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Evaluation of Triple Closely Spaced Parallel Runway Procedures for Off-nominal Cases

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Abstract— **This study used a high-fidelity simulator to explore the procedures for operations using three closely-spaced parallel runways. The concept aimed to achieve visual meteorological capacities under instrument meteorological conditions when landing aircraft on runways as close as 750 ft apart. This investigation studied procedures related to breakout maneuvers for triple parallel aircraft flying in an echelon formation. Two-thirds of the configurations evaluated had an off-nominal situation, which was manipulated as an independent variable. The off-nominal situation was either the wake of the lead aircraft drifting too close to the center or trailing aircraft or the lead aircraft deviating from its course and blundering towards the center and trailing aircraft. The location of the off-nominal situation (high or low altitude) and the position of the ownship (center or right runway) were also independent variables. Results showed that the pilot workload and situational demands were higher in the off-nominal as compared to the nominal scenario. Neither cause of breakout, location of breakout, nor position of ownship had a significant impact on workload or situation awareness. Pilots flew the breakout maneuvers across all conditions and scenarios accurately and safely, similar to the previous two runway studies. The results provide an assessment of the procedures for breakout maneuvers during off-nominal conditions.**

Keywords-VCSPR; simultaneous approach, triple approach, breakout procedures, off-nominal.

I. INTRODUCTION

The FAA allows simultaneous instrument approaches on two and three runways spaced 4300 ft or more apart, as well as Precision Runway Monitor (PRM) approaches on runways 3000 ft apart, at all but three of the 35 busiest domestic airports. When two parallel runways cannot be used simultaneously, arrival capacities halve, which cause delays during instrument meteorological and marginal visual conditions. The runway pairs can only be used for simultaneous arrivals when pilots can provide visual separation. Mundra et al. show that twenty four percent of all delays are caused when the arrival airport is unable to conduct visual approaches due to reduced visibility, lowered ceiling, haze, or fog. Sixty-six percent of these delays are associated with airports that have at least one pair of runways that are closely spaced (i.e., less than 3000 ft) [1].

Procedures for triple parallel runways have been examined for runways spaced by at least 2500 ft and for situations in which two, but not all three, aircraft are dependent on each other [5]. This paper pushes the limit by examining a new concept and procedures for three simultaneous arriving aircraft that are dependent on each other when the three parallel runways are spaced by 750 ft. The biggest concern with simultaneous landings on runways closer than 1200 ft are breakout maneuvers due to off nominal conditions.

This paper describes an advanced concept and procedures used to address off-nominal situations caused by wake and aircraft-blunders, for aircraft flying three simultaneous closely spaced runway approaches during IMC. The paper will describe the experiment, discuss the results on separation between the leader and follower aircraft, the accuracy of flying the breakout trajectory, workload, and situation awareness for the pilots under these off-nominal situations.

A. Background

Most of the previous research on very closely spaced parallel approaches has focused on dual runways [2] [3]. Some previous research has focused on modeling capacity gains for closely spaced parallel runways using different procedures [4]. The research on triple streams of aircraft has been mostly exploratory in nature, investigating the effect of adding a third stream of aircraft on capacity. There have been several procedures defined for triple simultaneous approaches, and each one of them defines a non-transgression zone or a safety net to protect against aircraft blundering or deviating from their intended path towards the other aircraft. In 2000, Hartsfield Atlanta International airport (ATL) commenced a research study to increase capacity [5] that would consider adding a third stream of aircraft to one of the pairs of runways, thus creating triple simultaneous approaches to increase capacity. Gladstone et.

al. (2000) [5] led a research effort that explored several procedures for ATL such as Simultaneous Offset Instrument Approach (SOIA) and Along-Track Spacing (ATS). These procedures were then adapted and further investigated for triple approaches for ATL.

The SOIA procedure has been successfully implemented in several airports with two runways including St. Louis International and San Francisco International. Since the runways are spaced closer than 3000 ft, one approach path is aligned to the runway and the other approach path is offset at a distance greater than 3000 ft. The aircraft continue on the approach path until they reach visual conditions, also referred to as the clear of clouds point. The weather minimums for SOIA at SFO are 2100ft/4nm visibility at break of clouds. The trailing aircraft on the offset approach must report visual contact with the leading aircraft prior to the Missed Approach Point (MAP) and then air traffic control will issue a visual approach clearance. Once the trailing aircraft receives the clearance, it executes a visual sidestep maneuver to align itself to the runway and land. If the trailing aircraft is unable to make visual contact, it executes a missed approach that takes the aircraft away from the runways. Each pair of aircraft maintains standard wake separation to avoid wake turbulence.

Along-Track Spacing (ATS) is another concept for dual closely spaced runways that involves the use of straight-in approaches to each runway. Deutsche Flugsicherung (DFS, 1999a) [6] proposed using 1.5 nmi diagonal spacing between the leading aircraft on one runway and the trailing aircraft on the other runway. Wake turbulence protection is provided by displacing the threshold of the trailing aircraft by 1500 m (4921 ft) and effectively raising the trailing aircraft's flight path by 80 m (262 ft). The concept of relying on a displaced threshold for vertical separation is called the High Approach Landing System (HALS). Similar to SOIA, wake protection between pairs is provided by standard separations. Also, ATS does not require a side step maneuver as is required in SOIA. Thus HALS provides a capability to fly dual streams of aircraft to closely spaced runways that have displaced ILS installed, which permit landings up to Category I minima, potentially allowing for more capacity benefits than SOIA.

