reduce flight costs without compromising the experiment is valuable.

6.2.3.5 Safety Considerations in the design of the experiment procedures:

Since we were simulating a dangerous situation by purposely driving a vehicle onto an active runway as an aircraft executed a low approach, several safety measures were employed.

- The Caravan always had at least one pilot with their eyes outside the airplane looking for the incurring traffic.
- In addition to the driver of the van a spotter always sat in the right seat to manage the radios and help watch the Caravan.
- Glide slope of final approach was increased to match the zero headwind glide ratio of the Caravan. Thus the Caravan would be better able to glide over the van if both vehicles lost their engines.
- Van always incurred from the east and faced 140° on Runway 32. That way the driver and the spotter could see the Caravan through the windshield.
- When the aircraft is at 1nm it is about 30 seconds from the touchdown point. Staging the incursion here gave pilots and drivers enough time to communicate and deal with any unexpected emergencies.

With these redundant measures in place it was necessary for three independent failures to occur to have any real danger of an accident.

6.2.3.6 Pilots

Five pilots participated in the study. Their total flight hours are presented below. Three of the pilots were or are professional pilots. Two of the pilots are General Aviation pilots.

Pilot	Total Hours	Experience
1	2,500	Professional
2	12,000	Professional
3	5,100	Professional
4	1,000	Private Pilot
5	2,000	Private Pilot

Table 6.1 – Pilot Hours

6.2.3.7 *Number of runs*

In total we conducted 98 approaches over five days. Due, in part, to operating constraints at Moffett, we conducted 68 approaches at night. We flew 7 Pseudo IFR and 8 Bravo Approaches.

6.2.4 Results

6.2.4.1 *Proof of Concept – System Validation*

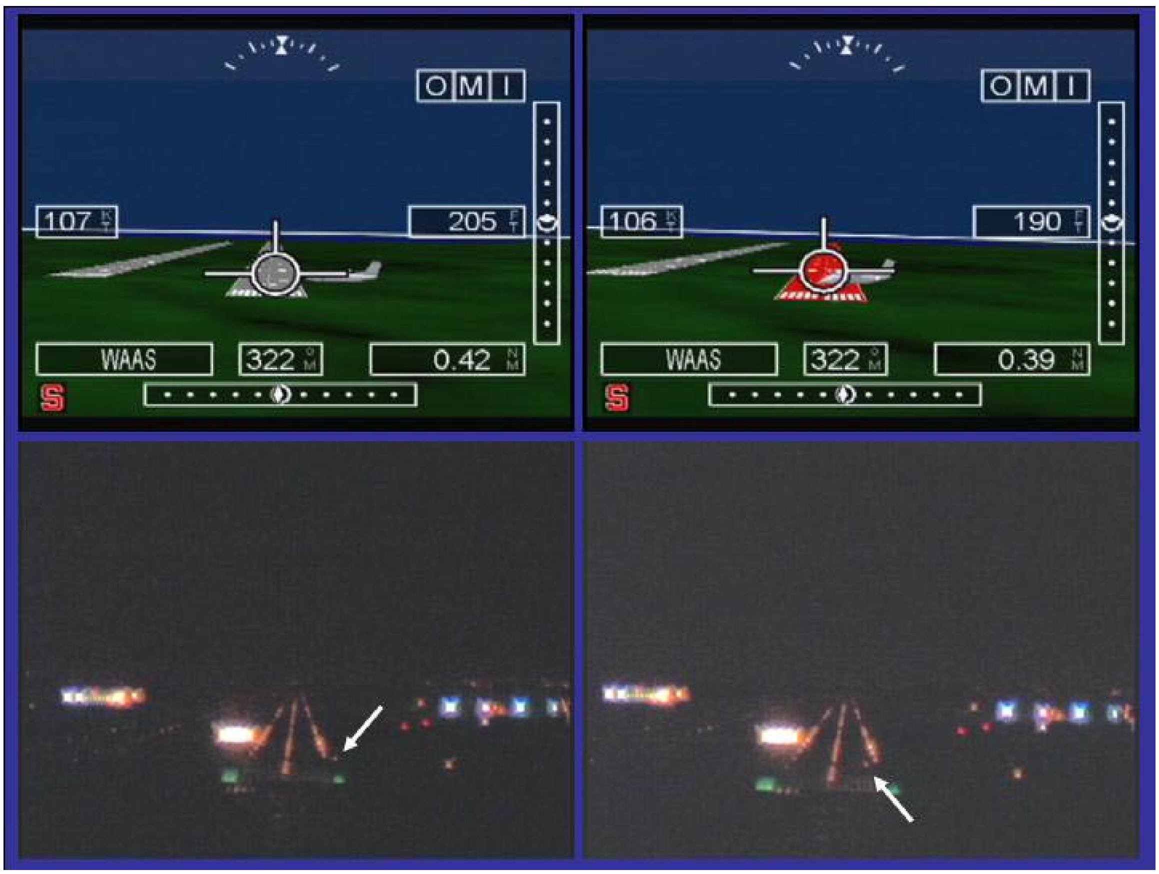

Figure 6.4 - Synchronized Synthetic Vision and Out the Window Views (white arrows show the taillight of the incurring van)

Figure 6.4 shows two sets of time-synchronized images from an incursion approach during the flight test on 17 April, 2001. The images on the left side of Figure 6.4 are the display and the out-the-window views before the incursion. In both images the van is visible just to the right of the runway edgeline. In the synthetic image the van is represented by the model of an aircraft that is partially obscured by the Flight Path Vector. In the OTW view the flashing taillight of the van is indicated by the white arrow. The images on the right hand side show the display and the OTW view after the van taxied onto the runway. Obviously position of the van matches well between the two views and in addition, the runway incursion alerting has changed the runway to red, indicating the incursion to the pilot.

It should be noted that pilots reported that it was easy to see the taillight of the van on this night. It is harder to see the van in the photo than it was on the night of the flight tests.

6.2.4.2 Reaction Times

We measured the pilots' reaction times by installing buttons on the yokes of the aircraft. The buttons were designed such that they were easy to use, would not interfere with the tasks of flying the aircraft and could be pressed without indication to the other pilot. The buttons were connected to a laptop that would record the GPS time at the instant the button was pressed.

Pilots were instructed to press their button when they saw the incursion. Seeing the incursion had specific definitions for the OTW and the display pilot (see §6.2.3.2). The time of the onset of the incursion was determined by reviewing the time-tagged videotapes.

6.2.4.3 Effect of Pilot Flying

To the fidelity of the measurement of the experiment the added task of flying the aircraft had no effect on the reaction time for either the display or the OTW pilot. Evidently the tasks of controlling the aircraft and scanning for the incurring traffic are complementary enough that the presence of one task does not impede the other. It is possible that in a higher workload cockpit environment this might not be the case.

6.2.4.4 Baseline Reaction Time Comparison

Figure 6.5 shows a summary timeline running from left to right for data from 44 standard approaches. Display Pilots, on average, responded to the incursions 2.4 seconds after the OTW Pilot. It is evident from the timeline that OTW Pilots generally anticipated the incursion by 0.5 sec and that Display Pilots took 0.4 sec to respond to the runway changing color from grey to red.

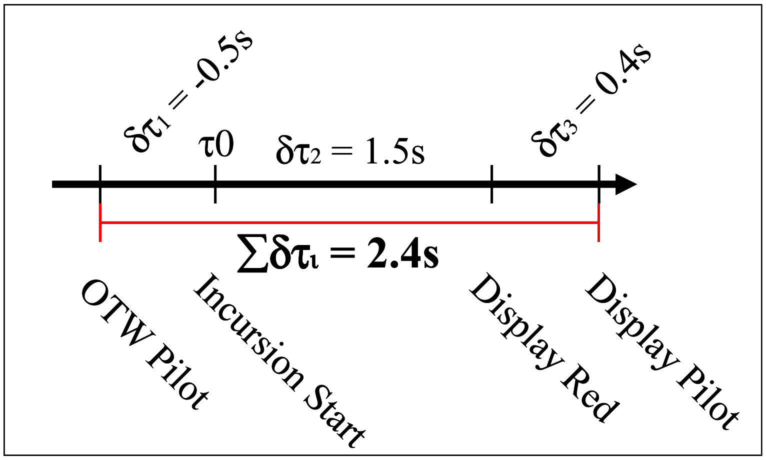

Figure 6.5 – Reaction Timeline

6.2.4.5 Corner Cases

Figure 6.6 shows the reaction times to the Pseudo-IFR Approaches. Each row shows one approach. Every row of the table that contains a red 'X' indicates that that pilot never saw the incursion, which in all cases was the pilot looking out the window. In the one approach where the OTW Pilot did indicate that he saw the van, he did so 14 seconds after the Display Pilot.

Display Advantage	PILOT1RT (GPS time)	PILOT2RT (GPS time)
∞	✗	185475.140
∞	186256.950	✗
∞	✗	188495.880
∞	189473.330	✗
∞	189724.830	✗
14.34s	190748.650	190734.310
∞	✗	191522.770

Figure 6.6 – Pseudo-IFR Approaches

Figure 6.7 shows the histograms of reaction times to incursions at AA and incursion at Bravo. The mean disp_advantage for incursions at AA is -1.9 sec whereas the disp_advantage for incursions at Bravo is 0.3.

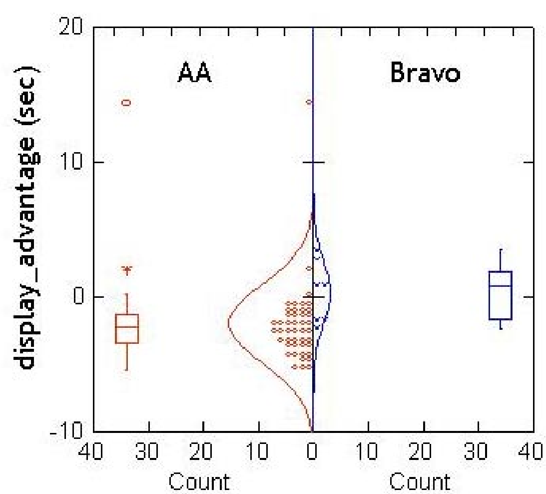

Figure 6.7 – Histograms of display_advantage for incursion at Taxiway AA and Bravo

6.2.4.6 Subjective Results: Quotes from the Pilots

In general, the pilots liked the displays. Their primary complaint was that the image of the pathway obstructs the rendered image of the traffic. Pilot 1: "*at 2 miles out the display is too busy in the center.*" Pilot 2 stated, "*[the] runway changing color was obvious but perhaps a bit too abstract.*" He preferred a text message across the screen similar to the method used in [Jones01].

