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Improving Aircraft Sequencing and Separation at a Small Aircraft Transportation System Airport

Kyle Helbing,* Theresa Spaeth,† and John Valasek‡
Texas A&M University, College Station, Texas 77843-3141

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Expanding services to some of the 4900 airports not currently served by scheduled air carriers can potentially ease traffic congestion and reduce flight delays at major airports. By developing new avionics and procedures for approach and landing during instrument meteorological conditions, the NASA small aircraft transportation system program demonstrated higher traffic volume general aviation operations at noncontrolled airports, without assistance from air traffic control. This paper proposes revised minimum separations and automated sequencing to help general aviation pilots maintain self-separation and make proper approach timing decisions in a self-controlled airport environment. Total holding time is the measure of merit, and evaluation was conducted with multiple pilots flying simultaneously in a real-time distributed simulation environment. A rudimentary human factors analysis was also conducted to determine the benefits of shifting some spacing functions from the pilot to the onboard systems, for the purpose of reduction in pilot workload. The effect of increased automation on pilot tracking performance was also measured. Results presented in the paper show that the proposed modifications can provide significant reductions in total holding time, thereby avoiding potential bottlenecks and improving efficiency. Reduction in pilot workload was observed, and low-time pilots exhibited improved tracking performance.

Nomenclature

D	=	distance remaining in approach, n miles
HT	=	individual aircraft holding time
V	=	airspeed, kn

Subscripts

i	=	index representing aircraft number
L	=	lead aircraft

I. Introduction

As globalization of business has been increasing at a rapid pace, so also has the need for communication between people in different locations. The internet and teleconferencing have served to fulfill this need in many cases; however, the need for people to use air travel has also increased. This increased traffic is already stretching the capacity of the current air traffic system and causing numerous delays. These delays cost U.S. airlines billions of dollars per year [1] in addition to the lost productivity of business travelers waiting in airports. One of the reasons for the delays is the hub-and-spoke system used by many major airlines [2]. In this system, a large percentage of air travelers must pass through a small number of airports. This system has shown that it is inadequate to handle the current traffic load, and delays will only worsen as the number of air travelers increases. These delays, coupled with time spent passing through security and travel time to and from the airport have made many regional trips faster by ground transportation than by air.

In order for air transportation to still be a viable option, system capacity must be increased. One way to accomplish this is to increase the number of landing facilities. Building many new airports creates both economic and space issues and is not a realistic solution. Fortunately, there are about 5400 public-use airports in the United States, of which approximately 500 are served by scheduled air carriers [2]. This means there are over 4900 airports that already exist that could be used to alleviate congestion. Dayjet, a new regional carrier, intends to make use of these airports by offering on-demand service in the new Eclipse 500.§ As more operators such as Dayjet emerge, large numbers of travelers will have the opportunity to shift from the major hubs to the smaller airports. To get the aircraft to these alternate airports that are in many cases closer to the traveler's actual destination, the broad concept of "free flight" will be utilized. Free flight has been described as providing pilots the flexibility offered by operating under visual flight rules while maintaining the level of protection provided by instrument flight rules operations [3]. Once the aircraft are in the vicinity of the airport, equipment and procedures must be in place to guide the increasing number of aircraft safely to landing because many of the smaller airports lack a control tower. Much work has already been done to address this problem by a NASA-led, nationwide project called the small aircraft transportation system (SATS) [4].

In the SATS high volume operations (HVO) program, the goal is to allow multiple aircraft to operate in the area around a nontowered airport called the self-controlled area (SCA) [5]. This is accomplished by having the aircraft hold in stacks at two initial approach fixes (IAFs), as shown in Fig. 1. However, in this area, due to the lack of radar and a control tower, the responsibility for aircraft separation will lie with the pilots [6]. If the aircraft is being operated in instrument meteorological conditions (IMC), the pilot will not be able to maintain separation visually. The technology that will allow these operations is data-linking [7]. Technology such as automatic dependent surveillance-broadcast (ADS-B), which broadcasts an aircraft's state vector and other information [8], along with

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*Undergraduate Research Assistant, Flight Simulation Laboratory, Aerospace Engineering Department, 3141 TAMU, College Station, TX 77843-3141; currently Engineer, 747 Stability and Control, Boeing Commercial Airplane Company, Seattle, WA; khelbing@tamu.edu. Member AIAA.

