# FLIGHT DEMONSTRATION OF 3D PERSPECTIVE SYNTHETIC VISION AND ADS-B FOR CLOSELY SPACED PARALLEL APPROACHES

*Chad Jennings, Mohamad Charafeddine, J. David Powell*

*Stanford University - Stanford, California*

*Skander Taamallah, National Aerospace Laboratory, the Netherlands*

## Abstract

Airports lose significant capacity during instrument conditions. Several plans are afoot to expand the nations' airports to achieve sufficient runway spacing for independent IFR approaches. The projected cost of the ten largest projects in the United States is $8 - 16 Billion. The ability to conduct Closely Spaced Parallel Approaches (CSPA) in Instrument Meteorological Conditions (IMC) could reduce the requisite runway separation and significantly lower that national expense. In addition the environmental impact of airport capacity increases would be significantly reduced. This paper presents a synthetic vision display and the supporting flight system to attempt to achieve this goal. The display presents the pilot with the information necessary to aviate, navigate and monitor traffic on the parallel approach. This paper also documents the first series of flight experiments to test the applicability of synthetic vision displays to CSPA Operations (Figure 1).

## Introduction

The airspace in the United States and around the world is primarily constrained by the landing capacity of the largest airports. In a statement to Congress by John Carr, the President of the Air Traffic Controllers Association said, "We need a concrete solution." He estimated that 50 miles of new concrete around the United States would solve the congestion problems evident during the summers of '00 and '01. As Figure 2 shows, other nations have made this same realization and are addressing this constraint with 46 airport and runway expansion projects worldwide. North America alone owns 22 of these 46 projects. The most expensive 10 projects have a total budget of 8-16 Billion.

**Figure 1. Aircraft for Synthetic Vision Closely Spaced Parallel Approach Flight Tests**

Ownship (blue – Cessna Caravan)

Bogey (tan and white – Piper Saratoga)

A significant portion of that price tag is driven by the need to have at least 4300 feet between runway centerlines to do independent approaches in IMC (3400 feet if the airport has a Precision Runway Monitor). In Visual Meteorological Conditions that requirement is 750 feet [5].

Since Closely Spaced Parallel Approach (CSPA) operations can be flown visually; researchers at Stanford have endeavored to create a cockpit instrument that approximates the visual scene. If the visual cues can be presented with the same fidelity on the instrument as they are out the window then perhaps pilots will be able to fly the same operations using that instrument as they can using the out-the-window scene. This paper presents a 3D perspective synthetic vision display and the supporting flight system to attempt to achieve this goal. The display (CSPA Display) presents the pilot with the information necessary to aviate, navigate his/her aircraft while monitoring traffic on the parallel approach by presenting the pilot with real-time traffic position, heading, velocity, and roll angle. The ADS-B datalink used in the flight tests was modified to accommodate the special data requirements of this research.

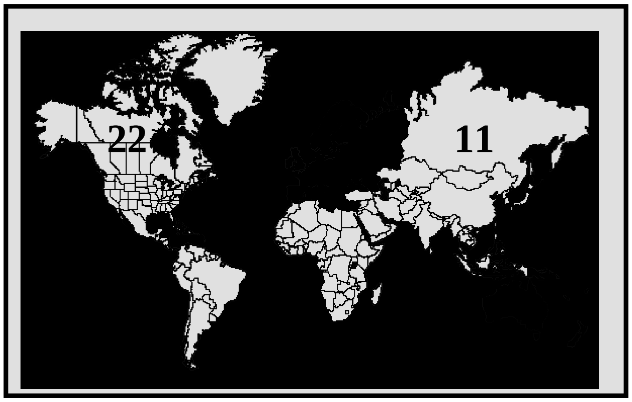

**Figure 2. Airport and runway expansion projects begun or completed between 1997 and 2002**

The flight test points were designed to approximate final approach during CSPA operations. Using a Piper Saratoga as the bogey and a Cessna Caravan as the ownship we flew more than 15 approaches, using three Caravan pilots, into Moffett Federal Airfield (750' runway separation). Caravan pilots were instructed to maintain a specified longitudinal spacing by using only the out-the-window scene or by using only the CSPA Display. Pilot acceptance of the CSPA Display was strong with pilots agreeing that the display increased their awareness of both the position and intent of the traffic. Quantitative results show that there was a measurable reduction in the mean longitudinal error between approaches when pilots used the out-the-window scene and those when pilots used the CSPA Display. In addition, several orchestrated CSPA blunders were flown to anecdotally ascertain how well the display conveyed the severity of the situation.

