Procedures for Off-Nominal Cases: Very Closely Spaced Parallel Runway Operations

Savita Verma,[1] Sandy Lozito,[1] Thomas Kozon,[2] Deborah Ballinger,[1] Herbert Resnick[3]

1 NASA Ames Research Center
2 NASA/ Raytheon Corporation
3 Raytheon Corporation

Abstract

This study investigated procedures to increase capacity in the terminal area using a high-fidelity flight deck simulator. The concept was developed to achieve visual meteorological condition capacities under instrument meteorological conditions when landing aircraft on runways 750 ft apart. The purpose was to investigate procedures related to breakout maneuvers on final approach during off-nominal conditions. Fifty percent of the simulation runs had an off-nominal situation. The off-nominal situation was either the wake of the lead aircraft drifting too close to the trailing aircraft or the lead aircraft deviating from its course and blundering towards the trailing aircraft. The location of the off-nominal situation was also a variable. Results showed that the workload and situational demands experienced by pilots were higher in the off-nominal as compared to the normal scenario. Pilots executed a breakout maneuver earlier for wake intrusion than for aircraft deviation. The location and cause of the off-nominal situation did not have a significant impact on workload or situation awareness. In general, the pilots flew the breakout maneuver accurately and safely. The results provide an assessment of the procedures for breakout maneuvers during off-nominal conditions.

Introduction

The NextGen air transportation system is being designed with the expectation that the volume of the traffic will double or triple by 2025 [1]. Many air transportation forecasts expect a significant growth for air travel demand. To meet this demand, parallel runways operations are a potential solution to increasing the throughput of an airport. Several airports like Chicago's O'Hare, Dallas Fort Worth and Denver International depend on parallel runways operations to meet growing demand. The FAA has successfully conducted independent approaches to parallel runways for over 40 years using the Instrument Landing System (ILS) navigation and terminal radar monitoring [2]. The simultaneous approaches that use standard radar are conducted on parallel runways that are at least 4300 ft apart. To conduct parallel approaches on runways that have 3000 ft spacing between them requires the use of Precision Radar Monitor (PRM) with an update of rate of 1.0 s. [2]

Some airports, like San Francisco International airport, can support approximately 60 landings per hour using both of the parallel runways that are 750 ft apart by using the Simultaneous Offset Instrument Approach (SOIA) [3]. SOIA approaches require the trailing aircraft in the paired approach to obtain a visual sighting of the lead aircraft, and at least a 2100 ft ceiling and 3 nm visibility. As weather degrades, the current navigation and surveillance systems, and existing procedures, do not provide the accuracy necessary to support SOIA approaches. This reduces the landing rate to half the Visual Flight Rules (VFR) capacity. In the SOIA procedures, air traffic control is responsible for pairing the aircraft, detecting any blunders and commanding breakout maneuvers, if required.

Independent simultaneous approaches, down to 2500 ft spacing, were examined by Airborne Information for Lateral Spacing. In that investigation autopilot-flown approaches with on-board warnings were provided to the pilot when a breakout needed to be performed due to an aircraft blunder [4].

To achieve significant capacity gains during both good and inclement conditions, runways closer than 2500 ft need to be explored. Building additional runways between current ones, or moving them closer, is a potential solution to meeting the increasing demand. The Raytheon Corporation, working with NASA developed the concept called Terminal Area Capacity Enhancing Concept (TACEC) [5]. The concept requires robust technologies and procedures that need to be

developed and evaluated such that operations are not compromised under instrument meteorological conditions. The reduction of runway spacing for independent simultaneous operations dramatically exacerbates the likelihood of wake vortex incursion and requires the calculation of a safe and proper breakout maneuver. The study presented here investigated procedures for breakout maneuvers due to off-nominal situations such as the blundering of the lead aircraft or its wake drifting towards the trailing aircraft. A real-time, human-in-the-loop simulation studied procedures using precision navigation, autopilot-flown approaches, with the pilot monitoring aircraft spacing and the wake vortex safe zone during the approach. There were aural and visual alerts provided to the pilots to manually perform the breakout maneuvers.