†Graduate Research Assistant, Flight Simulation Laboratory, Aerospace Engineering Department, 3141 TAMU, College Station, TX 77843-3141; thspaeth@tamu.edu. Student Member AIAA.

‡Associate Professor and Director, Flight Simulation Laboratory, Aerospace Engineering Department, 3141 TAMU, College Station, TX 77843-3141; valasek@tamu.edu. Associate Fellow AIAA.

§Data available on-line at http://www.dayjet.com/News/pressreleases/SATSPanelfinal060905.pdf [cited June 2005].

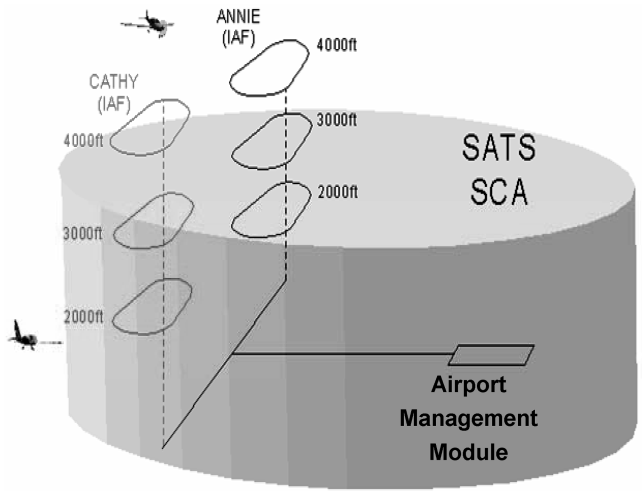

Fig. 1 Holding stack for two initial approach fixes.

negotiation with ground equipment [9] will allow the pilot to maintain separation without seeing the other aircraft. Large amounts of raw data, however, are useless to a pilot when they are also responsible for controlling the aircraft. Through work already in progress on the SATS project, ground sequencing modules and avionics to display aircraft positions are currently being developed.

The research presented in this paper is an extension of current research being performed for the NASA SATS program, and focuses on two specific areas: 1) improving the sequencing and spacing of aircraft of different speeds to make the airspace more efficient, saving time, fuel, and money, and 2) assisting the pilot with approach timing decisions to assure safe aircraft spacing while proceeding in an efficient manner. Rules and techniques for improving efficiency are presented, along with resulting time savings and potential safety improvements due to improved pilot tracking performance. The primary evaluation method is real-time distributed simulation with test cases performed by multiple pilots flying simultaneously in the simulation environment. A rudimentary human factors analysis is concurrently performed to assess the improved procedures.

The paper is organized as follows. SATS sequencing and the current logic are introduced, how a typical SATS SCA scenario is flown, and the proposed separation minimums rules. Next the SATS approach initiation is discussed, including current procedures and avionics assisted procedures for automated spacing. Human factors considerations and methodology are presented next, followed by a description of the real-time flight simulation facility used for conducting the tests. Numerical examples and results are then presented, followed by conclusions and recommendations for extending the work and results.

II. SATS Aircraft Sequencing

A. Current Airport Management Module Logic

In order for high volumes of aircraft to use the same airport, there must be a set procedure for determining the landing sequence of approaching aircraft. In the current version of the SATS airport, a ground-based system called an airport management module (AMM) is responsible for sequencing arriving aircraft. In the current system, when an aircraft is within 5 n miles plus 5 min of the left holding fix (LHF) or right holding fix (RHF) shown in Fig. 2, the pilot is expected to send a landing request to the AMM. If there is not an aircraft already at or assigned the fix and the aircraft is on the appropriate side of the airport, the AMM will grant the requesting aircraft a lateral entry [4]. A lateral entry means the approaching aircraft can descend to 2000 ft above the airport elevation while outside the SCA airspace (defined by the large circle in Fig. 2). The aircraft can then proceed to the assigned IAF, either the LHF or RHF.