When asked if the display makes detecting the incurring traffic in clear VMC easier Pilot 4 stated, *"... yeah, it's a no brainer. You don't have to look so hard. [traffic on the display] doesn't detract any from flying the approach whereas scanning for traffic on the field does*." *"[The traffic is] exactly in the direction you are looking when flying the display, whereas when looking out the window you spend time scanning*."

Pilots were very supportive of the display's performance in the Pseudo-IFR approaches. Pilot 5, "*I couldn't see the incursion in the twilight, but I didn't miss the runway going red…the display shows incursions for all entries [with the same cue]*"

6.2.5 Biases in the Results

The following factors are likely to lower the reaction time of the out-the-window pilots.

- The incursions happened either at Taxiway AA or Taxiway Bravo.
- The incurring vehicle was always the same van.
- The incursion would happen when the ownship was one nautical mile from the touchdown.
- The only vehicles moving on the field were those participating in the experiment.
- Since there were no other vehicles on the field, distracting communications on the tower radio frequency was minimized.

It is likely that these factors will lower the reaction time of the OTW Pilot more than the Display Pilot. The Display Pilot is reacting solely to the change in color of the runway. Even though they might be primed to the incursion they must wait for the color change. In contrast, the OTW pilot is trying to locate the traffic on the airfield and has more of an opportunity to anticipate the incursion. For these reasons it is probable that the results for the display advantage are conservative. A larger advantage could be expected from using the display in everyday scenarios when the circumstances of the incursion are less predictable.

6.3 Conclusions

Building on the successful simulation and verification test, the goals of the flight experiment were met by successfully flying a proof of concept display system and measuring the effectiveness and properties of alerting pilots to an incursion using the system or using the OTW scene. It is clear from the images in Figure 6.4 and the anecdotal data that the system worked well and that pilots found benefit in the traffic information on the Synthetic Vision PFD.

The 2.4 second lag of the Display Pilot stems from three sources. First, the OTW Pilots tended to lead the incursion start by about 0.5 seconds. Second, Display Pilots tended to lag the runway turning red by 0.4 seconds. This leaves a ~1.5 sec propagation delay through the system. On average the 1 Hz ADS-B accounts for 0.5 seconds of that delay and the remaining 1 second results from dropped messages due to antenna blockage and improper initialization of the UAT.

For pilots reacting to the runway turning red we measured a $\mu =$ 0.4 seconds, $\sigma = 0.9$ seconds. This measurement is very close to the mean reaction times of a similar measurement from the AILS study in [Abbott02]. In that study pilots responded to a text message on the PFD with a mean reaction time of 0.6 seconds. The standard deviation on the data recorded here makes any proper conclusion regarding these findings impossible. However it is interesting that these two values are so close. This order of magnitude of response time is probably what one can expect of a flying pilot for the response to an abrupt or discontinuous signal like a red runway or a text message. Both this study and the AILS have shown as much. As stated in §5.1.3.1, when the cue is continuous the response time is significantly higher because pilots take time to crosscheck redundant sources of information.

From flying the experiment at night and the Pseudo-IFR approaches we found that the display is very useful when conditions make seeing the ground traffic more difficult. Quotes from the pilots in §6.2.4.6 and the data, Figure 6.6, both support this claim. No matter what the conditions are outside, the runway still turns red on the display.

We also found that, for the incursions at Taxiway Bravo, the display pilots saw the incursion before the OTW Pilots. This stands to reason as the van is harder to see for two reasons. While the pilots are meant to scan the entire runway their attention is more focused on the runway threshold and touchdown spot. The incursion occurs about one nautical mile further away than it would if it happened at the threshold. The image of the aircraft is smaller and it is harder to pick up on a hugely foreshortened runway.

6.3.1 Operational Implications

Ultimately, the only relevant question for this experiment is: Does the display show the runway incursion in time? Because of the lag in the response of a large civil air transport aircraft, there is a go-around threshold on an approach. If a go-around is initiated after that threshold, then the pilot cannot help but touch the runway. The purpose of this analysis is to decipher where the go-around threshold is and how often the distribution of pilot reaction time reported in §6.2.4.2 puts the pilot past that threshold.

To determine the location of the go around threshold a two dimensional, piecewise linear analysis of a 747-400 on final approach was conducted.

How long in advance must the pilot initiate the go around so as to just miss the obstacle? That advance, ΔT, is expressed by:

$$\Delta T = t_{obstacle} + t_{arrest} + t_{engines} \quad (6.1)$$

Where:

- $t_{obstacle}$ is the time necessary to travel the vertical height of the obstacle.
- t_{arrest} is the time necessary to arrest the vertical descent
- $t_{engines}$ is the time to spool the engines and rotate to climb attitude.

The following values are assumed:

Quantity	Value
Vapproach (1.3 Vstall)	156 kt
Glideslope	3 deg
Time to spool engines	1-2 sec (747 approaches with 70% power)
Height of Obstacle on Runway	63 ft (height of 747)
Vertical acceleration during go around	1 m/s2
Vo (vertical descent rate at beginning of go around)	-826 ft/min, -4.2m/s
Vf final vertical speed after go-around	1000 ft/min, 5.1 m/s

Table 6.2 – Parameters in the Analysis

The process for the airplane is shown in Figure 6.8. The aircraft is stabilized on a perfect 3° glideslope. The pilot sees the incursion and initiates the go-around at point A by making changes in throttle and attitude. The simplifying assumption is that for the $t_{engines}$ seconds that the engines need to generate full thrust, the aircraft will maintain the approach throttle setting and descent pitch attitude. Then, after $t_{engines}$ the aircraft undergoes step changes to full power and climb attitude. Only now does the aircraft begin to accelerate upward and slow its descent rate. After t_{arrest} seconds the aircraft reaches its minimum altitude at point B, and Vy = 0m/s. This is obviously incorrect but making the simplification will yield a conservative estimate for ΔT.

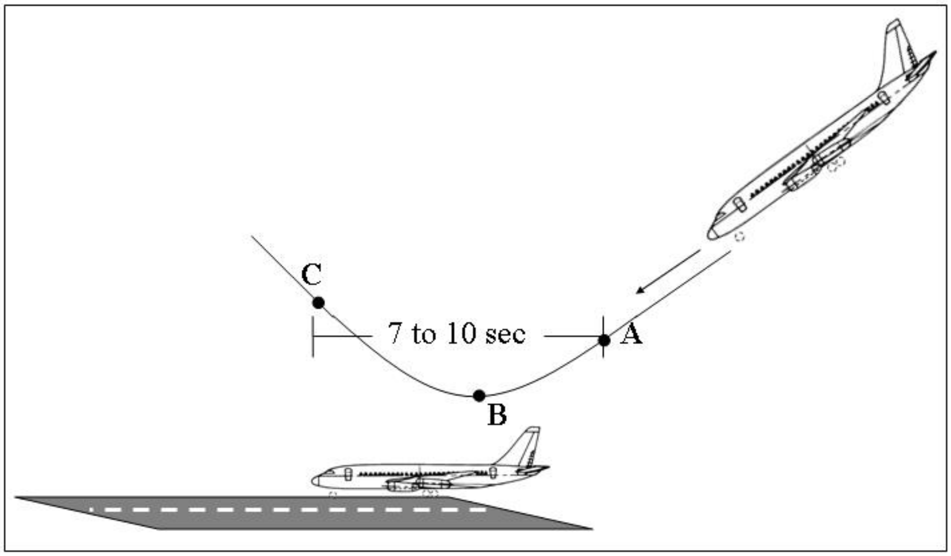

Figure 6.8 – Schematic of Final Approach and Go-Around – Velocity and time constraints yield Ay = 1 m/s^2

The unknown in the analysis is the average vertical acceleration of a 747 during a go-around. To estimate and verify this quantity we used two pieces of empirical data. From the users manual of a 747 simulator will pass through 1000 feet/minute about 7-10s after initiating a go around [Alter02]. Using our assumptions above it is straightforward to estimate the requisite vertical acceleration to achieve this climb rate.

To estimate the vertical acceleration, assume that the aircraft is descending at 156*sin(3) = 8.16kt = 4.2m/s. By

$$V_f = V_o + \frac{1}{2} A_y t^2 \tag{6.2}$$

we can solve for A_y to find that the average vertical acceleration must be approximately 1 m/s^2.

To double check that the estimate is valid we took a page from the 747 Pilot Operating Handbook that states that a 747 initiating a go-around at 100' AGL may lose approximately 40 feet of altitude. If one assumes the downward velocity and vertical acceleration calculated above and an engine delay of 1 to 2 seconds

$$S = V_o t + \frac{1}{2} A_y t^2 \tag{6.3}$$

then Eqn (6.3) reveals that the aircraft will descend 39 to 56ft. This corroborates with the 40 feet set out in the Operating Handbook so $A_y = 1$ m/s^2 is a reasonable assumption for the vertical acceleration of a 747 during a go-around.

Returning to the original task:

Time to clear obstacle: apply Eqn (6.3) with $A_y = 0$ $V_o = 4.2$ m/s gives

$$t_{obstacle} = \sim 3.6 \text{ seconds}$$

Time to arrest descent: apply Eqn (6.2) with V_o= -4.2m/s, V_f = 0m/s and A_y = 1m/s^2 gives

$$t_{arrest} = 4.2 \text{ seconds}$$

By assumption:

$$t_{engines} = 1\text{-}2 \text{ seconds.}$$

Solving Eq 6.1 gives $\Delta T = \sim 10$ seconds.