## Prior Research

The concept of reproducing the out the window scene or a portion thereof on a cockpit display has been researched for more than 50 years. Several groups around the world have built synthetic vision primary flight displays and installed them in research aircraft [1][2][9][12][14]. They have shown that synthetic vision cockpit displays hold enormous benefits for aviation from General Aviation to Civil Air Transport.

In response to the constrained landing capacity around the world NASA and Honeywell have undertaken a project called Airborne Information for Lateral Spacing (AILS). The goal of this effort is to develop a system that will enable CSPA operations at facilities with runways that are more than 2500 feet apart. 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 specific cautions and alerts. Another research project aimed at CSPA is the effort surrounding the Paired Approach Concept put forth in [13] and more deeply studied in [3]. 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 1000ft 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 [7] as part of her dissertation research conducted a series of flight tests wherein she verified that the roll angle of the bogey 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 [8]. Using a Monte Carlo simulation she calculated the probability of collisions and closely spaced runways versus certain parameters including; reaction time to blunders and ability to match the roll angle of the blundering aircraft.

Pritchett [11] conducted a simulation study in which she added symbology to a conventional PFD and navigation display to show the lateral, vertical, and longitudinal spacing of traffic on the parallel approach.

A logical next step is to combine these first two areas of research, and to leverage Houck and Pritchett's work to design and study a synthetic vision cockpit display specifically for CSPA Operations. Researchers at Stanford University replaced the standard PFD with a 3D perspective synthetic vision display and by augmenting or redesigning the navigation display. We have designed, implemented, tested, and flown a synthetic vision display for Closely Spaced Parallel Approaches. To this author's knowledge the flights conducted at Moffett Federal Airfield in Moffett, California in December, 2001 were the first flight testing of synthetic vision displays for CSPA.

## Display Design

### *Necessary Data*

To give a pilot the requisite functionality it is necessary to ascertain which variables are essential to the intended functions. This display will replace the standard PFD so ownship roll, pitch, heading, airspeed, and altitude must be included. In addition, the pathway depicted in the display gives cues sufficient to navigate the aircraft to the runway. The analysis of these variables and their applicability in synthetic vision primary flight displays is well documented in [1][2][14]. The question now remains, what are the essential variables to accurately and quickly convey the state of the traffic information such that the pilot can ascertain whether the traffic poses a threat?

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. [10]. Awareness of traffic during CSPA is a tactical effort and as such all of these data listed above may not be necessary. Pritchett [11] cites relative position (lateral, longitudinal, and vertical) and the nominal flight path as the essential information. To provide the pilot with additional cues to detect a blunder we have chosen to add roll and heading 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 bogey and the approach pathway for the parallel runway one can immediately infer the Total System Error for the parallel traffic.

### *Display Concepts*

Since a cockpit display for CSPA must convey traffic information when the traffic is outside the field of view of the Synthetic Vision Primary Flight Display (SV PFD) another display must be added to give traffic information when that traffic is abaft or abeam the ownship. The information on this second display must be sufficient for a pilot to monitor the state of the traffic for the entire approach, in the likely event that the parallel traffic is never in a location such that it is visible on the SV PFD. Studying what that display should look like is a primary mission of this research. In the