Background

To explore operations on runways closer than 3000 ft, NASA explored a new concept called Airborne Information Lateral Spacing (AILS). NASA developed the AILS concept to further examine independent parallel runway operations on runways as close as 2500 ft. The concept requires technologies that enable the use of precise navigation and surveillance data. Automation is presumed to detect blunders or situations that may require the aircraft to perform a break-out maneuver.

The AILS experiment was designed to study three variables- intruder geometry, runway separation (3400 ft or 2500 ft), and flight control mode (auto-pilot versus manual prior to the warning for breakout). The dependent variables were pilot reaction time and miss-distance in off-nominal situations that required the pilot to perform an escape maneuver. The study found that pilot reaction time to detect and perform break out maneuvers was not affected by runway separation. Across all conditions the average pilot reaction time was 1.11 s, with a standard deviation of 0.45 s. The experiment found a statistically significant effect for the flight control mode, with auto-pilot use prior to the emergency escape maneuver leading to longer reaction times.

TACEC would allow paired approaches on runways that are 750 ft apart in instrument meteorological conditions [5]. The concept includes a ground-based processor which identifies aircraft that could be paired approximately 30 minutes from the terminal airspace boundary. The aircraft are selected for pairing based on several parameters such as relative aircraft performance, arrival direction, and the size of aircraft's wake. The ground based processor then assigns 4-Dimensional (4D) trajectories to the aircraft in the pair. It is assumed that all aircraft will use differential GPS-enabled, high precision 4-D flight management system capabilities for the execution of these trajectories. Enhanced cockpit displays that depict both traffic and wake information will also be a requirement for these operations. The current study is different from the AILS experiment in that the algorithms and displays consider wake data, breakout maneuvers are dynamically generated, and the runways are only 750 ft apart.
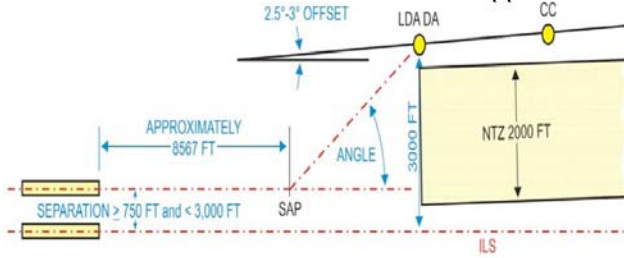
Breakout Maneuvers

The TACEC operational concept necessitates an understanding of unusual events where the approach path of one aircraft might intrude into the approach path of another aircraft. Although these events should be rare, such off-nominal events must be considered to insure the safety of the tools and procedures.

In the ILS/ PRM approaches earlier described, there are two approach controllers that monitor each runway. A non-transgression zone (NTZ) with a width of 2000 ft between the two parallel approach paths is defined. The PRM controller detects and initiates breakout when aircraft penetrates the NTZ ,and the pilots have to manually fly the breakout maneuver.

SOIA approaches have a similar procedure: the controllers monitor the SOIA flights using the PRM and other standard ATC equipment. Blunders are detected and breakout maneuvers are initiated by the controllers, similar to the ILS/PRM approaches. Breakout instructions that are provided by the ATC are usually long. It is interesting to note that an NTZ exists until the Missed Approach Point (MAP), and that the approach courses are separated by 3000 ft until that point. The trailing aircraft is always on the ILS offset. After exiting the Clear of Clouds (CC) point (shown in Figure 1), the trailing aircraft has about 25 s to obtain visual contact with the lead aircraft, before reaching the missed

approach point. If visual sighting is not obtained, then the aircraft has to execute a missed approach.


Figure 1   SOIA Approaches

The AILS experiment [4] also made provisions for breakout maneuvers. The on-board system detected potential conflicts between the lead and trailing aircraft. Separation responsibility was delegated to the flight crews. AILS defined the breakout maneuver as an Emergency Escape Maneuver (EEM). It required the aircraft to immediately climb and turn 45 deg away from the intruding aircraft. The navigation display showed an escape bug placed at 45 deg, but wake turbulence issues were addressed by existing separation standards.   The TACEC study examined breakout maneuvers that require a less extreme turn when compared to the AILS maneuvers.