The more common scenario is that the AMM will reply with a "standby" notification meaning the aircraft must perform a standard entry. A standard entry is given if there are aircraft already holding at

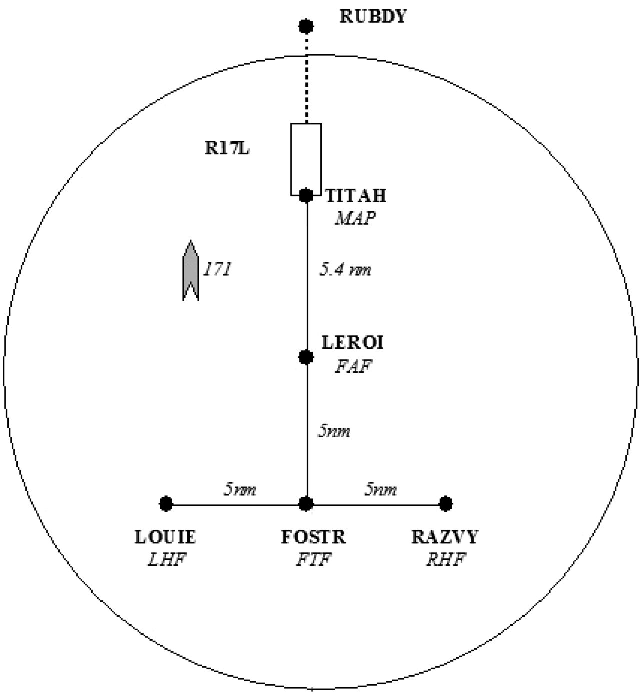

Fig. 2 SATS airport self-controlled area layout and approach fixes.

or assigned to the IAF or if the requesting aircraft would be required to pass over any part of the approach to get to the IAF. In the standard entry, the pilot will request ATC clearance to hold at the IAF at the lowest available altitude outside the SCA. Because the altitudes of 2000 and 3000 ft above the airport are within the SCA, 4000 ft would be the lowest possible altitude if another aircraft is not occupying it. Once the pilot is holding at the IAF and a spot opens within the SCA at that IAF, the AMM will send a notification to tell the pilot to enter the airspace and which aircraft to follow. The pilot then checks his avionics to make sure the 3000 ft altitude is clear and makes a request to ATC to descend into the SCA.

B. Proposed Sequencing Rule

In testing, it has been found that the current procedure does a good job of sequencing aircraft in most cases, but there are some exceptions. Consider a typical scenario consisting of a Piper Cub (Cub), Rockwell Commander 700 (C700), Mooney 201 (Mooney), and Cessna 172 (C172). These aircraft were chosen because their operation speeds represent a large range of aircraft with the higher speeds similar to those of the small jets likely to use the SATS system. The Cub requested landing from the AMM a little early (as could be expected with human operators) and before the C700 so it was given a lateral entry to the LHF. The C700 was then given a standby message and had to hold above the SCA because the Cub had been given the lateral entry. This was inefficient because the C700 arrived at the LHF approximately 5 minutes before the Cub and had to wait for its arrival and subsequent approach before it could begin its approach. To try to remedy this inefficiency, a new sequencing rule is proposed. Instead of giving lateral entries to the first aircraft to contact the AMM, the AMM would accept requests but wait to issue a lateral entry until an aircraft was within 5 n miles, at which point the aircraft would receive the lateral entry and therefore be the first one to make the approach from that IAF.

To measure the effectiveness of the proposed sequencing rule, a metric or measure of merit was created called total holding time (THT). The holding time for one aircraft is the time from when it arrives at the IAF until it can begin its approach. The THT is thus the sum of the holding times for all aircraft in the simulation and is given by Eq. (1). When a scenario with the same aircraft and initial conditions is repeated with different sequencing and/or spacing rules, the THT indicates the time saved and value of the rule change.

$$\text{Total Holding Time} = \sum_{i=1}^{N} \text{HT}_i \tag{1}$$

III. Approach Initiation

Once the aircraft is holding in the SCA, it must wait until the aircraft it is assigned to follow is sufficiently ahead of the following aircraft before it begins its approach. What constitutes safe separation must be defined as well as a procedure to maintain that separation. The instrument approach used in all of the evaluations conducted in the present work is a global positioning system (GPS) T-style approach using the fixes in Fig. 2. It is shown on a Jeppesen® style approach plate in Fig. 3.