If the incursion happens at 1 nm (where our data is valid) then the pilot will be at the touchdown point in approximately 20 seconds. From Eqn (6.1), the pilot needs 10 of those seconds to spool the engines, arrest the descent, and clear the obstacle.

The pilot then has 10 seconds of margin to see the incursion. From Figure 6.5, using the display costs the pilot 2.4 seconds leaving 7.6 seconds of margin. The pilot therefore has plenty of time to see the incursion. If we assume that the reaction time distribution with $\mu = 2.4$ seconds is Gaussian then we calculate a standard deviation of 1.54 sec. Hence, a reaction time of 7.6 seconds corresponds to a 4.9 sigma event with a probability of 4e-7. That means that given the distribution in our data our pilot will see the incursion too late and crash into the obstacle on the runway less than one time of every 2.5 million dangerous incursions. This result is so far into the tails of the distribution that this obviously stretches the integrity of the assumption that the reaction time distribution is Gaussian.

To obtain a more conservative and realistic estimate of the effect of the runway incursion display we can model the reaction time data with a different distribution. Models of transoceanic aircraft spacing employ the double exponential distribution [Kelly94] given by Eqn (6.4) and shown in red in Figure 6.9 below. For comparison Figure 6.9 also shows an over plotted Gaussian distribution. From the plot is clear that the double exponential weights the tails more heavily and hence is a more appropriate model to use as a basis for making conservative estimates.

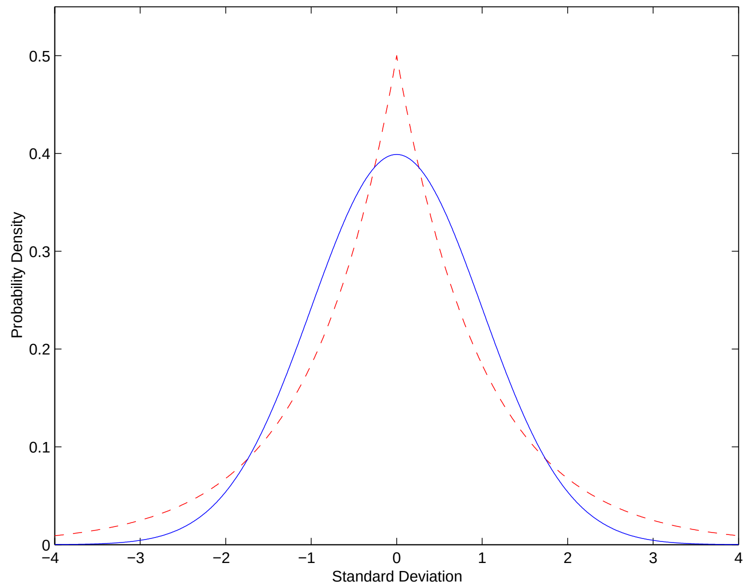

Figure 6.9 – Gaussian (solid blue) compared with Double Exponential (dashed red)

$$DE(x) = \frac{e^{(-\frac{|x-\mu|}{\beta})}}{2\beta} \tag{6.4}$$

It is possible to scale the first moment of a Gaussian distribution to the first moment of a double exponential by Eqn (6.5) [NIST STATS].

$$\beta = \frac{\sigma}{\sqrt{2}} \tag{6.5}$$

From the flight test the standard deviation of reaction times was measured at 1.54 seconds. Eqn (6.5) then yields Beta = 1.04s. It was previously found that the go-around threshold occurs at a reaction time of 7.5 seconds. The probability density function of the double exponential reveals that the probability of a pilot's reaction time exceeding the go-around threshold is 5e-4. On average there is a single Category A incursion and five Category B incursions every month. That totals roughly 72 dangerous incursions each year. Given the probability of undetected incursions found from the double exponential that results in one dangerous and undetected incursion every 27 years.

It is difficult to make a specific statement about safety statistics three decades hence. Given that the reaction times to the display were insensitive to visibility conditions and that the probability of a missed incursion is upper bounded by $5x10^{-4}$, it is possible to state that the probability of a missed incursion in all visibility conditions with the RIM is no greater than $5x10^{-4}$ per dangerous incursion. By the definition of Category A & B incursions, the probability of a missed Category A or B incursion is unity at the current time.

While it is impossible to specify a particular likelihood, it is reasonable to put bounds on the probability using the approach above. The right answer to this question almost certainly lies somewhere between the Gaussian and the Double Exponential. So at worst we'll achieve the behavior modeled by the Double Exponential distribution which, for all intents and purposes, would eliminate runway incursions as a safety threat in the National Airspace.

To realize the full benefit of the RIM it is necessary to have a surveillance method that will detect every vehicle with any possibility of causing an incursion. This would have to include all airport vehicles from aircraft to baggage carts. As it is unlikely that every vehicle will be equipped with its own ADS-B datalink [Jones01] has begun developing a ground surveillance system that fuses data from ADS-B, induction sensors in the concrete, and ASDE Radar to generate a complete picture of the traffic on the ground. The combination of this surveillance network and the Runway Incursion Monitor represent a significant improvement in safety.

6.4 Relationship/synergy with other research.

This runway incursion alerting symbology fits seamlessly with almost any SV PFD concept because it changes the color of elements that are already depicted in every SV PFD. In particular this alerting symbology is meant to fit within the synthetic vision display presented in the other chapters of this thesis. It is intended that the pilots get the runway incursion protection as a substantial safety bonus as they use the elements designed for closely spaced parallel approaches.

During CSPA operations it is necessary to convey information regarding the aircraft that pose traffic threats as well as the information necessary to aviate and navigate the ownship. The two largest sources of traffic threats during CSPA are the aircraft on the parallel approach and those aircraft on the ground. These two separate research efforts combine to provide pilots with a prototype display system designed to fully protect an approaching pilot who has airborne traffic abeam and/or traffic on the runway ahead.

Chapter 7
Implications for the National Airspace

This chapter integrates the flight test and human in the loop simulation results from Chapter 5 and incorporates them into a Monte Carlo analysis of blunders on Closely Spaced Parallel Approach. The goal is to ascertain the minimum safe runway separation (MSRS) for IMC operations given the characteristics of the display system.

Achieving the theoretical MSRS in practice assumes productization of the prototype presented in Chapters 3 and 4 as well as wide spread acceptance and use of that product. Changes of this magnitude in Civil Air Transport cockpits occur over tens of years and involve the participation of both government and industry. The development and testing of this prototype completes the proof of concept and the technological innovation to implement the system. The tasks of engineering a mature product and implementing it in the National Airspace (NAS) is likely to be the larger challenge.

7.1 Chief Results of the Simulation and Flight Testing

As reported in Chapter 5, several features and behaviors of pilots when using the displays were characterized. Most notably, during simulations of blunders on closely spaced parallel approaches the reaction time to a blunder was 4.4 seconds for pilots using the preferred Map display. In the flight tests we discovered that pilots could maintain a commanded longitudinal spacing to a mean error of 425 feet with a standard deviation of 300 feet. This results in a 95% confidence interval on the longitudinal spacing error achievable with the displays of 1020 feet.

7.2 Monte Carlo

7.2.1 Description

Monte Carlo Simulations get their name because they employ a gamblers faith in randomness to account for unexpected scenarios. A set of random and deterministic inputs are injected into a deterministic simulation and the results are recorded. Then a new set of inputs is chosen and the simulation is repeated. In this case the simulation is of a Closely Spaced Parallel Approach. Both aircraft are modeled as point masses. Heading changes are generated from roll angles which are in turn derived from the linearized roll dynamics of an early model Boeing 747. This CSPA simulation and the Monte Carlo wrapped around it were first developed by Houck [Houck01][Houck01a] and later adapted for this research. This technique has also been employed by the FAA in their analyses of runway separation requirements.

7.2.1.1 Inputs

The inputs to the simulation are listed in Table 7.1. For a complete explanation of the rationale of the choices for these variables see Chapter 7 in [Houck01a]. As new data has become available, three of the inputs, Flight Technical Error (FTE) of each aircraft, Longitudinal Spacing, and Pilot Reaction Time, have been adjusted. The rationale for those changes can be found in §7.2.2. In addition, an ADS-B delay model has been added.

Random Variables	Value	Type of Distribution
Flight Technical Error	200 feet maximum	Gaussian
Longitudinal Spacing	1000 feet maximum	Uniform
Pilot Reaction Time	0.4 - 4.4 seconds	Uniform
Relative Airspeed	+- 20kts	Uniform
Deterministic Variables		
Blunderer Airspeed	140 kts	
Maximum roll angle	30 deg (each aircraft)	
Maximum roll rate	10 deg/sec (each aircraft)	
Maximum Heading Change	30 deg (blunderer) 45 deg (evader)	
Actuator and antenna delay time	1.0 sec	
ADS-B Delay	See §7.2.2.4	

Table 7.1 – Random and Deterministic Inputs to the Monte Carlo Simulation

7.2.1.2 Outputs

The output of the Monte Carlo is the set of results from the CSPA simulations. The significant metric of each simulation is the minimum distance between the two aircraft during the approach, blunder, and subsequent evasion. If this minimum separation is less than the wingspan of a Boeing 747 then that CSPA is assumed to have resulted in a collision. If the distance of closest approach is greater than that for a collision but less than the wingspan of a 747 plus a 500 foot buffer zone then that CSPA is termed a near miss. The union of these two conditions is termed a Loss of Separation. It is interesting to note that two 747's will generate a Loss of Separation if each aircraft is aligned perfectly with their approach path and they have zero longitudinal spacing.

In every run of the simulation one of the aircraft deviates from its approach path. The dynamics of this deviation result in a rather dramatic blunder or a "Bad Blunder." Bad Blunders differ from more benign blunders in that they employ a greater roll angle and overall heading change. As a result, the outputs of this Monte

Carlo are the Probability of a Loss of Separation per Bad Blunder. There remain some steps of conversion to translate this into Probability of a Loss of Separation per approach. This conversion is achieved by means of the Safety Equation derived in §7.2.3.

