# FLIGHT TEST MEASUREMENT OF PILOT REACTION TIMES TO RUNWAY INCURSIONS: OUT-THE-WINDOW VS. SYNTHETIC VISION

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## Abstract

Researchers at Stanford University have developed and flight tested Runway Incursion Alerting System for aircraft on final approach. The system utilizes Synthetic Vision and ADS-B. The objectives of the flight test were to conduct a proof of concept and to compare the reaction times to incursion between pilots looking out the window and pilots looking at the display. In April 2001 we flew 98 approaches (incursions occurred on 72 approaches) into Moffett Federal Airfield. A specially equipped Ford Winstar Van generated the incursions while a Cessna Caravan flew approaches. Pilots looking out the window tended to see incursions at the runway threshold before the pilot using the display. The reaction time of the out the window pilot was a function of visibility conditions and the location of the incursion along the runway. The reaction time of the pilot looking at the synthetic vision display was insensitive to these factors.

## Introduction

In 1999 the FAA made the reduction of runway incursions the number one priority of the agency. Despite concerted and focused efforts, runway incursions still persist as a worldwide problem. Incursions in the U.S. jumped between 1999 and 2000 with 321 and 431 incursions respectively. 2001 shows the same rate as 2000 with 243 incursions between January and June (2000 was 245 for the same period). The accident on 8 October, 2001 at Milan-Linate that claimed 118 souls also stands as a hallmark of this dangerous and unsolved problem.

Researchers at Stanford University have developed and flight-tested a Runway Incursion Alerting System using a 3D perspective Synthetic Vision Display. The display fuses several information sources (GPS, attitude, and ADS- B) into a full color rendered version of the out-the-window scene. A runway incursion was indicated on the display by showing the image of the incurring vehicle on the runway and by changing the color of the runway (yellow for caution, red for alert). A Cessna Caravan was equipped with the display and supporting sensors and a Ford Windstar van, acting as incurring ground traffic, was equipped with GPS and an ADS-B transmitter (Figures 1 & 3).

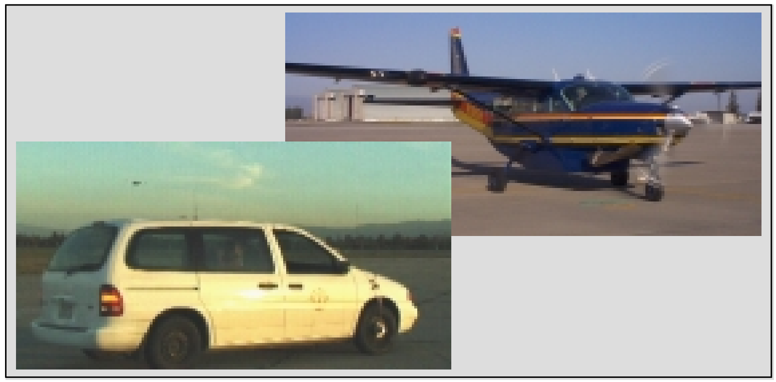

**Figure 1: Incurring Traffic, Ford Winstar Van Approaching Traffic, Cessna Caravan**

The goal of the experiment was to conduct a proof of concept and to measure the reaction times of approaching pilots to a runway incursion. We flew 98 approaches into Moffett Federal Airfield with incursions occurring on roughly 73% of the approaches. For safety considerations it was preferable to stage the incursion at the approach end of the runway. As a result of the unnaturally predictable nature of the incursions, pilots felt cued to the event and results, therefore, are skewed to lower reaction times. To mitigate this cueing two other types of incursions were staged. Several incursions occurred 6,000 feet down the 9,500-foot runway and another eight occurred at night with the lights on the van totally extinguished.

Results show that reaction times for the pilot with the display lag the pilot looking out the window by 2.4 seconds. Results also show that the