A. Current Approach Initiation Procedure

The goal of SATS is to maintain 5 n miles of separation between aircraft on the approach. This is easy if the preceding aircraft is faster than the following aircraft. The following aircraft simply begins its approach when the preceding aircraft reaches the final turning fix (FTF) shown in Fig. 2. However, this procedure becomes much more difficult if the following aircraft is faster than the aircraft being followed. If the approach is initiated with the spacing of 5 n miles, the gap will quickly deteriorate and with large enough speed differences, the faster aircraft will overtake the slower one, possibly resulting in a midair collision. The pilot must therefore make an approximation and determine how much spacing should be obtained before beginning the approach to ensure separation all the way to the runway. In practice, the aircraft would not begin the approach until the preceding aircraft had reached the final approach fix (FAF) shown in Fig. 2. This allowed 10 n miles of spacing, which was effective in maintaining separation, but also resulted in excessive spacing and wasted time in many cases.

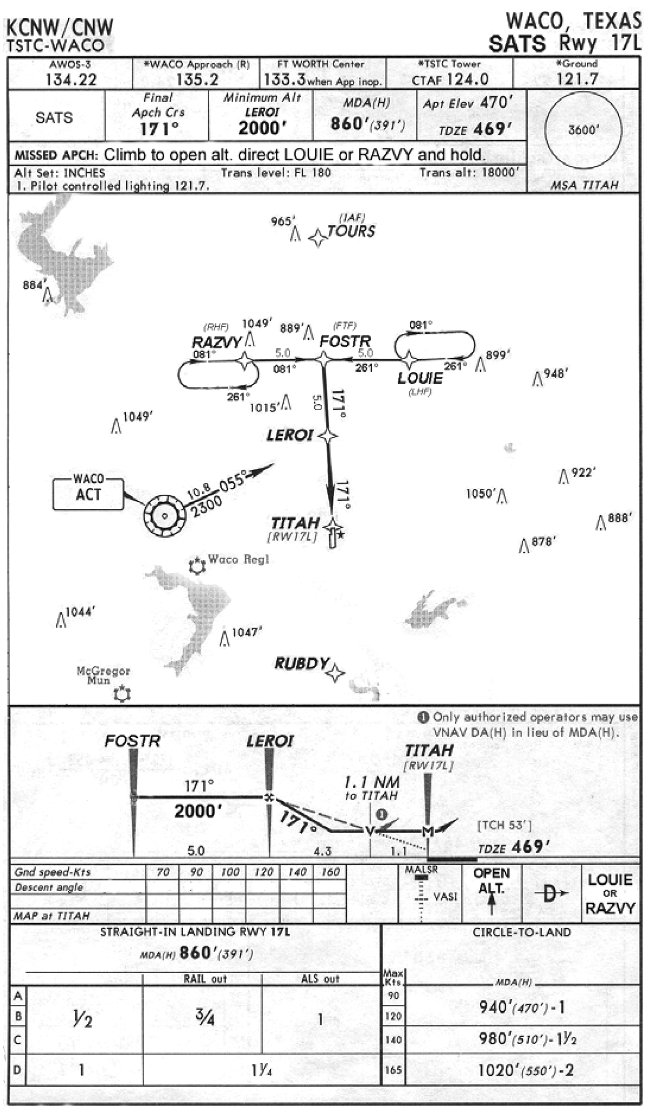

Fig. 3 Approach plate for SATS evaluation airport.

B. Avionics-Assisted Approach Initiation

To improve the efficiency of approach initiation, two things had to happen. First, the responsibility for making the calculations of how much initial spacing was required to ensure spacing throughout the approach needed to be shifted from the pilot to the avionics. Second, with the improved accuracy of the computer-calculated spacing, spacing minimums could be redefined to improve efficiency. The new spacing minimums will be discussed first as they are integral to the computer calculations.

1. *Redefining Spacing Minimums*

The use of 5 n miles as the spacing criterion is very conservative for the in-flight portion of the approach yet does not address aircraft needing time to decelerate and turn off the runway after landing. For this reason two criteria were implemented. First, the 5-n mile spacing was reduced to 2 n miles for all times the aircraft are in the air. Second, the restriction that arrivals at the runway need to be spaced by at least 2 min was added to ensure that the first aircraft has time to decelerate and turn off the runway before the next aircraft arrives. The second rule was added to facilitate the reduction of the in air spacing minimum without creating a hazardous situation at the runway.