7.2.2 Justification of Changed Parameters

7.2.2.1 FTE

During synthetic vision flight testing in a Boeing 757 at Eagle Creek, CO Rockwell Collins reported that pilots could fly within the confines of the 300ft wide and 300 ft tall tunnel [Langley Flight Test]. Based on those results a 1σ FTE of 200ft was chosen for the Monte Carlo analysis. 1 σ of 200ft yields a 95% confidence interval on FTE of 392ft, which is obviously conservative when compared with the Rockwell Collins data.

7.2.2.2 Longitudinal Spacing

In the flight tests we discovered that pilots could maintain a commanded longitudinal spacing to a mean error of 425 ft. with a standard deviation of 300 ft. This results in a 95% confidence interval on the longitudinal spacing achievable with the displays of 1020 feet. Using this flight test data estimates on the longitudinal spacing were included in the Monte Carlo analysis. Aircraft were restricted to 1000 foot long windows, -500 to 500 feet, 0 to 1000 feet, etc.

7.2.2.3 Pilot Reaction Time

From the human in the loop simulation study (Chapter 5) pilots preferred to use the Map Display and with this display reacted to simulated blunders in 2.3 seconds (mean) and within 4.4 sec 95% of the time for the map display. For this simulation it was assumed that 4.4 seconds is the maximum pilot reaction time.

7.2.2.4 ADS-B Datalink Model

To model the delay due to ADS-B a probability distribution function was derived to exactly match the ADS-B requirements [ADSB MASPS]. Reprint from Table 5.1.

Runway Spacing	Continuity Requirement	Maximum Update Period
1000 feet	95%	T < 1.5
	99%	T < 3
2500 feet	95%	T < 3
	99%	T < 7

Table 7.2 – ADS-B MASPS Requirements for Parallel Approaches

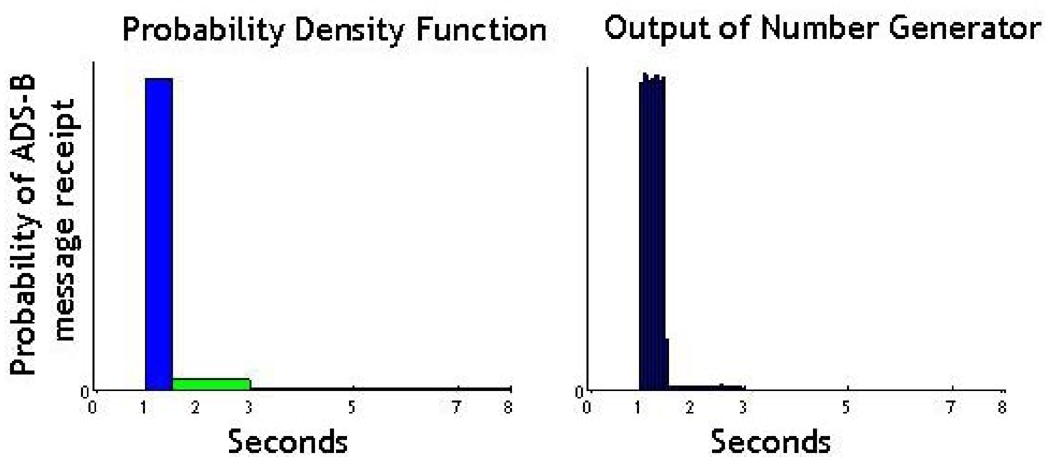

Figure 7.1 – Delay model based on ADS-B latency requirements

Assuming the tighter technical constraint of 1000 foot runway spacing yields a probability density function comprised of three uniform distributions, shown on the left in Figure 7.1. Then as the Monte Carlo runs an ADS-B delay is chosen such that the complete set of ADS-B delays over the course of the entire Monte Carlo matches the PDF. The right panel of Figure 7.1 shows a histogram from the ADS-B random number generator. It is easy to see that the shape of the left figure follows directly from the right.

A real world upper limit on delay must be chosen for this simulation. For example, a delay of 600 seconds (10 minutes) while statistically possible given the probability density function above is totally irrelevant to a simulation involving aircraft approaching parallel runways. As such upper limits were chosen based on the assumed closing speed of a blundering aircraft. In their parallel approach studies the FAA assumed an average lateral closing speed of a blunder of 125 ft/sec [FAA99]. At that speed an aircraft can cross the 1000 foot distance between runways in 8 seconds and a 2500 foot distance in 20 seconds. Therefore, 8 seconds is the maximum datalink delay time for the 1000 foot runway separation and 20 seconds is the maximum delay for the 2500 foot runway separation.

An additional and unvarying delay of 1 seconds was also included to account for the propagation and processing time of signals as they were transmitted along wires inside the aircraft from the antennas to the computers and then from the computers to the actuators.

7.2.3 Formal Derivation of Safety Equation

It is the goal of this analysis to ascertain how close Closely Spaced Parallel Approaches can be placed and still remain safe. The FAA has established safety criteria that define the likelihood of dangerous situations. As some situations are more dire than others the following definitions and their probability of occurrence have been established [NASModern02]:

- Hazardous Occurrences (Probability: Extremely Remote) – Results in serious or fatal injury to a small number of persons (other than the flight crew)
- Catastrophic Occurrence (Probability: Extremely Improbable) – Results in multiple fatalities.

The probabilities are defined as follows:

- Extremely Remote. Qualitative: Not anticipated to occur to each item during its total life. May occur a few times in the life of an entire system or fleet. Quantitative: Probability of occurrence per operation is less than 1 x 10^{-7} but greater than 1 x 10^{-9}.
- Extremely Improbable. Qualitative: So unlikely that it is not anticipated to occur during the entire operational life of an entire system or fleet. Quantitative: Probability of occurrence per operation is less than 1 x 10^{-9}.

These are the safety criteria for designers of systems to be implemented in the NAS; hazardous situations must be extremely remote and catastrophic situations are extremely improbable. For en route flight an operation is defined as one hour. For Category I landing an operation is the last 150 seconds of the approach. In this analysis an operation is defined as one approach. Furthermore, a hazardous situation is one where a blunder occurs and any part of the blundering aircraft comes within 500 feet of any part of the evading aircraft. A catastrophic situation results when aircraft centers of mass pass within a wingspan of each other, this situation almost assuredly indicates a collision. The output of the Monte Carlo must be translated to the 'units' of Probability of a Loss of Separation (P(LOS)) per CSPA in order to have a meaningful comparison with the accepted safety criteria described above. The relation of these probabilities is described in the Safety Equation, whose derivation follows.

Bayes' Theorem of conditional probability states that:

$$P(B \text{ and } A) \equiv P(B \mid A)P(A) \qquad (7.1)$$

If B $\subset$ A as shown by the Venn diagram in Figure 7.2 then the intersection of B and A is wholly contained in A and,

$$P(B) = P(B \text{ and } A) \qquad (7.2)$$

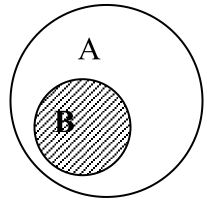

Figure 7.2 – Venn Diagram for Safety Equation Derivation

Bayes theorem can now be rewritten assuming that B ⊂ A.

$$P(B) = P(B \mid A)P(A) \tag{7.3}$$

Substituting terminology specific to this analysis into (7.3) yields

$$P(\text{Loss of Separation}) = P(\text{Loss of Separation} \mid \text{Bad Blunder})P(\text{Bad Blunder}) \tag{7.4}$$

$$P(\text{Bad Blunder}) = P(\text{Bad Blunder} \mid \text{Blunder})P(\text{Blunder}) \tag{7.5}$$

$$P(\text{Blunder}) = P(\text{Blunder} \mid \text{CSPA})P(\text{CSPA}) \tag{7.6}$$

These relationships assume that:

- Losses of Separation only happen during Bad Blunders (LOS ⊂ Bad Blunders)
- Bad Blunders only happen during Blunders
- Blunders only happen during CSPA Operations

Combining (7.4), (7.5), & (7.6) yields the final form of the Safety Equation

$$\begin{aligned} P(\text{Loss of Separation} \mid \text{CSPA}) = {} & P(\text{Loss of Separation} \mid \text{Bad Blunder})* \\ & P(\text{Bad Blunder} \mid \text{Blunder})* \\ & P(\text{Blunder} \mid \text{CSPA})P(\text{CSPA}) \end{aligned} \tag{7.7}$$

- *P*(Loss of Separation | Bad Blunder) is the result of the Monte Carlo Analysis.

- *P*(Bad Blunder | Blunder), in the FAA's analysis of precision runway monitor operations it assumed that out of 100 blunders occurring during a PRM approach 99 of them were "recoverable" meaning that the blunders were gentle enough that the pilot of the evading or blundering aircraft were able to detect and reverse the situation. Thus the Bad Blunder rate is stipulated at 1 Bad Blunder per 100 Blunders [Houck01][PRM91].
- *P*(Blunder | CSPA) is stipulated at 1 Blunder per 2000 Closely Spaced Parallel Approaches. [Houck01][Lankford00]
- *P*(CSPA) = 1. Every case run in this analysis was a CSPA Operation.

Eq. (7.7) also set the requirement for the number of Monte Carlo runs per condition. If the minimum possible result from the Monte Carlo is 10^{-4}, then the minimum result from (7.7) is $10^{-4} * 1/100 * 1/2000 = 5x10^{-10}$. This minimum is small enough to compare well with the hazardous (10^{-7}) and catastrophic (10^{-9}) safety thresholds. Therefore, 1 Near Miss in 10,000 runs per condition is adequate to get the required minimum probabilities from (7.7).

The Safety Equation expressed in (7.7) allows the Monte Carlo results to be translated into a Probability of a Loss of Separation that is numerically valid at the required thresholds.