This paper investigates breakout maneuvers for TACEC operations that propose very closely spaced parallel runways. The procedures are defined in the Experimental approach section and results describing the pilots' responses to the maneuvers are described in the Results and Discussion section.

Experimental Approach
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 runways that were set be 750 ft apart as shown in Figure 2. Because the simulation focused on TACEC approaches to very closely spaced parallel runways using south flow scenarios, only the west side runways (18R and 18L) were used. The outside runway was moved inward to create a 750 ft separation between the runways. Both the runways were assumed to be equipped to a CAT-IIIB level.
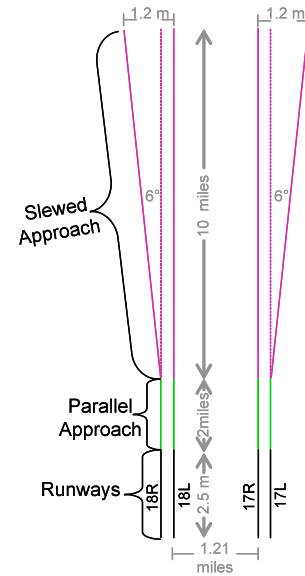
Figure 2 Final Approach geometry for TACEC

TACEC Procedures
The TACEC concept calls for TACEC-assigned 4D arrival trajectories for both aircraft to be paired at meter fixes located near the edge of the terminal airspace, normally 40-60 nmi from the airport [5]. 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 included.

The TACEC concept 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. Paired aircraft flew their assigned 4D trajectories with a high level of accuracy to meet timing constraints at the coupling point and ensure wake safety throughout the approach. A coupling point is defined at 12 nmi from the runway. From that point onward, the following aircraft precisely maintained spacing behind the lead aircraft to avoid wake using a speed control algorithm. The paths of the trailing aircraft were at a slewed angle when the aircraft was 25 nmi from threshold, then became parallel at about 2 nmi from the runway.

Onboard automation monitored the paired aircraft for potential conflicts. Automation also displayed predicted safe zone from the wake generated by the lead aircraft. Visual and aural

alerts are used to alert pilots to lead aircraft blunders or wake drifting towards the trailing aircraft. The navigation display depicted the breakout trajectory after crossing the coupling point. This breakout trajectory was dynamically generated considering wake, traffic, buildings and terrain of the airport surroundings. The locations of the breakout on the arrival path require different breakout maneuvers, which change the angle of the escape trajectory on the navigation displays. The pilots flew the breakout trajectory manually using the flight director when they received an aural and visual alert.

Displays

The displays were similar to displays used for the preliminary study of very closely spaced parallel approaches [9] and were based on previous research associated with flight deck displays [6] [7]. The Navigation Display (ND) and Primary Flight Display (PFD) are shown in Figure 3 and 4. The displays show both wake and trajectory information as well as standard flight instrument data.

After crossing the coupling point, and the pilot's prior acceptance of the coupling, the flight mode annunciation changes to show that the two aircraft are coupled for speed (C-SPD), coupled for lateral navigation (C-LNAV) and coupled for vertical navigation (C-VNAV). Since 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 lead aircraft drifted within one wingspan of the trailing aircraft, the color of the wake 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 outline of the lead aircraft symbol turned yellow, and then red when the lead aircraft deviated by at least 120 ft. The red warnings require a mandatory breakout, which the pilots flew manually. Once the pilots pressed the TOGA switch, the breakout trajectory, which had been displayed to the pilot in white, became the active route, and was then displayed in magenta.
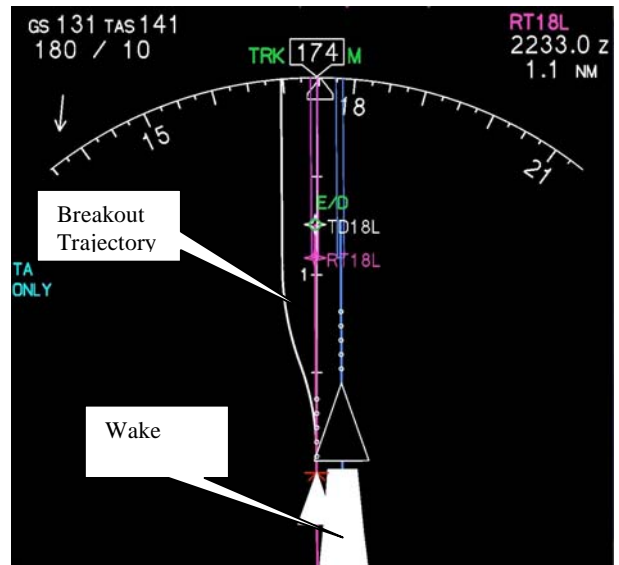