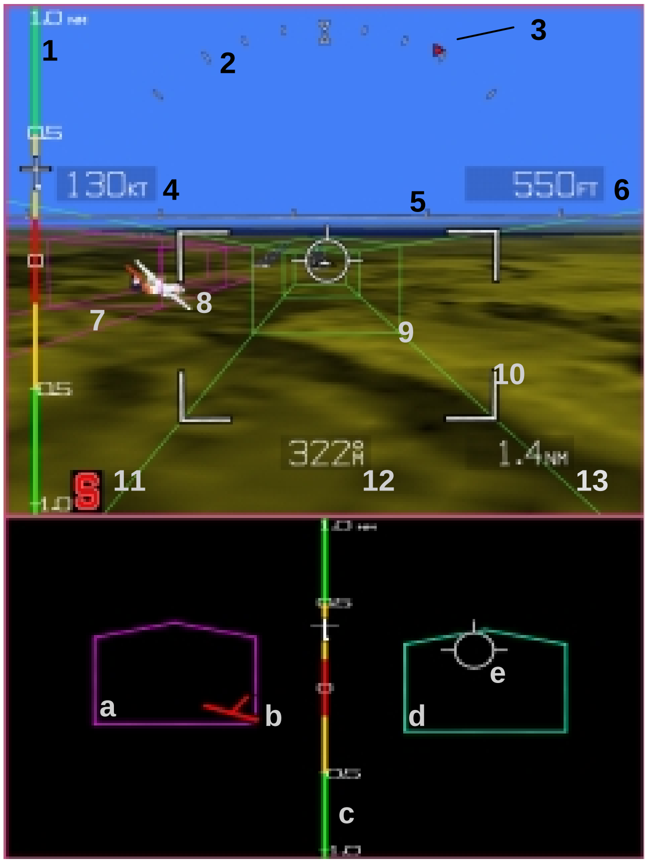

**Figure 3. 3D Perspective Synthetic Vision Display with Orthographic Display Showing a blunder**

course of the project several displays were designed to compliment the SV PFD.

### Primary Flight Display

Figure 3 shows the SV PFD with the Orthographic Display. The elements of the PFD are (from top left):

1. Longitudinal Spacing Indicator (nautical miles)
2. Ownship Bank Index
3. Roll Bug (Indicating bogey roll = 28°)
4. Airspeed (knots) (actually groundspeed in our flight tests)
5. Artificial horizon
6. Altitude above mean sea level (feet)
7. Parallel Approach Path (magenta)
8. Image of bogey aircraft (shown just about to leave the parallel approach path)
9. Ownship Approach Path (green)
10. Corner Tic-Marks and Flight Path Vector [2][6]
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 bogey aircraft, 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 bogey 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 bogey is above or below the horizon. However, because the image of the bogey is drawn in perspective, distance cues (size of objects) are vague. This trait makes it difficult to ascertain if the bogey is just inside or just outside of its pathway. The careful observer of Figure 3 can discern that the bogey is indeed at the edge of the pathway and will soon be deviating further from the magenta pathway.

### Orthographic Display

The lower portion of Figure 3 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 bogey is blundering. Elements of the Orthographic Display (Figure 3, from left to right):

a) Bogey's Current Cross-Section of Parallel Approach Path (magenta)
b) Bogey 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)

Quantities Shown (Figure 4, left to right):

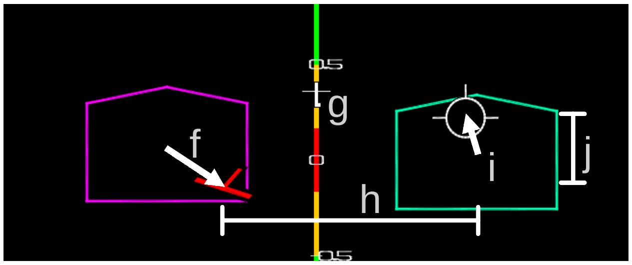

**Figure 4. Detail of Orthographic View**

f) Flight Technical Error (FTE) of the bogey (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.
   Roll of each 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° counter clockwise, defining the lateral direction. Z is up. The display is a pair of projections in the YZ plane, one for the bogey 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?

We chose to implement an Outside-In display referenced to the ownship pathway hoop 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, elements b. and c., respectively) remain precise indications of the lateral and vertical (Figure 4, elements g. and h.) 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.