7.3 Effects on National Airspace and Airport Infrastructure

The strategy for the data reduction is to determine what runway spacing produces a probability of a Loss of Separation equal to 10^{-7}/approach for a maximum reaction time of 4.4 seconds and operationally realistic longitudinal spacings. By the flight test results longitudinal spacing input is limited to 1000 foot windows, -500 to 500, 0 to 1000, 1000 to 2000 up through 5000 to 6000 where positive values indicate that the evader is behind the blunderer.

7.3.1 Results for Runway Spacing

Figure 7.3 shows the Probability of a Loss of Separation versus runway spacing and longitudinal separation. Each curve on the chart represents a different longitudinal spacing window. The intersection of the safety threshold and a given curve reveals the minimum safe runway separation. The red trace for longitudinal spacings of -500 feet to 500 feet behind the evader shows a MSRS of 1883 feet. Looking at the green curve for the evader 1000 to 2000 behind shows a minimum safe runway spacing of 1184 feet.

Space between the colored traces crossing the black safety threshold shows how many feet can be saved between the runways for each additional 500 feet of longitudinal spacing. Notice that the 500 feet between 500-1500 and 1000-2000 corresponds to a drop of approximately 500 feet of runway spacing. The question then became how much does the next 500 feet reduce the MSRS. Running the Monte Carlo at spacings greater than 2000 all the way up to a maximum of 6000 feet revealed no hazardous situations. Which means that the P(LOS) is below the minimum detectable probability of 5×10^{-10} (see §7.2.3) The sensitivity of runway spacing to longitudinal spacing greater than 2000 feet was surprisingly strong. The results were surprising enough to warrant a deeper Monte Carlo analysis at those large longitudinal spacings but this time with 100,000 approaches rather than 10,000 in the CSPA simulation. This reduced the minimum detectable probability by an order of magnitude. The result remained the same: for longitudinal spacings greater that 2000 feet there were no recorded Loss of Separation incidents. The result is logical. If an aircraft is sufficiently far behind a blunderer, it is impossible to have a collision. There is, however, a limit do to the wake vortex of the neighboring traffic. This wake limit will be discussed in detail later in this section.

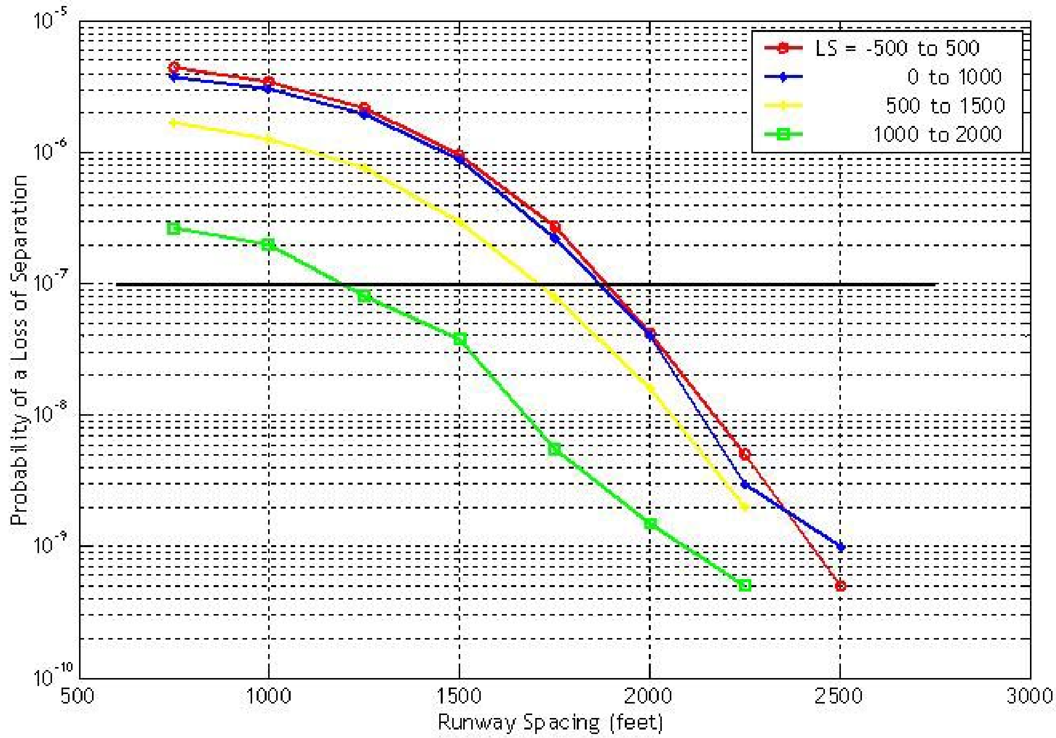

Figure 7.3 – Probability of a Loss of Separation vs. Runway Spacing and Longitudinal Separation

Each curve on Figure 7.4 represents a window of reaction time rather than a window of longitudinal spacing. Reaction times range from 0.4-1.4 seconds to 0.4 to 6.4 seconds. The windows are shaped like this because of the results of the human-in-the-loop simulations described in Chapter 5. Almost all distributions, no matter what the mean or the maximum extent included some very low reaction times to blunders so we have approximated those distributions with the limits shown here.

The trends of the data shown are intuitive. Lower reaction times yield lower runway spacings for a given P(LOS). What is interesting is that the spacing of the safety threshold crossings is about even. Thus lowering the maximum reaction time from 5 to 4 seconds will have the same magnitude effect on MSRS as a reaction time reduction from 4 to 3 seconds. Hence it is good to design displays for low reaction times but MSRS doesn't have the same sensitivity to this variable as it does to longitudinal spacing.

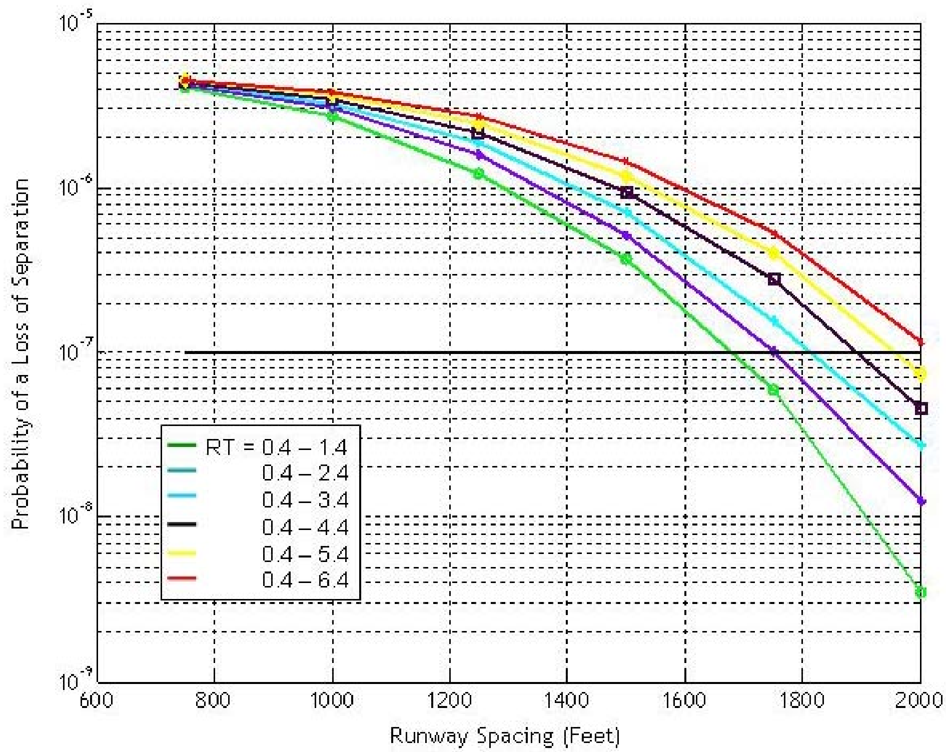

Figure 7.4 – Probability of a Loss of Separation versus Runway Spacing and Reaction Time to a Blunder

To better visualize this difference the sensitivity of minimum safe runway spacing (MSRS) to longitudinal spacing (reaction time = 0.4 to 4.4s) and reaction time (longitudinal spacing -500 to 500 feet) are shown in Figure 7.5. It is readily evident that the slopes of these two curves are radically different. The precipitous fall in MSRS can easily be seen with respect to longitudinal spacing. After 1500 feet the reduction in MSRS for every 500 feet of longitudinal spacing is very evident. Since no Loss of Separation instance were recorded at longitudinal spacings greater than 2000 feet, the MSRS value is clamped at the minimum runway spacing for Visual

Flight Rules (VFR). In contrast to the high sensitivity of MSRS to longitudinal spacing the relationship of MSRS to reaction time is relatively linear and a shallow slope at that.