Figure 3: Navigation Display during final approach

Figure 4: Primary Flight Display

Advanced Concept Flight Simulator (ACFS)

The human-in-the-loop experiment studied breakout maneuvers for paired TACEC approaches in the Advanced Cockpit 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.

Variables

Three variables were examined in this study to examine the TACEC concept. First was the presence or absence of an off-nominal situation that may warrant a breakout maneuver. The second variable was the cause of the breakout maneuver – wind causing the wake of the lead aircraft to drift towards the trailing aircraft, or the lead aircraft deviating from its original path and towards the trailing aircraft. The third variable being studied was the location of the off-nominal situation, which was above 500 ft, or between 200 ft – 500 ft above the ground. A total of 16 runs were performed in which 8 were normal and rest had off-nominal situations. In the runs that required a breakout maneuver, repeated runs were made for each cause of the breakout and location of the off-nominal situation.

Hypothesis

In the absence of previous research, the researchers predicted that the location of the off-nominal situation or the nature of the off-nominal situation would not affect pilots' behavior on the following parameters. Any differences observed will guide the formalization of procedures.

- Early breakouts
- Breakout response time
- Separation from lead at breakout point
- Accuracy of flying trajectory
- Workload
- Situation awareness

However, it is expected that there will 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.

Participants

The participants were nine 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.

Experimental Procedure

The study ran for nine 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 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 wake. At 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 were coupled with the leader's speed, and continued to monitor the separation between the two 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 had to perform a breakout maneuver.

To fly the breakout maneuver, the pilot had to press the Take-Off-Go-Around (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, The breakout performed above 500 ft altitude required an initial bank angle of 30 deg, and the breakout at altitude between 200-500ft required an initial bank angle of 10-deg. The pilots then followed the 'S' shaped breakout trajectory displayed on the ND.

Traffic Scenario

The traffic scenario had two aircraft: (1) The following aircraft in the pair, as represented by the ACFS, and (2) A Boeing 747-400, which was prerecorded and scripted for this study. The pilot who flew the ACFS simulator always landed on 18L. The recorded/scripted aircraft was the leader aircraft that always landed on 18R in the closely spaced parallel runway approach.

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 [10] after each simulation run but did not complete the pair-wise scale comparison that is part of the measure, so the six scales were analyzed separately.

Pilots also completed the Situation Awareness Rating Tool (SART) [8]. 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 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.

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) open-ended feedback provided by the pilot participants at the end of the simulation runs. Inferential statistical analysis techniques such as repeated measures Analysis of Variance (ANOVA) and binary logistic regression were employed to address the primary research questions of interest, and descriptive statistics were also reported to augment the results.

Early Breakout Assessment

During the course of the breakout runs, the traffic symbol color (aircraft deviation condition) or the traffic wake color (wake condition) would transition from white (nominal) to amber (warning), to red (breakout required). Under these conditions, the pilot participant's initiation of breakout should occur only when the color on the display transitions to red. However, it was noted that pilot participants would sometimes initiate a breakout when the traffic display transitioned to amber, resulting in a somewhat less than optimal breakout maneuver.