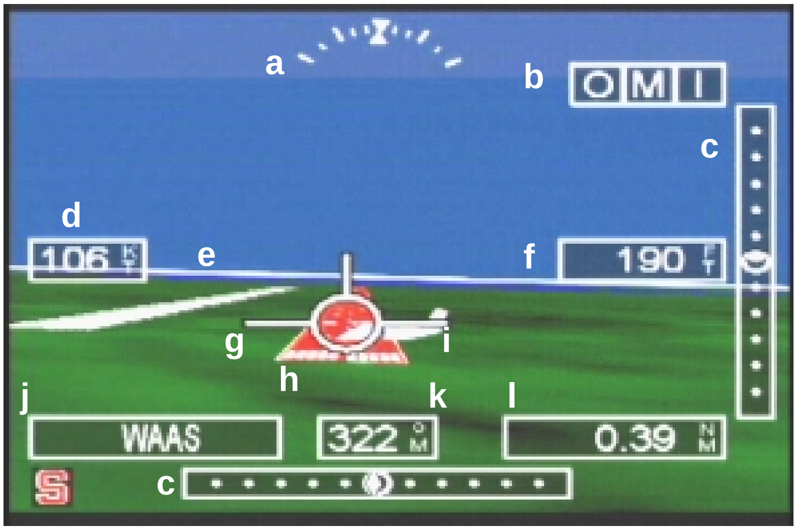


**Figure 2: Synthetic Vision Primary Flight Display Showing a Runway Incursion**

a. Roll Indicator
b. Outer, Middle, Inner Marker Annunciator
c. Course Deviation Indicator
d. Airspeed
e. Artificial Horizon
f. Altitude (above Mean Sea Level)
g. Flight Path Vector (4 second predictor)
h. Runway, colored red, indicating an incursion
i. Image of incurring traffic
j. Ownship data source
k. Magnetic Heading
l. Distance to touchdown

reaction times of the pilots using the visual scene are strong functions of the location of the blunder along the runway and to visibility conditions whereas the reaction times of pilots using the display are insensitive to these factors.

## Prior Research

The research documented in this paper strives to combine synthetic vision with aviation operations research. Many groups and individuals have investigated the correct format and properties of synthetic vision primary flight displays (SV PFD) [3][7][8][12][13]. In recent years it has become practical to install these systems in research aircraft suitable for flight testing [2][3][12][13]. These groups have shown that pilots can effectively aviate and navigate aircraft as small as a Piper Dakota and as large as a Boeing 757 using these displays.

The FAA's effort to field a Runway Incursion Prevention System has generated scores of papers culminating in a successful flight test in October 2000 [11]. This project combined surveillance, data links, algorithms [4] to generate a system that could detect aircraft by several means, ascertain whether an incursion was imminent or in progress and show that information to the pilot. The displays and symbology designed for this system are incremental departures from standard instruments in use today. This is precisely the correct strategy if the project goal is to field a system that will integrate into the NAS most efficiently.

What distinguishes this research from the prior art is that this research is a focused attempt to integrate ADS-B traffic information into an SV PFD. We built the display and integrated the components to generate the system to support the display. Then we conducted the first flight tests of synthetic vision displays with integrated real time runway incursion alerting.

## Display Design

The analysis of the variables to be depicted to enable a pilot to aviate and navigate an aircraft using only a SV PFD has been completed and the display systems have been constructed [2][3][7][12][13]. The strategy for including the runway incursion traffic alerting was to replicate the out-the-window view. In addition we wanted to augment that image with a symbology that, while compelling, would make the minimum possible change to the display. In this method we had the greatest chance of preserving the benefits of SV found by [2][7][8][13] 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 (Figure 2) but initial trials suggested that that cue was too far abstracted from