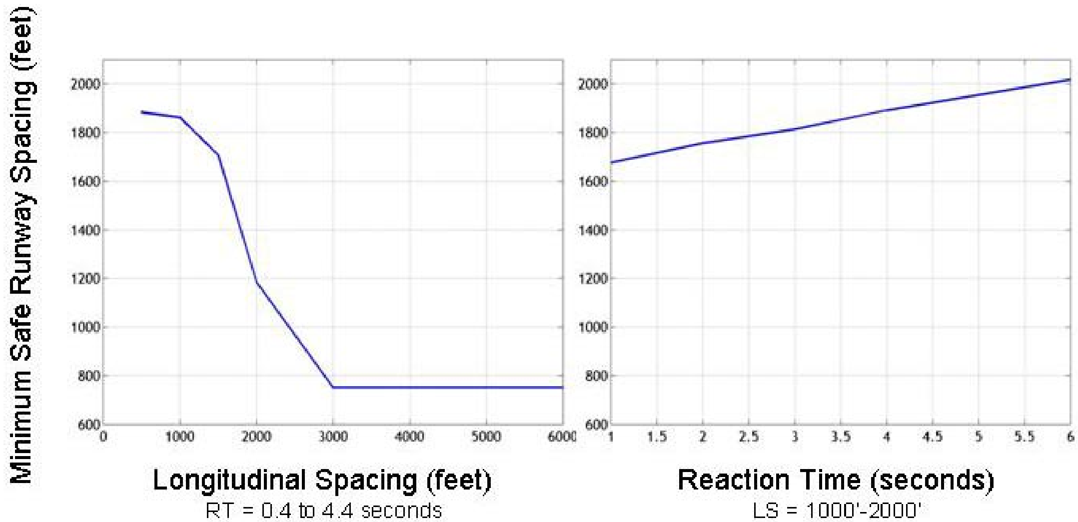

Figure 7.5 – Sensitivity Curves for Minimum Safe Runway Spacing versus Longitudinal Spacing and Reaction Time

A natural argument is to say, "If greater longitudinal spacing affords greater safety, then stipulate that aircraft maintain five thousand or ten thousand or fifteen thousand feet." While the foregoing analysis pushes to larger longitudinal spacings two other factors push the optimal answer down. Utilizing longitudinal spacings of ten thousand feet or more adversely affects the capacity of an airport. At these ranges this is almost equivalent to single runway operations. Secondly, the wake vortex of the parallel aircraft also constrains the size of safe longitudinal spacing. Just like the wake of one boat disrupting the smooth ride of another, the wake of one aircraft can not only cause a disruption to the smooth ride of another, but it can cause a catastrophic loss of control.[2]

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[2] An encounter with the wake vortex of a 747 after take off is a suspected contributing factor for the 12 November, 2001 crash of an Airbus A300 in Belle Harbor, Queens, New York. The accident claimed all 260 souls on the aircraft and 5 on the ground.

Figure 7.6 (not to scale) shows the worst case configuration of aircraft and wind direction for CSPA operations. The lead aircraft is upwind and hence the trail aircraft is confined to stay behind the danger zones by staying more than 2000 feet behind the lead aircraft, LS_{min}, and to stay ahead of the wake of the lead aircraft, LS_{max}. V_{xwind} is the crosswind component of the current winds.

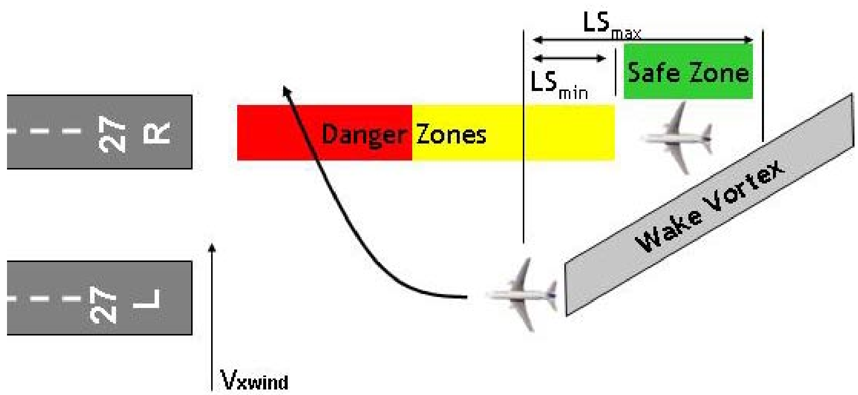

Figure 7.6 – Schematic of the Danger Zones , the Wake Vortex and the Safe Zone during a parallel approach with a worst case crosswind

It is the goal of the following analysis to determine limits on LS_{max} to see if the Safe Zone exists and has sufficient size such to be operationally useful for the worst case crosswind direction. For the case when the crosswind is coming from the side of the trail aircraft the wake vortex from the lead aircraft will blow away from the trail aircraft and then LS_{max} is essentially infinite.

The accepted transport model for a wake vortex is that the wake travels laterally with the local air mass and it tends to sink with respect to the local air mass. [Holforty03] reports that the dangerous portion of the wake is as wide as two wingspans ($2b_{lead}$) and that the wake danger begins when the edge of the wake touches the wings of the trail aircraft. Additionally if both aircraft have erred in their lateral control and are flying at the inner boundary of their approach corridor then the distance that the wake must travel to threaten the trail aircraft is given by:

$$d_{wake} = RunwaySpacing - \frac{b_{trail}}{2} - b_{lead} - 2e_{lateral} \quad (7.8)$$

The maximum value for $e_{lateral}$ without indicating a blunder on the pilot displays is half of the tunnel width, 150 feet.

Using the crosswind speed, V_{xwind}, the final approach speed of the aircraft, $V_{approach}$, and (7.8), LS_{max} can be expressed as:

$$LS_{\max} = d_{wake} \frac{V_{approach}}{V_{xwind}} \quad (7.9)$$

From the flight testing in Chapter 5, pilots of aircraft with similar approach speeds were able to stay within a Safe Zone 1000 feet long over the course of an approach. In the resulting discussion this requisite Safety Zone length has been increased by 500 feet to 1,500 feet to account for the uncertainty and unpredictability in the wake transport model.

The plots in Figure 7.7 show the limits of LS_{max} as functions of runway spacing and crosswind speed. The length of the Safe Zone (shown in green in Figure 7.6) can also be gleaned from these traces. The minimum length for the Safe Zone is shown on each plot (shown in green in Figure 7.7) The left plot assumes that two 737 sized aircraft with 100 foot wingspans are conducting a CSPA. The right plot assumes two 747-400ER's. An example for reading the chart: d_{sz} shows the length of the Safety Zone for the conditions of two 737 sized aircraft on approach and a crosswind of 10 kts. The result shows that the Safety Zone extends between LS_{min} = 2,000 feet and LS_{max} of 7,800 feet if the Runway Separation is 1000 feet. In any instance in the figure where the length of the Safety Zone is less than 1500 feet will be deemed unsafe because of the possibility of encountering the wake of the parallel traffic.

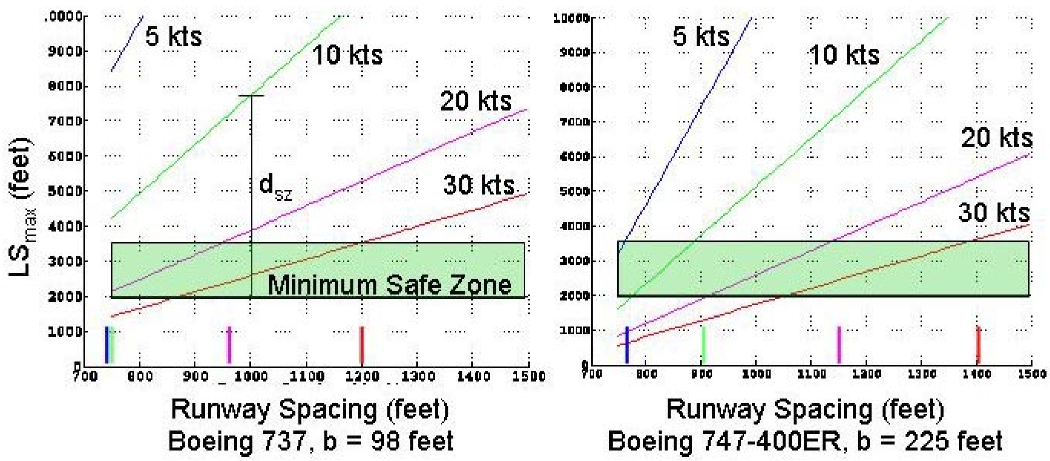

Figure 7.7 – LSmax vs. Runway Spacing and Crosswind Speed

The colored vertical lines along the abscissa show the MSRS for each crosswind speed depicted. The numerical values of these points are contained below in Table 7.3.

Aircraft	Crosswind Speed (kts)	Minimum Safe Runway Separation (feet)
737	5	750
	10	750
	20	975
	30	1200
747	5	800
	10	900
	20	1150
	30	1400

Table 7.3 – Minimum Safe Runway Separation vs. Aircraft and Crosswind Speed

The net result of this analysis is that Minimum Safe Runway Separation for IFR CSPA operations is a strong function of the size of the aircraft, the crosswind direction, and the crosswind speed. Once safety from a blunder by the parallel traffic is assured by maintaining at least 2000 feet of longitudinal spacing between paired aircraft (LS_{min}) then safety from the wake vortex must be assured by maintaining no more than LS_{max} as reported in Figure 7.7 or by assuring that the crosswind blows from the side of the trail aircraft toward the lead aircraft (opposite to that depicted in Figure 7.6). These constraints govern the Minimum Safe Runway Separation that is safely achievable.

In the end these results stipulate that, with the display system presented herein, it is not possible to achieve IFR CSPA at 750 feet for all Civil Air Transport aircraft in all wind conditions. However, the data in Table 7.3 does show that a significant increase in permissible crosswind and aircraft size is achievable if new procedures for longitudinal spacing are put into place and if the runway spacing is increased to 1400 feet.

7.3.2 Runway Spacing as a function of procedures

The results from the previous section have operational implications for pilots and air traffic controllers. The results state that significant reductions in runway spacing can be achieved if new technology and new procedures are adopted. Table 7.4 outlines these adoptions and the corresponding runway separation benefits. Current technology can enable 4300 and 3400 foot spacings. If pilots and controllers adopt GPS surveillance in lieu of radar, GPS navigation in lieu of or in addition to ILS, ADS-B, and new displays to convey the state of both aircraft, then runway separations of 1900 feet is safely achievable. These are significant changes to the operating environment of pilots and controllers and will require many further layers of development and deployment: equipage of aircraft, pilot training, procedure design, and certification. These tasks may stretch the final deployment 5 to 10 years into the future.

If, to the scenario above, positive longitudinal control is achieved and pilots can assuredly be placed and remain within the safe zone depicted in Figure 7.6 then the safe Instrument Flight Rules Closely Spaced Parallel Approach runway spacing can safely decrease to 1400 feet with no new restrictions on the wingspan of the aircraft or the crosswind speed. This tremendous change could obviate the need for many costly expansion projects. That benefit comes with the cost of not only changing the pilots' equipment but also that of the controllers. Controllers would now have the added task of getting paired aircraft delivered to the final approach such that it would be possible for the trail aircraft to say in the safe zone. This capability does not currently exist and would be a lengthy process to develop. Therefore, the benefits afforded by this paradigm shift are both significant and distant. Perhaps it would take 10 to 20 years to develop, implement, test, certify and deploy the instruments and infrastructure necessary to support IFR CSPA with runway spacing at 1400 feet.