A binary logistic regression analysis was implemented to assess potential differences across the study conditions, on the incidents of early breakout across the study conditions. The regression model included both levels of each of the independent variables as covariates, and the Wald statistic was computed to assess the significance of the model. Cause of breakout (aircraft deviation vs. wake) was found to be significant in the model (Wald = 4.459, df=1, $p< 0.05$) whereas location of breakout was not. Thus the hypothesis that there would be no difference in early breakouts due to the cause of breakout was not upheld, whereas location of breakout was upheld. Frequencies and percentages of early breakout response incidents are listed in Table 1.

Location --->	Above 500 ft	200-500 ft	Total
Early Breakout	AC Deviation	2 (11.1 %)	3 (16.7 %)	5 (27.8 %)
	Wake	7 (38.9 %)	6 (33.3 %)	13 (72.2 %)
	Total	9 (50.0 %)	9 (50.0 %)	18 (100 %)
Correct Breakout	AC Deviation	16 (29.6 %)	15 (27.8 %)	31 (57.4 %)
	Wake	11 (20.4 %)	12 (22.2 %)	23 (42.6 %)
	Total	27 (50.0 %)	27 (50.0 %)	54 (100 %)

Table 1: Frequencies and Percentages of Early Breakout by Location and Cause

As indicated in Table 1, 72.2% of the early breakout cases were observed in the wake condition, as compared to 27.8% cases in the aircraft deviation condition, suggesting that the salience of the wake situation might inspire a greater sense of immediacy to maneuver away from the cause of potential danger, even prior to the required breakout response. This may have occurred for a number of reasons. Wake behavior is relatively hard to predict, so the uncertainty of its characteristics may lead to more caution on the part of the pilot, even though the pilots were told that the predicted wake danger area displayed was calculated conservatively. Also, the wake display is large relative to the traffic symbol display. That is, the wake display shows the physical size of the nearby wake vortex, which tends to expand as the lead aircraft moves closer to the ownship. The traffic symbol display, on the other hand, changes color (as does the wake display), but remains static in size. It may be possible that the increased frequency of early breakout response under the wake condition may have occurred as a result of the relative "largeness" of the display, which on some level, might have signaled a situation that was perceived as more critical than it was, leading to a premature response. This may reflect a need for some adaptation of the displays to minimize this effect.

Breakout Response Time

Breakout response is defined as the difference between the time at which the wake or traffic symbol display transitions to the color red, which is the same time an aural alert occurs on the flight deck, and the time when the pilot initiates the breakout response. A two-way repeated measures ANOVA was used to test the hypothesis that there will be no significant main effects or interactions on the dependent variable of breakout response, with cause of breakout and location of breakout as the two independent variables. A significant main effect of breakout location was observed ($F=4.86$; $df=1,8$, $p \leq .05$), with breakouts occurring above 500 ft AGL showing a larger (i.e., slower) response time than breakouts occurring below 500 ft. No other significant effects were yielded from this analysis. Means and standard deviations associated with the significant main effect are shown in Table 2.

A breakout response time of less than 2s should be interpreted with caution. It is unusually low compared to what would be anticipated in the real world, where the novelty and non-expectancy of the situation might make it impossible to act this quickly. In the study the pilots expected an off-nominal situation and were ready to breakout, in some cases they even performed early breakouts, which explains the unusually low breakout response time. In actual operations, these off-nominal events should be rare, and the pilots would likely need more time due to their infrequency and unexpectedness. Thus, these times should be viewed as providing trend and relative information only.