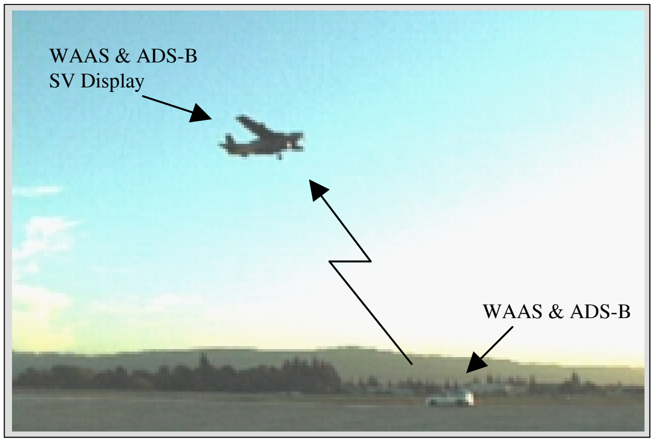


**Figure 3: Runway Incursion Alerting System During Flight Testing.**
Incursion in Progress

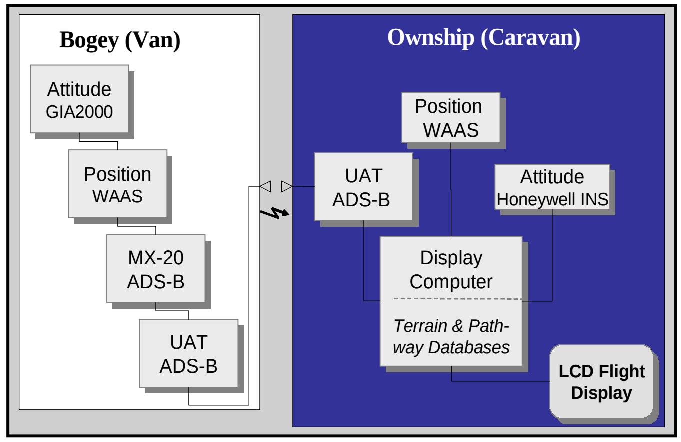


**Figure 4: Runway Incursion Alerting System - Block Diagram**

the cause. We settled on changing the color 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 simply, '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. Most other attempts to show traffic information on SV displays meet with significant challenges to show traffic that is outside the frustum of the display (see [10] for an example).

## Flight Test System

### *Vehicles*

To conduct our flight trials a multi-vehicle synthetic vision system was installed in a Cessna Caravan and a Ford Windstar van (Figure 3). The Caravan served as the ownship and the van as the incurring ground traffic.

### *Block Diagram*

As shown in Figure 4, the flight system is a centralized architecture using RS-232 serial communications. Equipment installed in the ownship (Caravan) is shown on the right and equipment installed in the bogey (van) is shown on the left. The information flow in the block diagram is from left to right. All sensor information flows to the display computer. An ADS-B data link from UPS Aviation Technologies was used to transmit data from the van to the ownship.

The van system was designed solely to determine van state parameters (position, velocity, heading) and feed them to the ADS-B data link. 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.

For a more detailed description of the flight test system see [10].

### *Timing Recorder Subsystem*

Two buttons were attached to the yokes of the Caravan. The buttons were designed and placed such that the pilots could press the button without interfering with the tasks of flying. The output of each button and a Novatel Millennium GPS receiver was routed to a laptop computer. The computer could then record the GPS time-of-week of button press for each pilot. With this subsystem the absolute reaction to an incursion could be recorded.

### *Sensors & Computers*

For the SV system 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 Stanford Prototype of the Wide Area Augmentation System [6]. Both vehicles used Novatel Millennium OEM3 Receivers in concert with Stanford University WAAS Algorithms for position and velocity. Heading of the van was derived from the components of velocity. In the ownship we used an Inertial Navigation System 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. 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 landscape mounted, 10.4", sunlight readable display between the two pilots.

### *Venue*

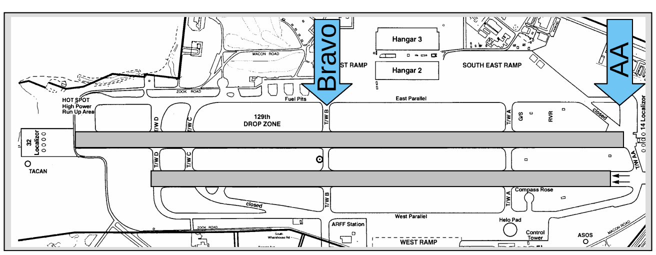


**Figure 5: Incursion Locations on Moffett Federal Airfield**

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 5 shows a map of the airfield. The Caravan approached on 32R (upper runway in Figure 5) and the van would incur either at Taxiway AA at the threshold or at Taxiway Bravo, 6,000' down the runway.

## Description of Experiment

### *Design of Experiment*

The experiment had two primary objectives:

- Complete a proof of concept flight of the display system.
- 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.

**Independent Variable**

- Visual Cue, Out-the-Window vs. Display

**Dependent and Derived Variables**

Reaction Time (RT): GPS time of all events in the experiment were recorded. The most important time tags are reaction times recorded by the pilots' button presses. With these data we can derive the central figure of merit for this experiment.

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

display_advantage is the number of seconds between the instants when the pilots signaled that they saw the incursion. 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.