If, in addition to ATC providing correct initial longitudinal spacing and pilots maintaining the spacing within the allowable band, the ATC takes on the added burden of always positioning the lead aircraft so that the crosswind will cause the wake to stay away from the trail aircraft, then runway spacing for safe IFR use of CSPA can be 750 feet. The author recognizes that implementing this new capability is an as yet unstudied issue. It is likely to require significant future research and development.

Runway Spacing	Air Traffic Control Procedure	Technology Necessary
4300	Same as today	standard approach radar
3400	Same as today	PRM radar
1900	Same as today	GPS surveillance & Navigation, ADS-B, new Displays
1400 (assumes 747 sized aircraft and 30 kt adverse crosswinds)	new longitudinal spacing paradigm	GPS surveillance & navigation, ADS-B and new Displays
800 (assumes 747 sized aircraft and light winds)	new longitudinal spacing paradigm	GPS surveillance & navigation, ADS-B and new Displays
750 (assumes 737 sized aircraft and adverse crosswinds less than 10 kts)	new longitudinal spacing paradigm	GPS surveillance & navigation, ADS-B and new Displays
750 (no constraints on aircraft size or on crosswind speed)	ATC must position lead aircraft downwind of the following aircraft	GPS surveillance & navigation, ADS-B and new Displays

Table 7.4 – Runway Spacings vs ATC Procedures and New Technologies

7.4 Major airports that will benefit from this technology

Now that it is clear that these changes will take place over years and decades it is interesting to muse over what would have been possible had these options been available to airport designers today. The two most expensive airport expansion projects in the U.S. are those at San Francisco International and Lambert Field in St. Louis. San Francisco International Airport currently has runways that are spaced 750 feet apart. The Airport has proposed and is currently studying several expansion options. All of these options require that the new runways be created on landfill. Figure 7.8 shows (printed with permission of SFO) a map of San Francisco International as it exists today and one of the new runway configuration designs. The dashed line shows an area of landfill. This proposal has generated sharp debates in the Bay Area over the fiscal cost of the runways, estimated between 2 and 10 billion dollars and the environmental costs to the bay.

This is an example of a project that could very well make use of the proposals outlined in the previous section if the technology and procedures could be developed in sufficient time.

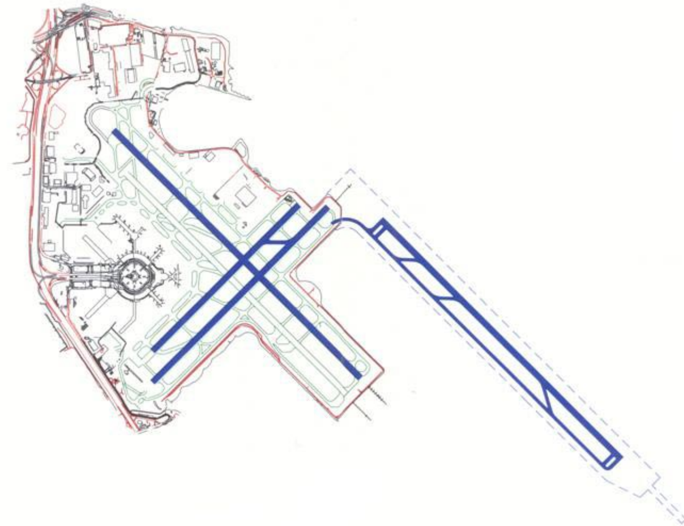

Figure 7.8 – San Francisco International: Dashed = bay fill

A cartoon of Lambert Field in St. Louis is shown in Figure 7.9. Currently there are three east-west parallel runways, the farthest of which are spaced at 1310 feet. The new runway is being constructed to the east of the field will be 4100 feet from the parallel runway. This is the runway that was detailed in Figure 1.1 that requires the acquisition of almost 2,000 parcels of land.

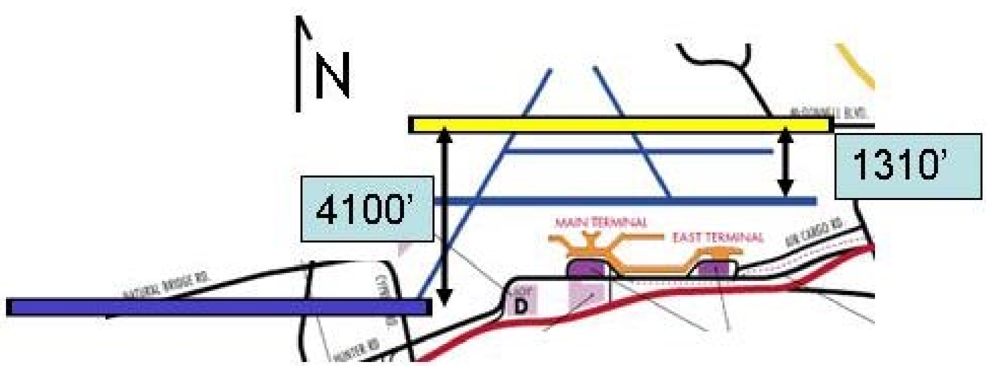

Figure 7.9 – Lambert Field, St. Louis

The system in this thesis might have made it possible to expand the northernmost runway (in yellow at the top of the image) rather than construct an entirely new runway.

Although the Lambert Field project continues, many airport expansion plans are currently (~2003) on hold due to the severe downturn in air travel due to the Attacks of 11 September and the ensuing War on Terror. This downturn is likely to be temporary and the crushing levels of air traffic congestion of the summers of 2000 and 2001 will return. Ironically, this downturn may provide the delay required to develop the technology in time to answer the demand of airports such as San Francisco International. Figure 7.10 categorizes the major domestic airports by their runway separation. Fifteen airports have runways spaced between 700 and 900 feet. Thirty four airports have runways spaced less than 3400 feet and would be served by this system whereas they could not be served by the Precision Runway Monitor System. Some of the airports listed here have already begun expansion plans (SFO) or expansion projects (St. Louis), but there are several that have not. It is the airports that have not begun expansion for which this system may bring better options that were previously impossible.

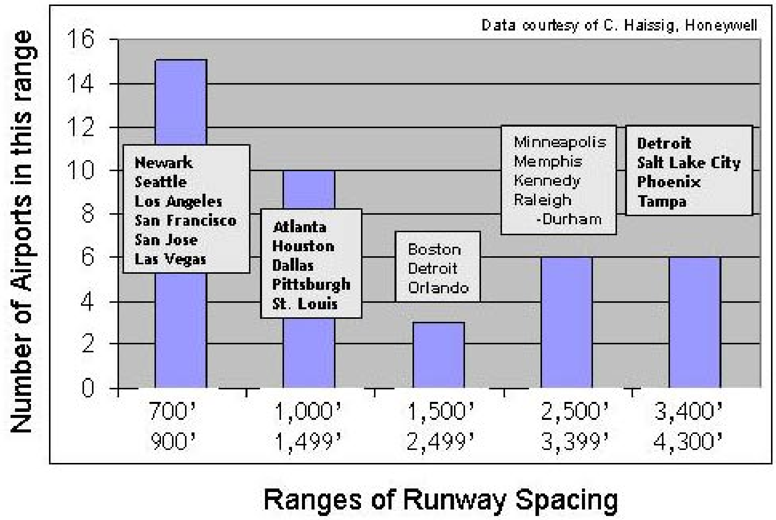

Figure 7.10 – Domestic airports categorized by runway spacing [Haissig98]

Airport planners are responding to expansion pressures that exist today and as such today's solution is to add real estate and build runways with greater spacing. As these expansion projects are multi-year efforts, the systems presented and proposed herein maybe able to provide future airport planners with previously unavailable options. It is also safe to say that these options will have significant savings, in terms of the financial size of expansion projects, the disruption to the communities around the airports, the efficiency of the airport, and the environmental impact of the airport expansion.

Chapter 8
Conclusions

8.1 Summary of Results

This research presents the first ever design, implementation, and characterization of a novel synthetic vision display and supporting flight system. The system uses a 3D graphics display called Synthetic Vision and an air-to-air datalink called Automatic Dependent Surveillance – Broadcast to present the pilot with the information necessary to aviate, navigate and monitor the two sources the potentially threatening traffic, those aircraft on the parallel approach and vehicles on the runway. It was discovered that a standard Synthetic Vision display would be inadequate to show information regarding traffic abeam the ownship. Thus, several concept displays to ameliorate this condition were designed, implemented and tested.

Over the course of several years of demonstrations and iterations three displays are presented; the Map Display, the Orthographic Display, and the Mixed Display. These three display concepts were characterized in Human in the Loop simulations to determine which display concept was most suitable for development for Closely Spaced Parallel Approach (CSPA) operations. Although pilots responded to a simulated blunder 15% faster with the Orthographic Display they unanimously preferred the Map Display format. The Mixed Display holds some interesting promise but more human factors design engineering is necessary to resolve a conflict between the two displays being combined.

This thesis also documents the first series of flight experiments to demonstrate the applicability of synthetic vision displays to both Closely Spaced Parallel Approaches and runway incursion avoidance. The chief result of the CSPA flight demonstration was a proof of concept that pilots could correctly extrapolate the real world position of the other aircraft by interpreting the imagery on the screen. In subjective data, pilots agreed with the statements that "The image on the screen faithfully represented the position and the roll of the traffic." Quantitative data measuring the error in longitudinal spacing revealed that pilots controlled longitudinal position with respect to the parallel traffic to within 1000 feet. The runway incursion flight experiment measured the reaction time of pilots to intentionally generated incursion.