$F=4.86, df=1,8, p=0.05$	Mean (sec)	SD (sec)
Breakout Location > 500 FT	1.42	1.20
Breakout Location $\leq$ 500 FT	0.84	0.38

Table 2. Significant Main Effect of Breakout Location on Blunder Response Time

The null hypothesis that there would be no difference in breakout response time due to the cause of breakout was upheld, but it was not upheld for the location of breakout. This effect may have

occurred as a result of the perceived immediacy of the response at an altitude of less than 500 ft, since airspace is highly congested close to major airports at lower altitudes, coupled with the proximity to the ground and the terminals requiring increased vigilance of flight crews at this stage of approach. Breakouts at lower altitudes introduce special concerns, because pilot errors carry an increased risk 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, the perceived immediacy of the response, combined with increased vigilance, may have contributed to the faster breakout response time. Operationally, this may suggest that the pilot participants are inherently and correctly assessing the need for a faster response to a dangerous situation, during flight times that may have other immediate and critical issues

Separation from Lead at Breakout Point

The dependent measure of aircraft separation at breakout is defined as slant range, or straight-line distance, between the leading aircraft causing the breakout and the ownship. Again, the effects of the two independent variables of breakout cause and breakout location on the dependent measure were tested in this analysis. A significant main effect of breakout cause on the dependent measure was observed ($F=37.21$, $df=1,8$, $p< 0.001$), with greater aircraft separation under the wake condition than under the aircraft deviation condition. No other significant main or interaction effects were observed from this analysis. The hypothesis that there would be no differences for cause of breakout was not upheld, but it was upheld for the location of breakout. Means and standard deviations describing the details of the significant main effect are listed in Table 3.

As a check on the reasonableness of the results reported in Table 3, a Kruskal-Wallis one-way ANOVA by ranks was implemented on the aircraft separation data, due to a possible violation of the variance homogeneity assumption. Consistent with results shown in Table 3, a significant main effect of breakout cause on aircraft slant range at breakout was observed (Kruskal-Wallis Test Statistic = 47.52, $df=1$, $p<0.0001$).

F=37.21 df=1,8 p<0.001	Mean (ft)	Standard Deviation
Aircraft Deviation	2820.45	174.48
Wake	2994.54	14.83

Table 3. Significant Main Effect for Cause of Breakout on Aircraft Separation

Again, it seems that the off-nominal situation caused by wake has special characteristics that might help to explain a greater degree of aircraft separation at breakout time. The pilots during the group discussion mentioned that the uncertainty regarding wake characteristics prompted them to make responses more quickly. Operational considerations might include adapting the aircraft deviation and wake displays to account for differences in which pilots react to the onset of situations that might evolve into blunders (e.g., premature maneuvering, possible lack of vigilance in the case of inadequate display format, etc.)

Accuracy of 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 ND 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 was averaged across time from the breakout point to the end of the flight. A two-way repeated measures ANOVA yielded a main effect of breakout location on each of the two dependent measures. Both of these results are consistent with respect to the directionality of the means. More cross track error and more track angle error were observed at breakout locations above 500 ft as compared to breakout locations at or below 500 ft. No other main or interaction effects were observed. ANOVA summary statistics on the significant results from this analysis are listed in Tables 4 & 5.

F=45.08 df=1,8 p<0.001	Mean (ft)	SD (ft)
Breakout Location > 500 ft	73.08	25.23
Breakout Loaction ≤ 500 ft	39.43	27.42

Table 4. Significant Main Effect of Breakout Location on Ownship Cross Track Error

| F=157.58 df=1,8 p<0.0001	Mean (deg)	SD (deg)
Breakout Location > 500 ft	3.41	0.95
Breakout Location ≤ 500 ft	1.42	0.74

Table 5. Significant Main Effect of Breakout Location on Ownship Track Angle Error

Also, 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. Most pilots complained about the stick shift, but did like the 10-deg bank angle at the lower altitude, since it allowed them to fly the breakout trajectory projected on the ND more accurately. Thus the cross track error and track angle error shown in the Tables 4 and 5 should be interpreted for its relativity to the different independent variables and as providing trend information.