**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

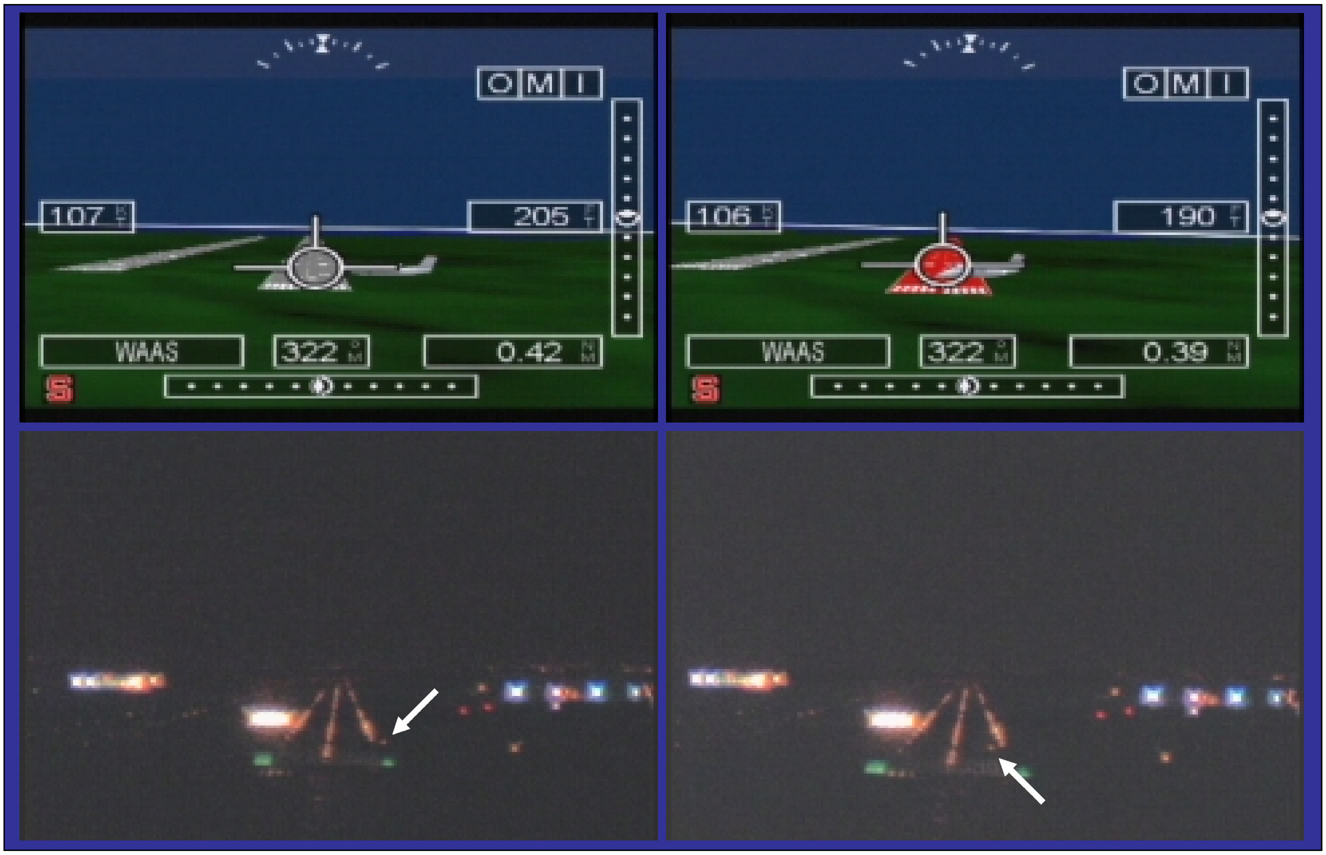


**Figure 6: Synchronized Before (left) and After (right) Images of an Incursion**

The taillight of the van is highlighted by the white arrows. When the van taxis onto the runway, the runway color is changed to red.

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.
- Bravo Approaches. To simulate a more common runway incursion incident scenario we conducted incursions at Taxiway Bravo, some 6,500’ feet down the runway.

**Number of Runs**:

In total we conducted 98 approaches over five days. To attempt to lessen the cueing of the pilots to the van’s incursions we flew 27% of the approaches without incursions. Due, in part, to operating constraints at Moffett, we conducted 68 approaches at night. We flew 7 Pseudo IFR and 8 Bravo Approaches.

**Flight Operations**

The order of events during an approach was as follows:

**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.

**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. The OTW Pilot was instructed to press his/her button when the van was 50 feet (2 car lengths) from the runway edgeline and moving toward the runway. Fifty feet from the edgeline is the point of no return for the van. At this point is would be almost impossible for the van to stop without generating an incursion. The Display Pilot was instructed to press his/her button when the display turned red. The display was coded to turn red when the van got to within about 50' of the edgeline (see [9] for a full description of the algorithm to change the colors of the runway).

**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.

**Low Approach – Without Incursion.** Pilots were to maintain 75' AGL until they flew past the van. At that point they could initiate their go around.

**Safety Considerations in the design:**

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.

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

**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 |

## Results

**Proof of Concept**

Figure 6 shows two sets of time synchronized images from an incursion approach during the flight test on 17 April, 2002. The images on the right side of Figure 6 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. The synthetic image of the van 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 left 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.