The final stage of the research was to assess the impact of these technologies on the National Airspace; specifically on the projected frequency of runway incursions and on the Minimum Safe Runway Separation for Closely Spaced Parallel Approaches in Instrument Meteorological Conditions.

By extrapolating the reaction time results and conducting a kinematical analysis of an aircraft on approach it has been shown that the occurrence of dangerous runway incursions can virtually be eliminated by deploying a synthetic vision system equipped with a runway incursion alerting symbology and the Runway Incursion Monitor algorithm.

Utilizing the longitudinal spacing error results from the flight testing, and the reaction time characterizations from the human in the loop simulations the effect of deploying this display on minimum safe runway separation is calculated. It has been found that the minimum safe runway separation for IMC operation can safely be reduced to 1900 feet. If, in addition, significant changes are made in Air Traffic Control procedures for longitudinal aircraft spacing, the analysis shows that the display system presented herein will allow for runway separation of 1400 feet with no new restrictions on aircraft size or crosswind. Furthermore, with certain restrictions on aircraft size and crosswind, the runway spacing can be reduced to 750 feet. These results have tremendous implications for pilots, controllers and the public. They will also have large impacts on the financial and environmental costs of airport expansion projects.

8.2 Future Research

This thesis described the technical innovation of a display system to enable a new and important aviation operation. It is a logical extension to divide future work into those two categories: displays and operations.

8.2.1 Display Focused Work

Supervisory Control with Synthetic Vision: A pilot's job is rapidly evolving from one involving regulatory and tracking control to a higher level task of supervisory control. To that end flight displays must serve two functions: First and foremost the displays must satisfy the requirements such that pilots can safely aviate and navigate the aircraft. Second, pilots must be able to monitor the state of the automation AND the state of the aircraft under automatic control. Should pilots need to immediately retake control of the aircraft they should spend no time "reacquiring" the situational awareness necessary to fly the aircraft or aviate. They can take some time to restart the navigation tasks but resumption of aviate tasks must be immediate. Given the greater compatibility of the synthetic vision primary flight displays it is conceivable that these displays would be better suited to supervisory control tasks as defined in [Sanders93] than the displays in modern cockpits today. It would be interesting to know how well pilots could monitor a system using a synthetic vision display in comparison with a standard cockpit display.

Synthetic Vision Compared to NASA's AILS System: As described in Chapter 2 NASA discontinued a line of promising research. The AILS system was designed to give pilots conducting CSPA down to 2500 feet breakout instructions should a blunder from the parallel approach commence. The Stanford University Synthetic Vision Display System and the AILS System have been presented at the same conferences and in the same sessions. Each group extols the virtues of their approach but a direct comparison to determine a 'winner' has not been made. This is an expensive proposal since it would require a high fidelity simulator.

8.2.2 Operations Focused Work

CSPA Operations with Synthetic Vision and Highway in the Sky: A new paradigm of landing aircraft was proposed in Chapter 7. The notion of strictly controlling longitudinal spacing with information from an air-to-air datalink is unheard of in the current Air Traffic Control system. The technology was shown to work in this research but the effort to integrate the procedures into the control tower is untouched. What should the approaches look like? What should the separation of responsibility be between the pilots and the controllers?

Highly Curved Approaches: Currently most transport category aircraft line up for a straight in approach somewhere between 5-15 nm from the threshold. The primary reason for this is so the pilots have ample time to get stabilized on the ILS approach. Technically, getting stabilized means controlling the energy of the vehicle (height and speed), and making sure that the position and velocity states all fall within acceptable parameters ie, position in the approach path and velocity headed toward the runway. With Highway-in-the-Sky it is possible to fly much more complex curved approaches with much shorter final straight sections. This gives some freedom to the design of the approaches for an airport is the approaches are not constrained to be straight for the last x miles. What is currently unknown is: What is the minimum safe straight in final approach length as a function of aircraft type?

Following that can any gains in airport efficiency be generated by utilizing such an approach?

8.2.3 Integrated Display and Operations

4D Control of an Aircraft Using Synthetic Vision: Professor Amy Pritchett at Georgia Tech. has been a longtime proponent of developing cockpit technology in concert with the procedures to ensure the most seamless integration of the two. If, as the results of this thesis suggest, aircraft should be delivered to the final approach fix at precisely hh:mm:ss.ss then pilots might appreciate having an integrated 4D synthetic vision display with which they could control, position, velocity, and time of arrival. To this author's knowledge, while this capability in Synthetic Vision has been discussed it has never been verified in flight.

IFR Scud Running: Scud running is an often used but seldom recommended practice of flying an aircraft and squeezing between an overcast layer and the terrain. In the worst case for an unfortunate pilot the weather is worsening and the terrain is rising and very quickly this pilot can find themselves pulling up into the clouds to avoid a Controlled Flight Into Terrain accident. A very challenging notion is to offer real-time updating Highways in the Sky to pilots caught in this predicament. This project not only involves the artful generation of displays but the development or application of some sort of "look-ahead" path planning algorithm and then the seamless integration of that algorithm into the display.

As with any endeavor in the scientific method a good research project will always uncover more questions and generate more possibilities than it answers questions.

8.3 Epilogue

Aviation has a wide range of enabling technologies at its disposal. GPS, ADS-B and Synthetic Vision have a demonstrable synergy. Despite the potential benefits, aviation is not on the cusp of a breakthrough. As a matter of fact breakthrough and commercial aviation are an oxymoron. Innovation, development and deployment do occur in aviation but each step is slower than the previous. All the same, the creep towards greater capability and more efficient usage of available technology is inexorable. Some day, pilots will fly (or supervise) an aircraft landing in thick clouds on a parallel runway 750 feet from another *active* runway. The slow pressure of the flying public will eventually push today's enabling technologies into widespread use.

When reliable air-to-air datalinks and immediate visualization tools do come into practice, the world will be able to make better use of smaller airports. The need to expand or construct new airports will diminish. Runway incursions, and the resulting death toll, will become a thing of the past. That state of affairs will have tremendous impact on economies, communities and environments the world over.

What is perhaps more important and less obvious is that by the time that these technologies make it into a cockpit they will have been in public use for years. People will have been inventing uses for distributed information coupled with useful displays that are far beyond aviation. That is a powerful vision.

Chapter 9

Appendix A

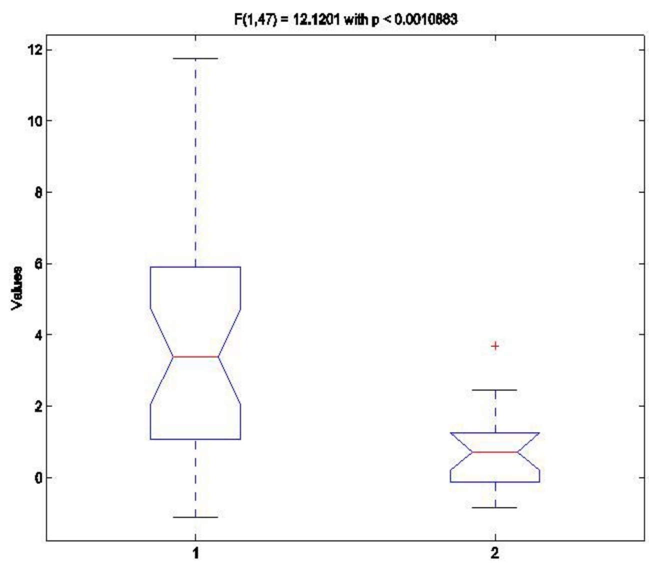

Figure 9.1 – Sample Box Plot

In several places throughout this document statistical data is presented with boxplots and Analysis of Variance (ANOVA) statistics. As not all readers are familiar with these devices this short appendix explains their features.

9.1 Box Plots

The box plots are representations of distributions of data. It is not assumed that these distributions are Gaussian. The red line at the waist of the notch is drawn at the median of the distribution. The upper and lower extents of the box lie at the upper and lower quartiles of the data. The extent of the notch is a MATLAB generated confidence interval on the mean of the distribution. The whiskers show the extent of the data that lies within 1.5*IRQ. IRQ is the inter-quartile distance and is defined by the length of the box. If the distribution is Gaussian then the box lies between +- 0.7 sigma, and the whiskers extend to contain +- 2.6 sigma (99 percent of the data). Any datapoints that are outside the whiskers are considered outliers and are marked with a red '+'.

Features such as the mean and the spread of the data, as well as asymmetry are apparent for a single distribution. These plots are useful to visualize and compare distributions. In it can quickly be surmised that the means of these two distributions are likely to be different by noticing that the vertical extent of the notch from Distribution 1 does not intersect with the vertical extent of the notch from Distribution 2.

9.2 Understanding Analysis of Variance (ANOVA) Results

To quantify the difference between distributions an Analysis of Variance (ANOVA) is conducted. Using as an example, ANOVA results are returned in the following format, The difference between the means of the two distributions is significantly significant with $F(1,47) = 12.12$ and $p < 0.001$.

$F(x,y)$ is the Fisher Ratio and it is the ratio of the inter variable variances with the intra variable measurement variances; likened to electrical engineering terms $F(x,y)$ is analogous to the signal to noise ratio. A Fischer Ratio of 12 signifies that the magnitude of the difference of the means between the two distributions is 12 times larger than the statistical measurement noise within the distributions. x is the number of inter variable degrees of freedom, N-1. In our example we are comparing 2 distributions so x = N-1 =

2-1 = 1 and y is the number intra variable degrees of freedom for all the variables. Y = sum(number of measurements in each variable)-number of variables. p, then, is the probability of the measurement noise generating a ratio of this size. Therefore the chances are 1 in 1000 that we would incorrectly calculate a Fischer Ratio of 12 for these distributions. If $p < 0.05$ then the difference between the means of the distributions is said to be statistically significant.

As the reader evaluates the data presented in these formats one should be asking, "How significant is the difference between the distributions in this plot?" How sure is the author that the difference in the means of these variables is real? The answer comes in the size of F and p. The larger F is and the smaller p is the more surely one can state that the difference between two distributions is a product of some real effect rather than the chance happenings of statistical noise.

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