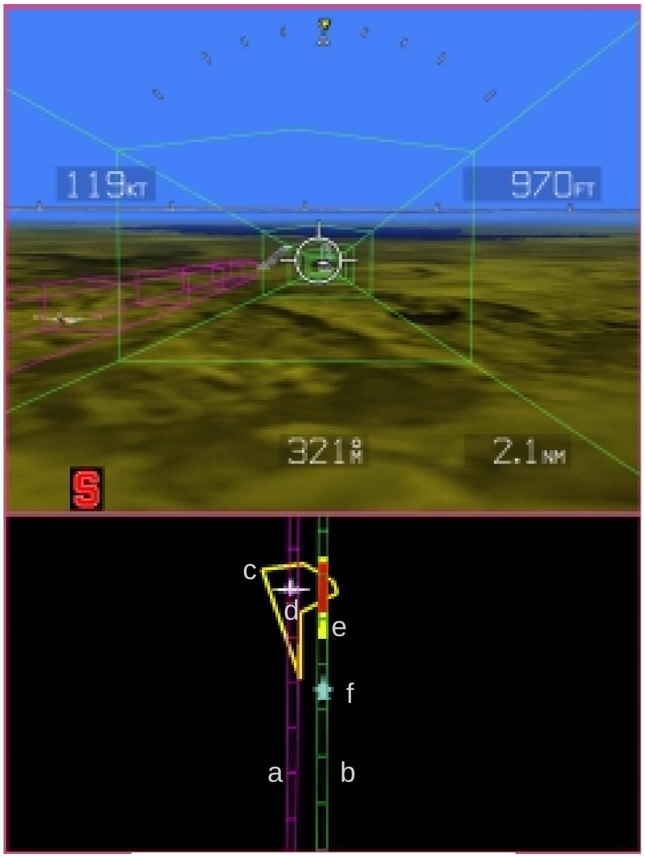

**Figure 5. Map Display**

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 bogey. It is important to note that this trait is what makes this display a pair of projections. In Figures 3 and 4 the left side of the display is the projection for the bogey and its current pathway hoop and the right side is for the ownship.

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

**Map Display**

Figure 5 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
d) Image of Bogey Aircraft
e) Danger Zone Indicator
f) Image of Ownship

Quantities shown:

- Current TSE 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 bogey 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 Dash 8 is the bogey aircraft and the blue outline of an F-23 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 bogey aircraft 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 (bogey is drawn in white and the ownship in light blue) [10]. 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.

### Map/Ortho Mixed Display

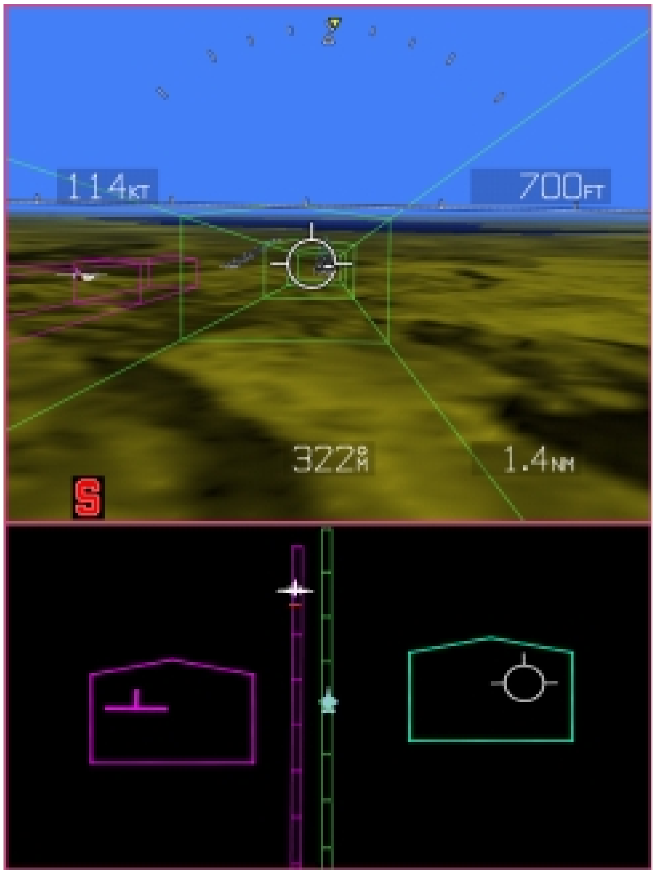

**Figure 6. Mixed Display**

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 section). The Mixed Display (Figure 6) is a first cut attempt to combine the traits of the Orthographic and Map Displays.