Gladstone et. al (2000) [5] described four procedures with three approach streams developed for ATL with two sets of parallel runways. The procedures include Independent SOIA Triples, Dependent SOIA Triples, Angled SOIA Triples, and Triples using Along-Track Spacing (ATS). The Independent SOIA for triples procedure requires an independent monitor for each runway and has a 2000 ft No Transgression Zone (NTZ) established between each pair of simultaneous streams. The Dependent SOIA triples build on the current standard that allows dependent approaches to two parallel runways with a minimum of 2500 ft between runways and a diagonal separation of at least 1.5 nmi between aircraft, with one NTZ established between the north and south pairs of runways. So, on ATL's north runways there is one aircraft on 26R, whereas on south runways, the in-board runway has a straight in aircraft, the out-board runway has the aircraft on a SOIA, and the trailing aircraft follows the lead aircraft by 1.5 nmi. The Angled SOIA triple approach is similar to the Independent approach with NTZs except the aircraft on the SOIA is offset by 3 degrees. The ATS triple approach was similar to the Dependent SOIA approach in that there was one approach stream on the outboard runway for the north set of runways and there were two straight-in approaches to the south runways. The two aircraft on the south runways are separated by 1.5 nmi diagonally. The procedures described above still require considerable testing and development, since standards don't exist for most of them, especially the ATS concept.

All the procedures for triple runways described in the previous paragraphs have runway spacing of at least 2500 ft apart. Only two aircraft out of the triples are in a formation or dependent on each other, so the third aircraft is not dependent, which limits the capacity benefits. The breakout procedures for the triples in Gladstone's study were similar to those used with SOIA. The Multiple Parallel Approach (MPAP, 2002) [7] team performed a real time simulation to evaluate simultaneous instrument landing system approaches to three parallel runways spaced 4000 ft and 5300 ft apart. The MPAP team introduced blunders to test the concept's ability to maintain adequate separation between aircraft on final approach. Here, the controllers were responsible for separation between aircraft on a triple approach, and they used Precision Runway Monitor with a 1.0 sec update rate to help with the task.

The concept investigated in this paper has three runways spaced at 750 ft from each other, and the three aircraft flew in an echelon formation (see Figure 1). The pilots were responsible for separation and were provided new tools and procedures to achieve the same. The following section describes the concept, and the procedures for the triples using Terminal Area Capacity Enhancing Concept (TACEC) [8].

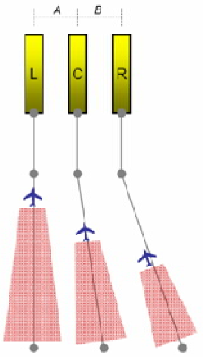

Figure 1. The line formation for triples

II. EXPERIMENTAL APPROACH

A. Airport and Airspace Design

The experiment used a fictitious airport (KSRT) loosely based on the current Dallas/Fort Worth International Airport (DFW) layout and operations except for three parallel runways that were set to be 750 ft apart. Because the simulation focused on TACEC approaches to very closely spaced parallel runways using south flow scenarios, only the west side runways (18L, 18C and 18R) were used. The outside runway (currently 18R) was moved inward to create 18C with a 750 ft separation between the runways and a third 18R was also added at 750 ft. All three of the runways were assumed to be equipped to a CAT-IIIB level.

B. TACEC Procedures

TACEC calls for the three aircraft to be paired at meter fixes located near the edge of the terminal airspace, normally 40-60 nmi from the airport [8] and given TACEC-assigned 4D arrival trajectories to the runway. Flights in the simulation began 25 nmi from the airport, assuming they were already paired. Routes to the airport included approach and departure routes and procedures similar to those for DFW airport. This study focused upon arrivals, and no departures were studied.

TACEC [8] allows for any aircraft arriving from any of the four arrival meter fixes (NE, NW, SE, and SW) to be paired for a simultaneous parallel landing, based on aircraft characteristics and relative timing criteria. The three paired aircraft flew their assigned 4D trajectories with a high level of accuracy to meet timing constraints at the coupling point and to ensure wake safety throughout the approach. TACEC assumes augmented Global Positioning System (GPS) and ADS-B (Automatic Dependent Surveillance-B). The coupling point, which refers to the point at which the speed of the multiple aircraft becomes dependent, or “slaved” to one another, is defined at 12 nmi from the threshold of the runway. From that point onward in the simulation, the center aircraft precisely maintained 12 s spacing behind the lead aircraft, and the right aircraft maintained 24 s behind the lead aircraft using a speed algorithm to avoid the wake and for safe separation. The approach paths of the two trailing aircraft were at a slewed angle from the center of the runway- six degrees for the aircraft on the center runway and 12 degrees for the aircraft on the right runway, when the aircraft were 25 nmi from the threshold. All three aircraft turned straight and parallel to each other at about 2 nmi from the runway.