Workload

Participants completed the NASA TLX workload questionnaire after every run. In general the pilot's workload was quite manageable and was below average. A statistically significant difference was observed between the breakout condition and the nominal condition for the dependent variable of overall workload (F=6.17, df = 1,8, p<=.05), with higher workload experienced in the breakout runs as compared to normal runs. Further analyses depicted significant differences between the normal and breakout conditions on the sub elements of workload such as effort (F=10.81 ; df=1,8 ; p<0.05) and frustration (F=7.16, df=1,8,p<0.05). Marginally significant differences were also observed on mental demand (F= 4.77, df=1,8, p=0.06), and

temporal demand (F=4.53, df=1,8, p=0.06). Means and standard deviations of all workload sub-scale assessments, comparing nominal vs. breakout conditions, are graphically depicted in Figure 5.
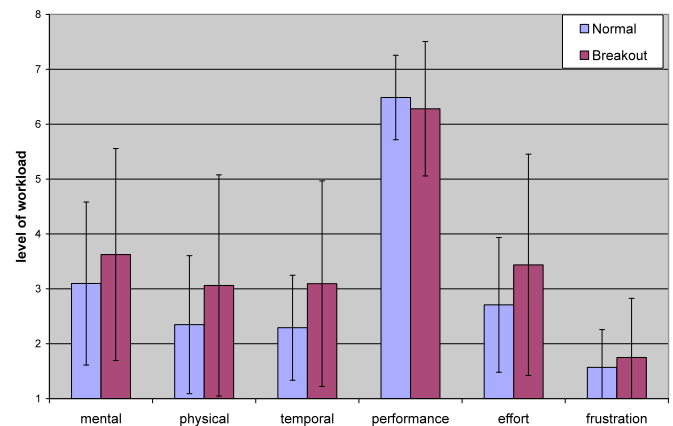
Figure 5. Effects of Breakout on Pilot Workload Measures (error bars represent ± 1 standard deviation)

Analysis of workload assessment within the breakout condition was also done. There were no significant differences in the workload experienced by the pilots as a result of location or cause of breakout.

Situation Awareness

Participants rated the ten SART scales after every simulation run. Each scale has seven points, where 1 represents 'little' or 'no' and 7 represents 'a lot' or 'very.' These ten scales were combined to three broader categories concerned with the a) demands of the situation b) the 'supply' or personal resources that the participants has 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 normal and breakout conditions on situation awareness of the pilot participants yielded a significant difference on the subscale of situational demands ($F=15.42$, $df=1,8$, $p<.01$). Also higher pilot workload levels were experienced in the off-nominal (i.e., breakout) condition, which correlate with higher levels of instability, variability, and complexity, 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. Less striking differences were observed between the nominal and breakout runs on the other two situation awareness variables of personal resources and situation provision. This may be due to the anticipation of a breakout anytime, which required equal levels of alertness and concentration. It is interesting to note that between the nominal and breakout scenarios the pilots experienced equally high levels of information quantity, and quality, and familiarity. The means and standard deviations of the three situation awareness variables across both conditions are graphically depicted in Figure 6.
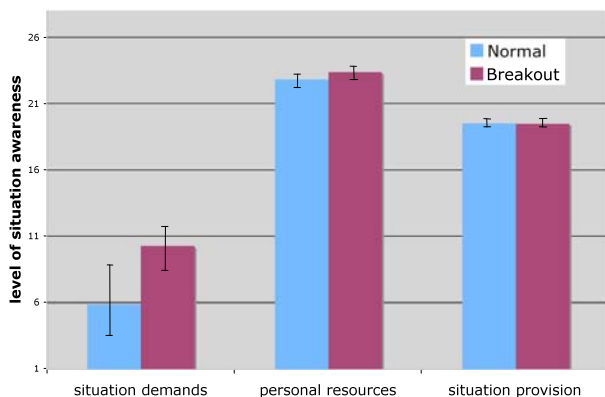
Figure 6. Effects of Breakout on Pilot Situation Awareness Measures

(error bars represent ± 1 standard deviation)

Further analyses of the SART data within the breakout condition revealed no significant difference as a result of the location or the cause of the off-nominal situation. The pilots experienced similar levels of situation awareness irrespective of the cause of the breakout (wake or aircraft deviation) or the location of the breakout.

Summary

The TACEC procedures were investigated in a human-in-the-loop simulation incorporating new tools and technologies. Scenarios included nominal and off-nominal cases. Statistically significant differences were observed in this current investigation using the analyzed digital data collection variables and some of the subjective variables. However, it is also interesting, and reassuring to note that the pilot participants successfully "flew" the simulator through all of the study scenarios, both accurately and safely within and across all conditions.