### 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 bogey 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. The study to determine which display is preferred by pilots and which yields the best performance in terms of reaction time to a blunder and workload is currently underway at Stanford.

## *Particular Symbology*

### Longitudinal Spacing Indicator

The Longitudinal Spacing Indicator (Figure 3, element 1 and element C) shows the distance in nautical miles to the traffic along the final approach heading. Traffic ahead of the ownship is shown on the upper half of the colored bar, and traffic behind is shown on the lower half. The color coding is as follows: Red ± 0.2 nm; Yellow ± 0.5 nm; Green ± 1 nm. If the aircraft is more than ± 1 nm from the ownship the indicator is shown in blue and it latches to the top or bottom of the color bar. This indicator can be placed in the center of the Orthographic Display or along either side of the PFD. Figure 3 shows the bogey 0.4 nm ahead of the ownship.

### Roll Bug

The Roll Bug (Figure 3, element 3) shows the roll of the bogey aircraft 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 bogey. Moreover, if the bogey is on the left side then any time the roll bug is right of your own roll indicator then the bogey is rolled toward you. The roll bug turns red when the roll angle of the bogey aircraft exceeds 20 deg. Figure 3 shows that the bogey is rolled + 28 deg.

Houck [7] showed that by matching the roll angle of the blundering aircraft, evading aircraft could greatly increase the miss distance. This symbol was designed partly to allow pilots to monitor if their roll matches that of the bogey.

### Danger Zone Indicator

The yellow contour in Figure 5 shows the Danger Zone. [15]. Assuming air transport aircraft dynamics, if you are outside the Danger Zone and the bogey 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 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 3 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: pay close attention to the actions of the bogey. 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: pay very close attention to the actions of the bogey.

## Flight System

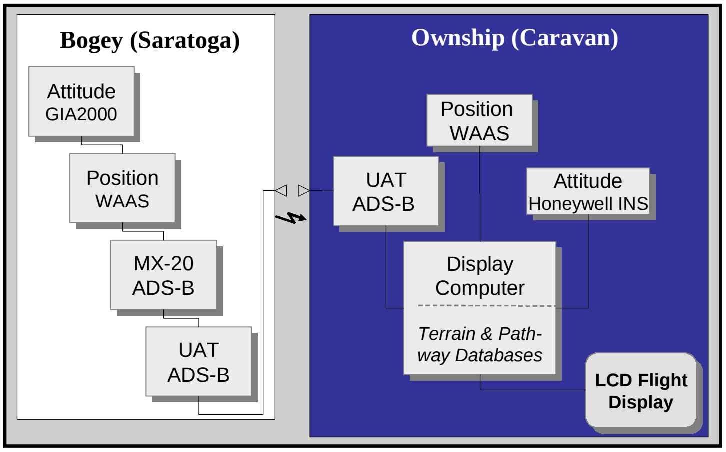

**Figure 7. Flight System Block Diagram**

### *Aircraft*

To conduct our flight trials a multi-vehicle synthetic vision system was installed in a Cessna Caravan (blue aircraft in Figure 1) and a Piper Saratoga. The Caravan served as the ownship and the Saratoga as the bogey aircraft.

### *Block Diagram*

Shown in Figure 7, the flight system is a centralized architecture using RS-232 serial communications. Equipment installed in the ownship is shown in the blue rectangle and equipment installed in the bogey is shown in the white rectangle. The information flow in the block diagram is from left to right. All sensor information flows to the display computer. A modified ADS-B data link from UPS Aviation Technologies was used to transmit data from the bogey to the ownship.