Onboard automation based on ADS-B monitored the three aircraft for potential emergency situations. The automation displayed a predicted hazardous zone for the wake generated by the lead and center aircraft in the cockpits of the second and third planes. ADS-B lateral position and intent information was used to detect and display any deviation from the proposed approach path that would encroach on either of the trailing aircraft. Visual and aural alerts were given to the pilots when the lead-aircraft’s blunders or wake presented a dangerous situation to the trailing aircraft. The navigation display depicted a breakout trajectory after the aircraft crossed the coupling point. This breakout trajectory was dynamically generated and considered wake, traffic, buildings and terrain of the airport surroundings. When the breakout was required at different altitudes on the arrival path different bank angles for the breakout maneuvers were used and the curvature of the breakout trajectory changed on the navigation displays. The pilots flew the breakout trajectory manually using the flight director when they received an aural and visual alert.

C. Displays

The displays were similar to the displays used for the study of two runway very closely spaced parallel approaches [2] and were based on previous research associated with flight deck displays [9] [10]. The Navigation Display (ND) and Primary Flight Display (PFD) are shown in Figures 2 and 3. The displays show wake and trajectory information along with standard flight instrument data.

After crossing the coupling point and the pilot’s prior acceptance of coupling with the lead aircraft, the flight mode annunciation changes to show that the three aircraft are coupled for speed (C-SPD), coupled for lateral navigation (C-LNAV) and coupled for vertical navigation (C-VNAV). The two trailing aircraft were coupled with the lead aircraft. The autopilot flew the approach, the pilot primarily monitored the aircraft performance and the displays for the remainder of the flight. If the wake of the adjacent aircraft drifted within one wingspan of the own-ship aircraft, the color of the wake hazardous zone on the display turned to yellow, and then turned red when the apex of the aircraft was in the wake. Similarly, if the lead aircraft deviated from the planned trajectory towards the following aircraft’s path by 60 ft, the lead aircraft symbol turned yellow, and then red when the lead aircraft deviated by 120 ft. The red warnings, accompanied by an aural alert “breakout, climb” required a mandatory breakout, which the pilots flew manually. When the pilots pressed the Take-Off-Go-Around (TOGA) switch, the breakout trajectory, which had been displayed to the pilot in white, became the active route, and was then displayed in magenta.

D. Advanced Concept Flight Simulator

The human-in-the-loop experiment studied breakout maneuvers for triple TACEC approaches in the Advanced Concepts Flight Simulator (ACFS) located at NASA Ames Research Center. The ACFS is a motion-based simulator that represents a generic commercial transport aircraft, enabling it to be reconfigured to represent future aircraft. It has the performance characteristics similar to a Boeing 757 aircraft, but its displays have been modified to study different advanced concepts. In this study, the cockpit displays described in the previous section were integrated with the flight display systems in the cockpit. The visual systems offer a 180 deg horizontal and a 40 deg vertical field of view. This simulator is capable of providing various visibility conditions and was set to IMC for this experiment.

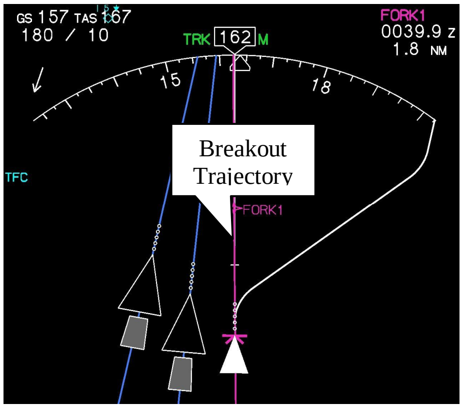

Figure 2: Navigation Display during final approach

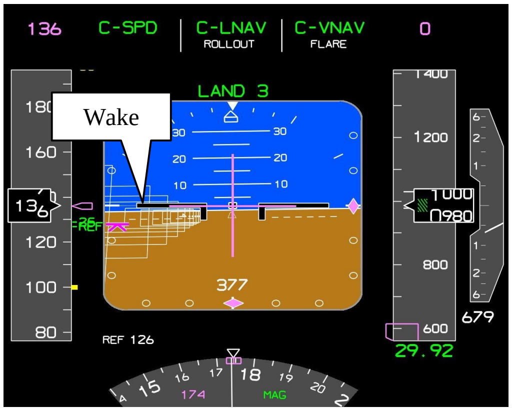

Figure 3: Primary Flight Display

E. Variables

Four independent variables were examined in this study of the TACEC concept for triple runways. First was the presence or absence of an off-nominal situation that may warrant a breakout maneuver. The second independent variable was the cause of the breakout maneuver – wind causing the wake of the lead aircraft to drift towards the following (center) aircraft, or the lead aircraft deviating from its original path and towards the trailing aircraft. The third independent variable was the location of the off-nominal situation, which was above 500 ft, or between 200 ft – 500 ft above the ground. The fourth independent variable under study was the position of the own-ship or the simulator which could either be approaching the center or right runway. A total of 24 runs were performed for each participant in which 8 were normal and 16 had off-nominal situations. In the runs that required a breakout maneuver, repeated runs were made for each breakout cause, breakout location, and position of the aircraft.