While early breakouts are not entirely consistent with the concept, the breakout maneuvers were successfully "flown," and safety was not compromised when they did occur. Wake, possibly due to its salience in the displays did cause more early breakouts than the blundering of the lead aircraft. During group discussion, pilots indicated that the warnings associated with aircraft blundering were not clear and visible.

The overall breakout aircraft slant range separation mean was over 2500 ft and the breakout trajectory was also quite accurately flown across all conditions. The location of the off-nominal situation did impact the slant range between the lead and trailing aircraft, and also the accuracy with which the breakout trajectory was flown. The pilots in general preferred the initial 10 deg bank angle they flew on breakout trajectories initiated between 200 ft and 500 ft and provided feedback that it was easier to fly than the more aggressive 30- deg initial bank angle used for breakouts at higher altitudes. The pilots also provided the feedback that the ability to see the trajectory on the ND aided them in flying the trajectory accurately.

The pilots experienced higher workload and situational demands placed on them during breakout as compared to the normal landings. 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 provide support for the contention that very closely spaced parallel runway approach procedures, when implemented wisely, can increase efficiency of flight operations, while

maintaining an adequate level of safety. Hence, the results attest to the potential promise of the current concept under investigation.

References

[1] Joint Development and Planning Office, 2004, The Next Generation Air Transport System Integrated National Plan, JPDO Report.

[2] Massimini, V.S., 2006, Simultaneous Independent and Dependent Parallel Instrument Approaches. Assumptions, Analysis, and Rationale, Mitre Report MP 06W0000127.

[3] Magyratis, S., Kopardekar, P., Sacco, N., & Carmen, K.,2001, Simultaneous Offset Instrument Approaches – Newark International Airport: An Airport Feasibility Study, DOT/FAA/CT-TN02/01.

[4] Abbott, T. S., & Elliot, D. M., 2001, Simulator Evaluation of Airborne Information for Lateral Spacing (AILS) Concept, NASA/TP-2001-210665.

[5] Miller, M.E., Dougherty, S., Stella, J., & Reddy, P.,2005, CNS Requirements for Precision Flight in Advanced Terminal Airspace, Aerospace, 2005 IEEE Conference, pp. 1-10.

[6] Hardy, G. H., & Lewis, E. K., 2004, A Cockpit Display of Traffic Information for Closely Spaced Parallel Approaches, AIAA-2004-5106, AIAA Guidance, Navigation, and Control Conference and Exhibit, Providence, RI4.

[7] Rossow, V. J., Hardy, G. H., and Meyn, L. A., 2005, Models of Wake-Vortex Spreading Mechanisms and Their Estimated Uncertainties, AIAA-2005-7353, ATIO Forum, Arlington, VA.

[8] Durso, F. T., Hackworth, C. A., Truitt, T. R., Crutchfield, J., Nikolic, D., & Manning, C.A.,1998, Situation Awareness as a Predictor of Performance for En Route Air Traffic Controllers, Air Traffic Control Quarterly, 6(1), pp. 1-20.

[9] Verma, S. A., Lozito, S., & Trot, G.,2008, Preliminary Guidelines on Flight Deck Procedures for Very Closely Spaced Parallel Approaches, International Council of Aeronautical Sciences, Anchorage, Alaska.

[10] Hart, S., & Staveland, L.,1988, Development of a Multi-Dimensional Workload Rating Scale: Results of Empirical and Theoretical Research, In P. Hancock & N. Meshkati (Eds.), Human Mental Workload, Amsterdam, The Netherlands, Elsevier, pp. 139-183.

Email Addresses

Savita.A.Verma@nasa.gov

Sandra.C.Lozito@nasa.gov

Thomas.E.Kozon@nasa.gov

Deborah.Ballinger@nasa.gov

Herbert_L_Resnick@raytheon.com

27th Digital Avionics Systems Conference
October 26-30, 2008