2. *Shifting Calculation Responsibility to the Avionics*

Even with the simple original 5-n mile spacing rule, it can be very difficult for the pilot to accurately determine the initial spacing needed to maintain spacing throughout the approach. With the new rules, it would be nearly impossible from a human factors standpoint to expect the pilot to be making the calculations while controlling the aircraft. By using aircraft speeds given in an ADS-B message or deriving speed from position reports, the avionics can easily determine when it is safe for an aircraft to begin its approach and satisfy the spacing minimums throughout the approach. The pilot can then be notified that it is safe to begin the approach. Equations (2–4) represent the conditions that must be satisfied for the avionics to give the pilot a notification to begin the approach. Equation (2) is the constraint that 2 n miles of spacing currently exists, and Eq. (3) represents 2 n miles of spacing when the lead aircraft arrives at the runway. Equation (4) satisfies the 2 min of spacing at arrival. It should be noted that the number 15 in the equations represents the distance from the IAF to the runway along the approach path. This is the distance remaining in the approach for the following aircraft before approach initialization. Currently, these equations assume constant approach speeds and are only used for the initial notification to begin the approach. With minor modification, these could be used for dynamic spacing throughout the approach to notify the pilot of the following aircraft that speed changes are necessary to avoid a potential spacing violation.

$$15 - D_L \geq 2 \tag{2}$$

$$15 - V_F \frac{D_L}{V_L} \geq 2 \tag{3}$$

$$\frac{15}{V_F} - \frac{D_L}{V_L} \geq 2 \tag{4}$$

A more extensive exploration of the human factors implications of shifting calculation responsibility to the avionics is contained in the next section.

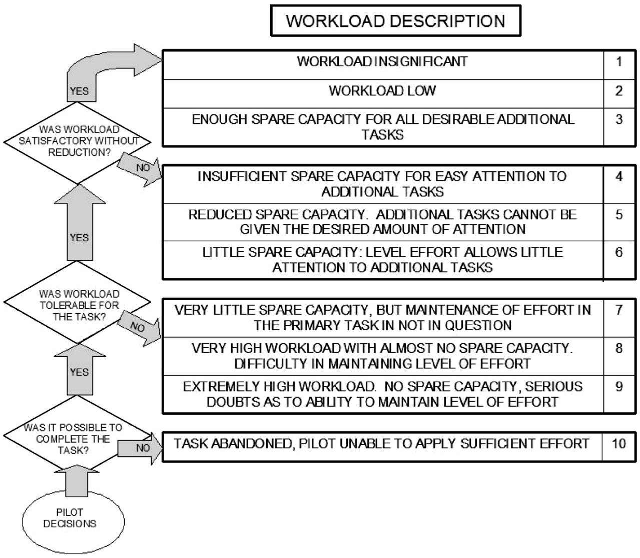

Fig. 4 Bedford workload rating scale [11].

IV. Human Factors

Potential safety improvements due to the avionics handling the spacing calculations are harder to measure quantitatively; however, pilot performance can be measured and used as an insight into improvements. By using human factors techniques, a reduction in pilot workload can be measured. Although it might take years of evaluation to see a tangible improvement in flight safety, a reduction in workload will reduce the probability of pilot error and decrease the likelihood of a human factors related accident [10]. This area of accident reduction is especially critical because the FAA estimates 75% of all aviation accidents are human factors related.

A. Methods of Evaluation

To properly evaluate the human factors benefits of system assisted spacing, criteria of varying emphases have been employed. The first evaluation method is the Bedford workload rating scale (Fig. 4). The Bedford scale is similar in format to the Cooper–Harper scale but specifically addresses pilot workload by using the concept of spare capacity [11]. Pilots determine their ability to handle additional tasks and then use the Bedford scale to arrive at a numerical score for pilot workload. The pilots score each phase of the flight so that the merits of automation can be evaluated for each phase.

Another evaluation method is to characterize the pilot's situational awareness during sequencing operations by a three-level model. Level 1 is the pilot's perception of the available information, which includes aircraft instrumentation and the behavior of the aircraft. Level 2 is the pilot's comprehension of the current situation such as understanding the current position of the aircraft within the flight (e. g., in a holding pattern, on approach), and Level 3 is the pilot's prediction of future status such as the prediction of potential aircraft conflicts [12]. Pilot survey questions have been designed to target each level and ask the pilot to rate their situational awareness as none, poor, fair, good, or excellent. These data, compiled along with pilot comments, not only indicates the pilot's current situational awareness but also identifies areas for improvement in current procedures and systems.