The bogey system was designed solely to determine aircraft state parameters (position, velocity, heading, roll, wind, wind speed) and feed them to the ADS-B datalink. In turn that information was routed to the display computer. Although the ADS-B hardware and software procured from United Parcel Service - Aviation Technologies (UPS-AT) operates as a bi-directional data link we only used it as a one way conduit. The input interface device to the data link is a software application called the MX-20. The MX-20 accepts data from the Stanford University WAAS computer and sends that data to the Universal Access Transceiver (UAT). The UAT in the ownship receives that data and packs it serially to the display computer.

### *Sensors & Computers*

The critical variables to be sensed are position and attitude for both vehicles. The position of both vehicles is given by differential GPS, specifically the Wide Area Augmentation System [4]. Both vehicles used Novatel Millennium OEM3 Receivers in concert with Stanford University WAAS Algorithms for position and velocity. We installed a GIA-2000 from Sequoia Instruments Inc. to sense roll and roll rate of the bogey. In the ownship we used a commercial grade IMU from Honeywell to sense roll, pitch and heading.

The display computer is a ruggedized rack mounted 850 MHz Pentium III with an nVidia Gforce3 graphics card. The C code to render the views uses the standard Open GL libraries as well as Open GVS from Quantum3D. The computer then fuses the state information of both vehicles with the terrain and pathway databases and renders both the 3D out-the-window view and the lower view (Orthographic, Map, Mixed Display). The display computer also records the GPS time tagged state data from both vehicles for post processing. The refresh rate of the display is 36 Hz.

The VGA image is then shown on a portrait mounted, 10.4", sunlight readable display between the two pilots. Figure 10 is an unedited image that shows the location of the display in the cockpit of the ownship.

**Table 1. System Components and Refresh Rates**

| ***Component*** | ***Instrument Update Rate [Hz]*** | ***Instrument Update Rate in Ownship [Hz]*** |
|---|---|---|
| WAAS GPS (ownship) | 10 | 10 |
| WAAS GPS (bogey) | 4 | ≤ 1 |
| GIA-2000 | 50 | ≤ 1 |
| Honeywell IMU | 50 | 50 |
| ADS-B | ≤ 1 | ≤ 1 |
| Display Refresh | 36 | 36 |

### *Modifications to ADS-B Basic Message*

The ADS-B message is not well suited to support a synthetic vision display for CSPA. The position resolution afforded by the MX-20 was too coarse for these operations. Roll and extra digits of latitude and longitude needed to be stuffed into an already full ADS-B Basic message. Fortunately, we could restrict our flight test workspace to an area of approximately 100 $km^2$, centered at Moffett Federal Airfield. Therefore some of the digits in latitude and longitude would be constant for the entire flight. Replacing these digits with roll and finer resolution position allowed us to stuff the ADS-B Basic message with extra data at the expense of operational workspace. It should be understood that this solution is appropriate for research purposes only. A new ADS-B data message is needed in a truly operational system that supports synthetic vision displays for CSPA.

## Flight Testing – Synthetic Vision for CSPA

### *Objectives of test*

The primary objective of the flight testing was to conduct of proof of concept focusing on the following questions:

- Does the image of the bogey 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 bogey 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? In other words, can the pilot fly and do station keeping with the information provided on the display?
- What does a blunder look like on the display?

### *Description of Experiment*

**Test Points**

To answer these questions a series of 18 approaches were flown. 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 bogey aircraft while the safety pilot monitored the situation. The planned final approach speed of the bogey aircraft was known to the ownship pilot. Station keeping approaches were flown both eyes out and eyes in.