F. Hypotheses

In the absence of previous research on triple-runway closely-spaced approaches, the researchers predicted that the location of the off-nominal situation or the nature of the off-nominal situation or the position of the ownship (center versus right runway) would not affect pilots' behavior on the following parameters:

- Separation from lead at breakout point
- Accuracy of flying trajectory
- Workload
- Situation awareness

However, it was expected that there would be differences in situation awareness and workload experienced by the pilots in the runs that have the off-nominal situation versus the runs that do not.

G. Participants

The participants were eight recently retired pilots from commercial airlines; all were male and all of them had experience with glass cockpits. Their average experience as a pilot was about 38 years. Their average number of years since retirement was less than two.

H. Experimental Procedure

The study ran for eight days with one pilot participating each day. At the beginning of the day, the pilot was familiarized with the project, the concept, and the new displays in the cockpit. The pilot received a demonstration of the ACFS and hands-on training on the flight deck displays and related procedures.

Since procedures for triple Very Closely Spaced Parallel Runways (VCSPR) were being explored in this study, each pilot flew the ACFS in the left seat (as captain) along with a confederate who acted as the first officer. The role of the pilot was to fly in auto pilot mode and monitor the displays to check separation with the lead aircraft and with wake. Prior to the coupling point the pilots heard a chime, saw the acknowledgement button light up, and received a "TACEC Coupling" message on the lower Engine Indicating and Crew Alerting System (EICAS) display. At this point the pilots pressed the accept button. They flew as the center or as the trailing aircraft and both of those aircraft were coupled with the leader aircraft on the left most runway. They were coupled with the leader's speed and continued to monitor the separation between the three aircraft. The flight mode annunciation also changed to show that the two aircraft were coupled for speed (C-SPD), coupled for Lateral navigation (C-LNAV) and coupled for Vertical navigation (C-VNAV). If the pilots received a visual and aural alert from the displays they were required to perform a breakout maneuver.

To fly the breakout maneuver, the pilot would press the TOGA switch, disengage the autopilot, leave the auto throttle on, and fly the breakout trajectory shown on the ND. Pressing the TOGA switch would capture the breakout trajectory, and the pilots used the flight director to fly the trajectory. They flew different breakout trajectories at different altitudes, with the breakout above 500 ft altitude requiring an initial bank angle of 30 deg, and the breakout at altitudes between 200-500ft requiring an initial bank angle of 10-deg. They had an initial heading change of 20-deg if they were the center aircraft on 18C and a heading change of 40-deg if they were the trailing aircraft on 18R. In all the above cases, the aircraft had to climb to 30,00ft as a part of the break out procedure. The pilots then followed the 'S' shaped breakout trajectory displayed on the ND. The trajectory was 'S' shaped so that the final leg of the trajectory became parallel to the runways. The final leg of the breakout trajectory was 1.5 nmi abeam for 18C and 3.0 nmi for 18R.

I. Traffic Scenario

The traffic scenario had three aircraft: (1) The ACFS (B757) was always one of the two following aircraft (center or trailing) in the triplet, and the other two aircraft were scripted, depending upon the experimental condition, and (2) the leader aircraft was a Boeing 747-400, which was prerecorded and scripted for this study and landed on 18L under nominal conditions. The pilot who flew the ACFS simulator always landed on either 18R or 18C or performed the breakout, depending upon the simulator position for the particular data collection run. Operationally, the trailing aircraft should be upwind of the cross wind, but this is not always possible so scenarios included adverse crosswind.

J. Tools used for Data Collection

Several tools were used for collecting subjective data from the pilots. All participants completed a demographic survey before the simulation runs were conducted. The survey collected information about the pilots such as their age, experience, and number of hours flying different aircraft types, any experience with SOIA approaches, and experience using personal computers.

All pilots were asked to complete a Post Interaction Survey at the end of all the runs. This survey allowed them to rate the information content and the usability of the displays.

The participants completed the NASA Task Load Index (TLX) rating scales [12] after each simulation run but did not complete the pair-wise scale comparison included as part of the TLX, so the six scales were analyzed separately.

Pilots also completed the Situation Awareness Rating Tool (SART) [11]. The SART gathers a participant's rating of situation awareness (SA) for the preceding period of time on ten different scales. Each scale has 7 points, with the end points representing the opposite ends of the construct. Participants circled the point on the scale that most closely represented their experienced level of SA. The ten SART ratings together with TLX were gathered from every participant at the end of each run – a total of 16 ratings per participant were collected.

In addition to the assessment instruments described above, the flight simulator's digital data collection system was used. A host of objective flight data for each of the simulation runs was collected on some of the variables pertinent to the hypotheses of the experiment. All collected data were indexed with a common timestamp, which was used as the basis of time synchronization as it updates in real-time while the simulation run advances. All digital data were collected at a rate of 30 Hz.

III. RESULTS & DISCUSSION

Statistical analysis of the study data focused on three areas: (1) the flight simulator's digital data collection outputs, (2) the pilot participants' workload and situation awareness assessments, and (3) verbal feedback provided by the pilot participants at the end of the simulation runs.