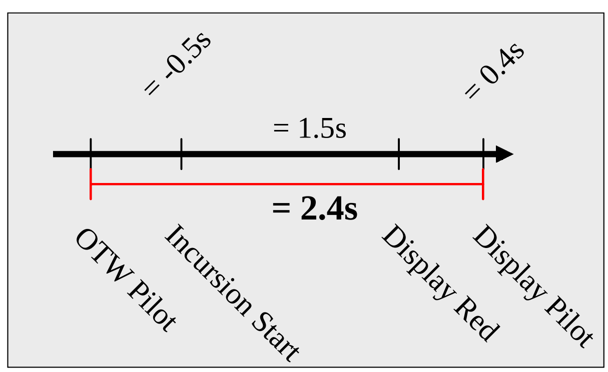


**Figure 7: Reaction Timeline**
Display Pilots lag OTW Pilots by 2.4 seconds.

### *Reaction Times*

**Baseline Reaction Time Comparison**

Figure 7 shows a summary timeline for data from 44 standard night time 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.

| Display Advantage | PILOT1RT (GPS time) | PILOT2RT (GPS time) |
|---|---|---|
| | X | 185475.140 |
| | 186256.950 | X |
| | X | 188495.880 |
| | 189473.330 | X |
| | 189724.830 | X |
| 14.34s | 190748.650 | 190734.310 |
| | X | 191522.770 |

**Figure 8: Pseudo-IFR Approaches**

An 'X' signifies that the pilot never saw the incursion. The Reaction Times (RT) are recorded in GPS time of week.

**Corner Cases**

Figure 8 shows the reaction times to the Pseudo-IFR Approaches. A red X marks no response from the pilot. On all but one of these approaches the pilot looking out the window NEVER saw the van. In the one approach where the OTW Pilot did indicate that he saw the van, he did so 14 seconds after the Display Pilot.

Figure 9 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.

### *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 [11].

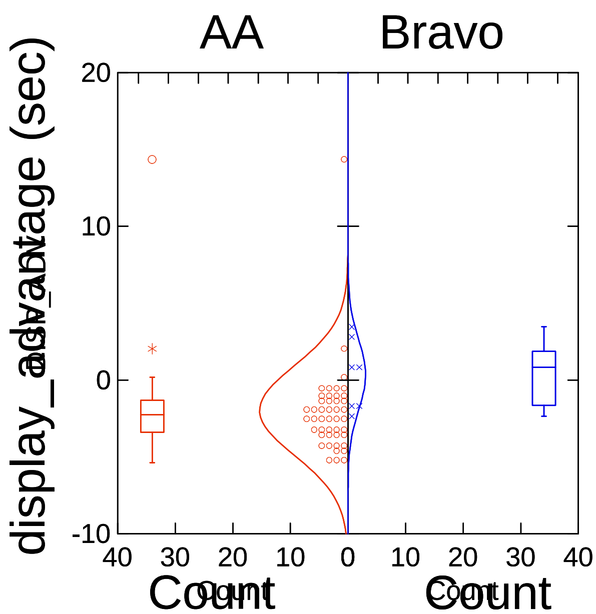


**Figure 9: Histograms of display_advantage for incursions at Taxiway AA and at Bravo.**

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 Corner Cases. 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]"

## Conclusions

We met the goals of the experiment 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 and the anecdotal data that the system worked well and that pilots found benefit in the traffic information on the SV 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 [1]. 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.

We found that the display is very useful when conditions make seeing the ground traffic more difficult. Pilot opinion and the data 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 aircraft 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 almost a 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.

### *Biases in the Results*

The scenario of the incursions was designed assure the safety of the crew and vehicles. These standard procedures gave rise to the unnaturally predictable nature of the runway incursions. We attempted to mitigate cueing the pilots by not staging incursions on 27% of the approaches.

The following factors are likely to lower the reaction time of the 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 [Figures 2 & 6]. Even though they might be primed to the incursion they must wait for the color chance of the runway. In contrast, the OTW pilot is trying to locate the traffic on the airfield. From the data collected here and from the AILS study [1] it is reasonable to expect pilots to respond to an obvious message on the PFD in about 0.5 sec. For these reasons the authors feel that the results for the display advantage are conservative and we would expect a larger advantage from using the display in everyday scenarios.

### *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 SF PFD. In particular this alerting symbology is meant to fit within the synthetic vision display presented in [10]. That paper presents a synthetic vision display and supporting system to enable Closely Spaced Parallel Approaches (CSPA).

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 traffic abeam and ahead.

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