| | Statement | Pilot 1 | Pilot 2 | Pilot 3 |
|---|---|---|---|---|
| 1 | The image on the display **faithfully represented the position** of the traffic. | 4 | 4 | 4 |
| 2 | The image on the display **faithfully represented the roll angle** of the traffic. | Always eyes out in Roll Mode | 4 | 3.5 |
| 3 | The display **improved my situational awareness** of the traffic when I was eyes out | 5 | 4 | 4 |
| 4 | The display **improved my situational awareness** of the traffic when I was eyes in. | Always eyes out. | 4 | 4 |
| 5 | The orthographic view was clear and easy to understand | 5 | Never used this display. | 5 |
| 6 | The map view was clear and easy to understand | 4 | 4 | 5 |
| | Time flying traffic display | 3.9 hrs | 1.4 hrs | 0.5 hrs |

**Figure 8. Subjective Data on Pilot Reactions**

🟩 🟪 🟨 🟧 🟥
5 4 3 2 1
5 = Strongly Agree
4 = Agree
3 = Neutral
2 = Disagree
1 = Strongly Disagree

For safety reasons the blunder approaches were carefully orchestrated. These approaches started also started 8 nm from the touchdown point and progressed identically to a station keeping approach. The ownship was always headed for Runway 32R and the bogey for 32L. The ownship would always be ordered to follow the bogey 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 bogey. If both pilots did not have visual contact the blunder portion of the approach was aborted and both aircraft would make closed traffic on their respective runways for another approach. 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 bogey would announce that it was about to blunder, wait for confirmation from the ownship, and then roll right and blunder from 32L to 32R.

### Pilots

Three pilots flew the 18 approaches. Two of the pilots are ATP rated with an average of 3,000 hrs of Pilot-In-Command time. The pilots flew the display in this experiment for a total of 5.8 hours.

## *Results*

### Subjective Data on Pilot Reactions

Following each flight the pilots were asked to rate their responses to the six statements listed in Figure 8. Responses were recorded on a scale of 1 to 5 where a score of 5 indicated "Strongly Agree" (green); 3 indicated "Neutral Opinion" (yellow) and 1 indicated "Strongly Disagree" (Red) Figure 8 shows the responses for each pilot. Most of the

### Station Keeping Performance

Figure 9 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.

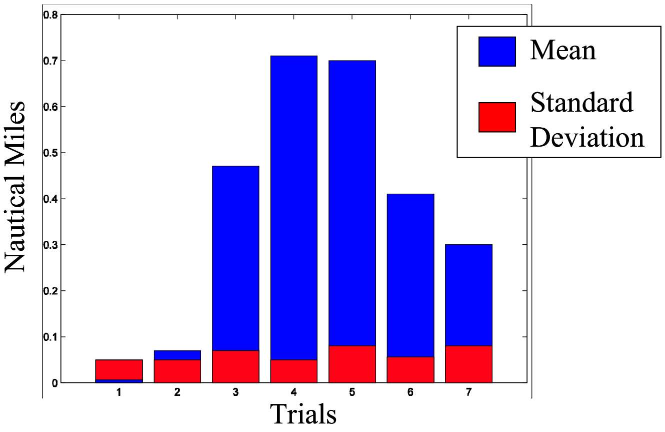

**Figure 9. Station Keeping Performance**

## Conclusions

We met the goals of this research effort which were to test fly a proof of concept of traffic on a synthetic vision primary flight display and to collect data on station keeping performance using that display.

Subjective 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

**Figure 10. CSPA Display Flight Testing**

Moffett Federal Airfield, Moffett, California

bogey. The display also seems to increase pilots' situational awareness of the traffic.

The station keeping results are also 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 the display is useful for refining a pilots' estimate as to how far away the traffic is and hence reducing the bias in the error.

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.

During the course of working on this project we learned that a single synthetic vision display is insufficient to convey CSPA traffic information. This is so for two reasons: the traffic may execute its entire approach outside the field of view of the PFD and second, the distance cues are too weak in a perspective display to precisely convey the location of the other aircraft. While the SV PFD does show elevation and azimuth to the traffic it must be augmented with some other display that shows the relative position more precisely. We present three of these supplemental displays in this paper, the Orthographic Display, the Map Display, and the Mixed Display. Each display has particular strengths and weaknesses.