Aircraft Separation from Breakout through 30 Seconds Past Breakout

The dependent measure of aircraft separation is defined as slant range, or straight-line displacement distance between two aircraft. Analysis of aircraft separation as it changes in time from breakout point was implemented, to determine if there were any instances of unsafe separation between aircraft during the most critical phase of the breakout maneuver, i.e., the time span that immediately follows breakout point, defined as breakout time through 30 seconds past breakout time. Separate analyses were performed in comparing (1) Leading and center aircraft separation, and (2) Center and trailing aircraft separation. Table 1 shows summary statistics associated with these data and Figures 4 and 5 show the aircraft separation for all flights as it changed over time originating from breakout point:

Leader/Center Separation	**Mean (ft)**	**SD (ft)**	**Max (ft)**	**Min (ft)**
Breakout Point	2550	96	2675	2437
15 Seconds Past Breakout	2863	158	3218	2534
30 Seconds Past Breakout	2854	322	4352	2987
Center/Trailing Separation				
Breakout Point	2854	59	2979	2794
15 Seconds Past Breakout	2872	134	3191	2545
30 Seconds Past Breakout	3651	502	4559	2918

Table 1. Aircraft Separation Following Breakout

As indicated in Table 1, and Figures 4 and 5, there is a clear trend towards increased separation between each of the two pairs of aircraft analyzed, with some overall increase 15 seconds past breakout, and a larger increased separation at 30 seconds past breakout. The only apparent exception to this trend is shown in Figure 5, showing the separation between the center and trailing aircraft, where some runs show a relatively small decrease in separation 15 seconds past breakout, prior to increased separation 30 seconds after breakout.

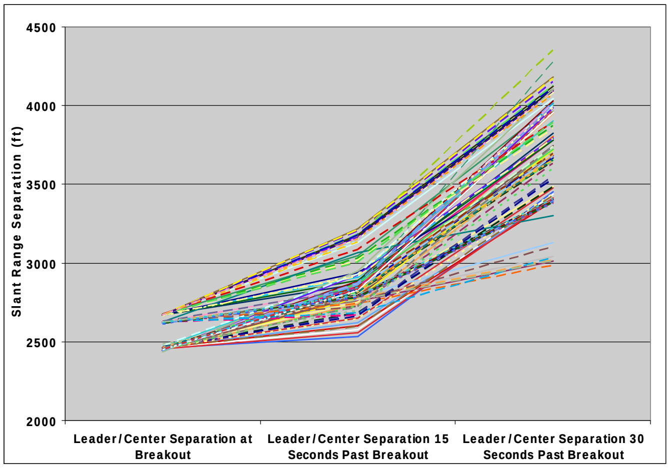

Figure 4. Aircraft Separation Immediately Following Breakout: Leader/Center Slant Range (each time-series represents one simulation "flight")

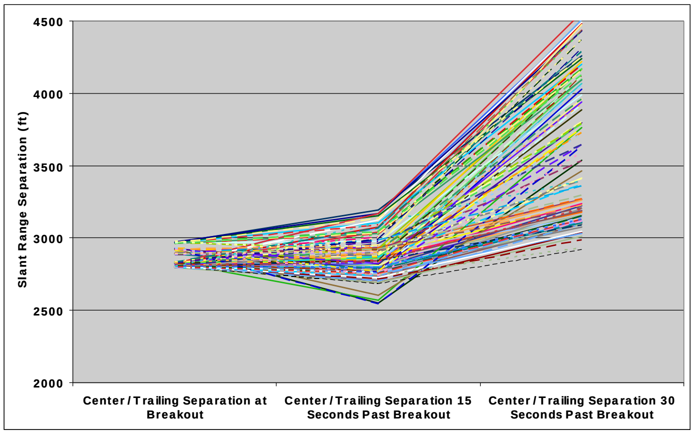

Figure 5. Aircraft Separation Immediately Following Breakout: Center/Trailing Slant Range (each time-series represents one simulation "flight")

It is suggested that this trend in the data reflects the complex geometry of the breakout maneuvers in the case of the center aircraft which needs to separate itself from the leader aircraft towards the trailing aircraft, which may initially decrease separation for a very short period of time. Even so, during this critical window of time, there were no cases where the slant range between the center and trailing aircraft was less than 2500 ft, indicating zero instances of unsafe separation (Figure 5). Furthermore, no instances of unsafe separation between the leader and center aircraft were observed (Figure 4). These data compare with the data collected by FAA's MPAP [7], where they defined a test criterion violation (TCV) as 500ft of separation between the aircraft. Using the same definition, no TCV occurred between the lead and center aircraft or between the center and the right most (trailing) aircraft.

Clearly, the objective evidence shows no single instance of unsafe separation during the critical 30 second time period past breakout. In addition, inferential findings comparing study conditions were uncovered which augment this result. Tables 2 and 3 provide ANOVA statistics (F values) on the dependent measure of aircraft separation 15 seconds past breakout.