The Orthographic Display, while more precise than the Map Display, is an abstraction of the approach. The Map Display is a format to which pilots are more accustomed. It can convey a more comprehensive view of the approach while still giving some detail regarding the bogey aircraft and its whereabouts with respect to its approach pathway. Some combination of these traits will be required for the CSPA display that is to be implemented. The Mixed Display, because of the superposition of a vertical and a horizontal projection (Orthographic and Map, respectively) is probably not the optimal combination of information.

Finally, the data presented here is too small a sample to draw conclusions regarding global acceptability of these displays. What can be inferred from the pilot responses is the system functioned well enough to show 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 it becomes possible to reevaluate the requisite runway spacing to conduct independent parallel approaches in IMC. Perhaps then, runway expansion projects worldwide will become smaller, less expensive, and less intrusive on the environment.

## Acknowledgements

The authors would like to thank and acknowledge the following people for their contributions to this research:

- Sky Research Inc.
- Flight Operations at Moffett Federal Airfield.
- Tom Mosher, UPS Aviation Technologies
- Stanford University Flight Test Team

Lastly, the authors would like to thank the FAA – Satellite Program Office for funding this research.

## References

[1] Alter, K.W., Barrows, A.K., Jennings, C.W., Powell, J.D., (1998) In-flight Demonstrations of Curved Approaches and Missed Approaches in Mountainous Terrain. *Proceedings of the ION GPS – 98*. Nashville, TN.

[2] Barrows, A.K., Alter, K.W., Jennings, C.J., Powell, J.D., (1999) Alaskan Flight Trials of a Synthetic Vision System for Instrument Landings of a Piston Twin Aircraft, *SPIE*, Orlando, FL.

[3] Bone, R., Mundra, A. Olmos, B.O. (2001) Paired Approach Operational Concept. *Proceedings of 20th Digital Avionics Systems Conference.* Daytona Beach, FL.

[4] Enge, et. Al. (1996) Wide Area Augmentation of the Global Positioning System, *Proceedings of the IEEE*, Vol. 84, No. 8, August pp. 1063-1088.

[5] FAA. (1999) Aeronautical Information Manual, Department of Transportation Federal Aviation Administration, Washington, DC.

[6] Grunwald, A.J., Robertson, J.B.,Hatfield, J.J., (1980). Evaluation of a Computer –Generated Perspective Tunnel Display for Flight-Path Following. NASA TP1736, Langley, VA.

[7] Houck, S.W., (2001*) Multi Aircraft Dynamics Navigation and Operation*. Ph.D. Dissertation, Stanford University.

[8] Houck, S., Barrows, A., Parkinson, B., Enge, P., Powell, J.D. (1999) Flight Test of WAAS for Use in Closely Spaced Parallel Approaches. *Proceedings of ION GPS – 99*. Nashville, TN

[9] Jennings, C.W., Barrows, A.K., Alter, K.W., Powell, J.D. (2000) Synthetic Vision Displays for Instrument Landings and Traffic Awareness – Development and Flight Testing. *Proceedings of 19th Digital Avionics Systems Conference*. St. Louis, MO.

[10] Johnson, W. , Battiste, V. (2001) *Cockpit Display of Traffic Information.* Demonstration CD. Flight Deck Display Research Group, NASA Ames Research Center.

[11] Pritchett, A. (1999) Pilot Performance at Collision Avoidance During Closely Spaced Parallel Approaches. Air Traffic Control Quarterly, Vol. 7(1) 47-75.

[12] Sachs, G., Sperl, R., Nothnagel, K. (2002) Development and Test of a Low-Cost 3D-Display for Small Aircraft, *SPIE Aerosense*, Orlando, FL.

[13] Stone, R. (1998) Paired Approach Concept Increasing IFR Capacity to Closely Spaced Parallel Runways. United Airlines World Headquarters, Chicago, IL June 17th

[14] Theunissen, E. (1997). *Integrated Design of a man-Machine Interface for 4-D navigation.* Delft University Press, ISBN 90-407-1406-1.

[15] Teo, R., Tomlin, C., (2001) Provably Save Evasive Maneuvers against Blunders in Closely Spaced Parallel Approaches. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Montreal, August 2001