LEADER / CENTER AIRCRAFT SEPARATION	Mean (ft)	SD (ft)
Cause: F=89.87 df=1,7 p<0.0001		
Aircraft Blunder	2791	94
Wake	2958	253
Location: F=20.45 df=1,7 p<0.01		
Breakout Location > 500 ft	2949	268
Breakout Location ≤ 500 ft	2800	62

Table 2. Aircraft Separation 15 s past breakout: leader/center slant range

CENTER/TRAILING AIRCRAFT SEPARATION	Mean (ft)	SD (ft)
Location: F=44.73 df=1,7 p<0.001		
Breakout Location > 500 ft	2924	169
Breakout Location ≤ 500 ft	2828	89
Location: F=40.39 df=1,7 p<0.001		
Center Ownship	2962	128
Trailing Ownship	2791	100

Table 3. Aircraft Separation 15 s past breakout: center/trailing slant range

A statistically significant main effect of breakout cause was observed ($F=89.87$, df=1,7, $p<0.0001$) on the dependent measure of slant range between the leader and center aircraft. Aircraft separation was greater under the wake condition, as compared to the aircraft blunder condition. This effect may be due to the relative uncertainty of wake behavior, resulting in the pilots attempting to achieve more separation when the wake drifts to allow for the unpredictable performance of wake phenomenon.

A statistically significant main effect of breakout location was observed in comparing the slant range separation between and leader/center aircraft ($F=20.45$, df=1,7, $p<0.01$), and also between the center/trailing aircraft ($F=44.73$, df=1,7, $p<0.001$), where separation was greater at the higher altitude breakout. This effect reflects the different post-breakout geometries between the aircraft, where breakout procedures require an initial 30 degree bank angle at higher altitudes, and only a 10 degree bank angle at lower altitudes.

While a main effect of center/trailing ownship was not realized on the dependent measure of aircraft separation between the leader and the center aircraft at breakout, it was realized in comparing the aircraft separation between the center and trailing aircraft at breakout ($F=40.39$; df=1,7; $p<0.001$). Separation was greater when the ownship was the center aircraft, as compared to the trailing aircraft. This might be indicative of the unique position of the center aircraft, where separation involving the ownship and two other aircraft are necessary to maintain safety, whereas the trailing aircraft needs to maintain separation with only one other aircraft. Due to this unique physical position between the other two aircraft, special vigilance may have been exercised by the pilot, resulting in increased separation.

Accuracy of Breakout Trajectory: Cross Track and Track Angle Error

Trajectory accuracy is measured by the actual ownship/simulator position against the breakout trajectory generated by the system and displayed on Navigation Display averaged across time. Two measures of ownship trajectory particularly sensitive to breakout maneuvers include cross track error and track angle error. For each flight simulation run, cross track error and track angle error were averaged across time from the breakout point to the end of the flight. Two-way repeated measures ANOVA yielded main effects of breakout cause, breakout location, and center/trailing ownship on each of the two dependent measures. All of these results are consistent with respect to the directionality of the means across both track angle and cross track error. More cross track error and more track angle error were observed (1) when the cause of breakout was wake, (2) at breakout locations above 500 ft as compared to breakout locations at or below 500 ft., and (3) when the ownship was the trailing aircraft. ANOVA summary statistics on the significant results from this analysis are listed in Tables 4 & 5.

	Mean (ft)	**SD (ft)**
Cause: F=10.37 df=1,7 p<0.05		
Aircraft Blunder	**73**	**79**
Wake	**103**	**102**
Location: F=48.09 df=1,7 p<0.001		
Breakout Location > 500 ft	**130**	**110**
Breakout Location ≤ 500 ft	**46**	**38**
Center/Trailing Aircraft: F=5.20 df=1,7 p=0.05		
Ownship Center	**73**	**91**
Ownship Trailing	**104**	**91**

Table 4. Significant Main Effects on Ownship Cross Track Error

The pilots flew the breakout trajectories with higher precision under the condition where aircraft deviation led to a breakout. It is possible that the uncertainties and unpredictable nature of aircraft deviations and a faster developing hazardous situation might have led the pilots to precisely follow the breakout trajectory generated by the automation.

The effect of breakout location may have occurred due to the perceived immediacy of the response at an altitude of below 500 ft, since airspace is highly congested close to major airports at lower altitudes, requiring increased vigilance of flight crews at this stage of approach. Lower approach altitudes introduce special concerns, with possible pilot errors creating an increased chance of dangerous consequences. Pilots are also keenly aware of other possible factors, such as low altitude wind shear, which could have the effect of complicating an already dangerous situation. Hence, perceived immediacy of the response, combined with increased vigilance, may have contributed to this effect. From an operational perspective, this may suggest that the pilot participants are inherently assessing the need for a very accurate response to a dangerous situation during flight times that may have other immediate and critical issues.

Also, the location effect may in part reflect breakout procedures, where the maneuver below 500 ft has an initial bank angle of 10 deg, which is fairly easy to execute with the side-stick control used in the ACFS, allowing the pilots to fly the breakout trajectory projected on the ND more accurately. Therefore, this result should be interpreted for its relativity to the other independent variables and as providing trend information.

	Mean (deg)	**SD (deg)**
Cause: F=10.50 df=1,7 p<0.05		
Aircraft Blunder	**2.28**	**1.62**
Wake	**2.87**	**2.59**
Location: F=58.75 df=1,7 p<0.001		
Breakout Location >500 ft	**3.65**	**2.46**
Breakout Location ≤ 500 ft	**1.50**	**1.08**
Center/Trailing Aircraft: F=10.09 df=1,7 p<0.05		
Ownship Center	**1.96**	**2.02**
Ownship Trailing	**3.20**	**2.16**

Table 5. Significant Main Effects on Ownship Track Angle Error

It seems likely that the effect of center/trailing ownship on track angle and cross track error is related to the perception that the center aircraft may be the most vulnerable to possible unsafe separation or wake, due to its dual proximity to both the leading and the trailing aircraft. Hence, it is speculated that a potentially dangerous situation requiring breakout might generate more psychological discomfort when in the center position, motivating a greater degree of vigilance in conducting the breakout maneuver. On the other hand, when the ownship is the trailing (right most) aircraft, the most immediate concern involves possible unsafe separation/wake with only one aircraft, causing less initial discomfort and vigilance required to escape the potentially dangerous situation.

Workload

Participants completed the NASA TLX workload questionnaire after every run. Data were collected on each of the six TLX workload measures, and a variable measuring overall workload combining all six of these measures was derived.

Data analysis comparing breakout vs. non-breakout runs on each of the workload measures was implemented. ANOVA results indicated that pilot workload was significantly higher in breakout runs as compared to non-breakout runs in 5 of the 7 workload measures, as well as the overall workload composite measure ($p<0.05$). This was expected, since breakout procedures require pilots to manually fly the ownship according to the breakout trajectory rather than monitor the displays in the normal approach procedures. Figure 6 shows the mean score of each of the 6 workload measures, as well as the overall composite score, broken down by run category (breakout / non-breakout).

Looking at the data collected from the breakout runs only, it was found that the pilots' overall workload was reasonably manageable with a mean composite score of 21.98 (sd = 5.83), where 6 indicates low workload and 42 indicates high workload. A significant main effect of breakout location was observed on this composite score (F=6.97; df=1,7; $p<0.05$), where the higher altitude breakout generated higher workload (mean=23.15, sd=6.13) than the lower altitude breakout (mean=20.79, sd=5.31). It seems likely that this effect is due to the differing breakout procedures, where the higher altitude breakout requires a bank angle maneuver of 30 degrees while the breakout at lower altitudes requiring only a 10 degree bank angle, making one maneuver more aggressive than the other. In addition to this main effect of breakout location, a significant interaction effect of breakout cause by center/trailing ownship on composite workload was also observed (F=11.07; df=1,7; $p<0.05$). Under the aircraft blunder condition, higher workload was observed when the ownship was the center aircraft, and under the wake condition, higher workload was observed when the ownship was the trailing aircraft. Figure 7 shows this interaction graphically.

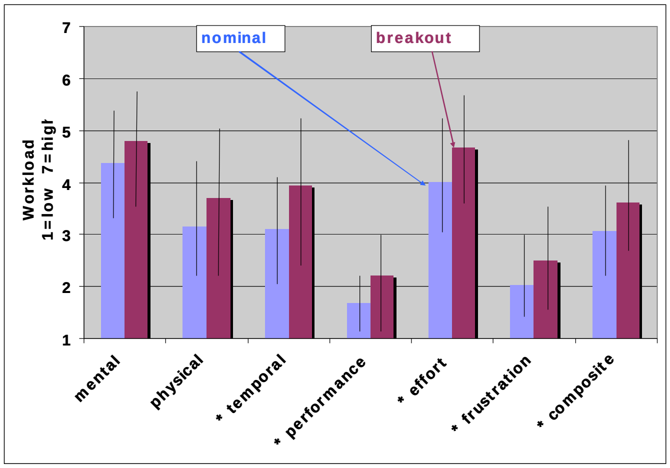

Figure 6. Effects of Breakout on Pilot Workload Measures (* indicates $p<0.05$; error bars represent ± 1 standard deviation; composite score on a scale of 1-7)

Again, since blundering aircraft have an unpredictable nature, it makes sense that the pilots of the center ownship would have more workload than pilots of the trailing ownship under the aircraft blunder condition, since the center ownship has two neighboring aircraft it needs to maintain safe separation with, and the trailing aircraft only needs to maintain separation with one. However, wake could seem to pose a greater concern with the trailing aircraft, since the trailing aircraft may perceive the need to avoid the wake generated by the two aircraft in front of it whereas the center aircraft needs to avoid the wake from the leader aircraft only.

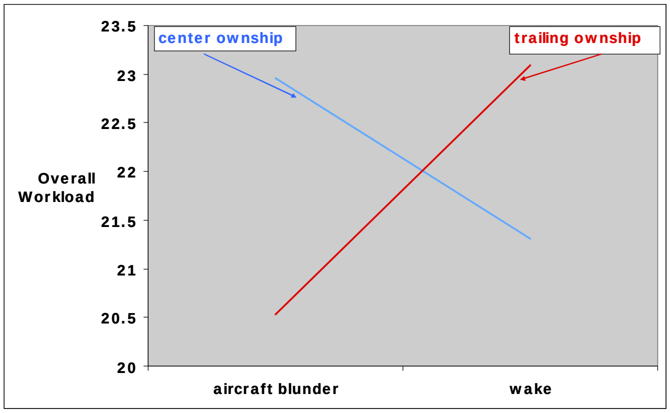

Figure 7. Significant Interaction Effect of Breakout Cause by Center/Trailing Ownship on Overall Pilot Workload

Situation Awareness

The SART scale, mentioned earlier, measures situation awareness on ten scales. Participants provided ratings on each of these ten scales after every simulation run. All collected SART data were then used to derive three broader categories [11] concerned with a) the demands of the situation b) the ‘supply’ or personal resources that the participants have to bring to the situation and c) situational provision that the situation provides in the form of information through displays. The first broad category combines the three SART scales - instability, variability and complexity of the situation, where the values can range from 3 to 21. The second broad category of personal resources combines the SART scales on alertness, spare mental capacity, concentration, and division of attention, where the resultant scores can range from 4 to 28. The third broad category, situation provision combines the three SART scales on information quantity, information quality, and familiarity, and the resultant value can range from 3 to 21.

Statistical analysis comparing nominal and breakout conditions on situation awareness of the pilot participants yielded a significant difference on the scale of situational demands (F=25.46, df=2,6, p<.01). The situation demands of the breakout runs were higher than the nominal runs. This result is consistent with the result of higher pilot workload levels in the off-nominal (i.e., breakout) condition, which correlate with higher levels of instability and variability, as compared to the nominal condition. This would be expected, since the off-nominal condition requires that pilots safely maneuver the aircraft by following the breakout trajectory, rather than implement normal approach procedures. Results on personal resources indicate almost no difference between nominal and breakout runs. This may be due to the anticipation of a breakout anytime, which required equal levels of alertness and concentration across nominal and breakout runs. Likewise, there was almost no difference between the nominal and breakout runs in situation provision, suggesting equal amounts of information quantity, information quality, and familiarity, providing some support for the efficacy of the TACEC concept. The means and standard deviations of the three situation awareness variables across both conditions are graphically depicted in Figure 8.

Further analyses of the SART data within the breakout condition revealed no meaningful significant effects. Hence, the pilots experienced similar levels of situation awareness irrespective of the cause of breakout, the location of the breakout, or center/trailing ownship. Finally, relative to the possible range of values for each of the three composite situation awareness measures, Figure 8 indicates high levels of personal resources and situation provision, with moderately low levels of situation demands, suggesting that situation awareness was maintained throughout the course of the current investigation, providing support for the TACEC concept.

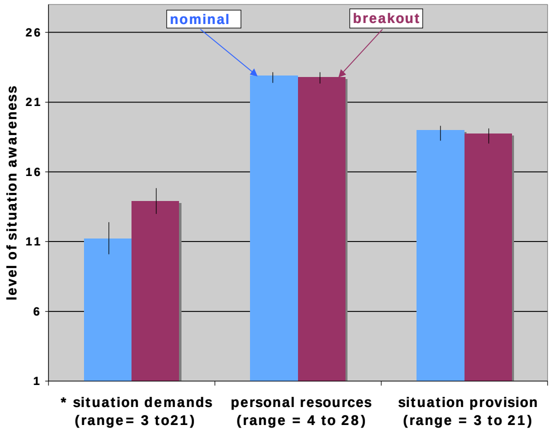

Figure 8. Effects of Breakout on Pilot Situation Awareness Measures (* indicates p<0.05; error bars represent ± 1 standard deviation)

IV. CONCLUSIONS

Triplet aircraft procedures were investigated in a high fidelity human-in-the-loop simulation incorporating new tools and technologies involving very closely spaced parallel runway operations. Scenarios included nominal and off-nominal cases. Statistically significant differences were observed. The results indicated that overall, pilots successfully “flew” the simulator through all of the study scenarios, both accurately and safely within and across all conditions.

An analysis of aircraft separation between leader/center aircraft and between center/trailing aircraft during breakout indicated zero instances of unsafe separation. During breakout, the minimum observed slant range between all aircraft across all conditions was 2437 ft., which is well above the FAA’s MPAP test criterion violation threshold of 500 ft separation between aircraft. Further analysis of aircraft separation during breakout indicated statistically significant differences of cause and location of breakout, as well as center vs. trailing ownship, suggesting that pilots may be more inclined to fully trust the automation to guide them along the breakout trajectory when confronted with an aircraft blunder, and separation may vary as a result of differences in breakout procedures at different altitudes, as well as the unique position of the ownship among the triplet aircraft. Analysis of cross track and track angle error indicated that overall, the breakout trajectory was flown quite accurately across all conditions.

The pilots experienced higher workload and situational demands placed on them during breakout as compared to the normal approach procedure. While realizing these differences, the results also indicate that workload was manageable, and an adequate level of situational awareness was maintained across all conditions. Overall, the data indicate that very closely spaced triplet parallel runway approach procedures can increase efficiency of flight operations, while maintaining an adequate level of safety. While more research is necessary, these results attest to the potential promise of the current concept under investigation.

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