V. Real-Time Flight Simulation Facility

Simulations and test scenarios supporting this research were conducted in the Texas A&M University flight simulation laboratory (FSL). The engineering flight simulator (EFS) is the FSL's modular, real-time, nonlinear, 6-degree-of-freedom fixed base simulator [13] and is shown in Fig. 5. It contains a cockpit with reconfigurable, multifunctional displays that can be rapidly modified and tailored to fit individual project needs for a wide range of general aviation, commercial, and military cockpit displays. The main cockpit of the EFS runs on four high-performance PCs. There is one Linux PC that interfaces with the cockpit hardware such as the control stick and throttle and also computes the dynamics of the aircraft based upon the control inputs, using a nonlinear 6-degree-of-freedom model. The other three PCs run Microsoft Flight Simulator (MSFS) version 2004, driven (over the network) by the states computed by the Linux PC. Each of these three computers connects to an LCD projector for the out-the-window view of the cockpit simulator; each projector projects a 6×8 ft section of the view. Two of these three computers also drive 15 in touch-screen LCDs for the two multifunction head-down displays (HDDs) installed in the cockpit.

Fig. 5 Engineering flight simulator cockpit showing head-down displays and three-screen egocentric view.

Fig. 6 Flight simulation laboratory additional pilot stations.

To facilitate flight scenarios with multiple human pilots, three identical single-pilot stations are used (Fig. 6). Each station uses a high-performance Windows PC running MSFS and is equipped with a yoke/throttle combination as well as rudder pedals with toe brakes. The output of MSFS for each individual pilot station is displayed on a 30 in widescreen LCD. The use of MSFS for out-the-window visuals on both the pilot stations and the EFS allows for the easy transition between visual meteorological conditions (VMC) and IMC visuals. VMC visuals are used for pilot familiarization whereas IMC visuals were used for the actual testing. Additionally, each station has a single 15 in LCD touch-screen HDD, which can be used for a number of purposes such as displaying cockpit gauges, a primary flight display (PFD), and a moving map display. All three pilot stations interface with the EFS allowing four pilots to simultaneously and interactively fly in the simulation environment.

VI. Simulation Examples

The purpose of the examples is to evaluate the proposed changes to SATS sequencing and spacing, in the context and scope of four aircraft operating simultaneously in the SCA environment under IMC. The four simulation aircraft range from small single engine aircraft with approach speeds as low as 80 kn to large piston twins with approach speeds reaching 140 kn. This speed range will encompass the majority of aircraft that use the potential SATS airports and will expose the challenges of sequencing aircraft with significantly differing approach speeds. Each scenario ended after all aircraft have completed the approach and landed and were typically 30–45 min in duration.

Seven test cases were evaluated, and Table 1 contains the aircraft type, cruise speed, distance to IAF, and intended IAF for Cases I–III. These initial cases were conducted as batch simulations without human pilots, using the multi-agent intelligent distributed airspace simulation (MIDAS) [14]. MIDAS is an open architecture, distributed simulation system that uses a collection of rules-based logic software agents to represent autonomous pseudoaircraft traffic in the SCA. This approach was used to test for THT improvements because the pseudoaircraft agents do not introduce the human variable into the results. Case I is a nominal scenario using the current SATS sequencing and spacing rules. Case II is the same scenario as Case I, but using the proposed sequencing change introduced in the SATS aircraft sequencing section. Case III is also the same scenario as Case I, but with both the proposed sequencing change from Case II and the redefined spacing minimums introduced in the approach initiation section. Theoretically, with the new spacing and the aircraft arriving at their IAFs at different times, the THT could be reduced to a just a few minutes. This cannot be achieved, however, because once an aircraft has begun a holding circuit, it must complete it to be back on course for the approach, even if spacing is available halfway through the turn. Because one circuit of a hold is approximately 4 min and the aircraft in the test scenario have close spacing to start, each aircraft has to complete at least one holding circuit before beginning its approach.

To evaluate the effect of automated spacing on pilot performance, a rudimentary human factors analysis was conducted using one scenario with two test cases. The human factors tests were conducted with four pilots, primarily because this is the same number of aircraft used in the THT tests. Previous studies on the number of pilots to use in piloted simulation investigations found that large numbers of pilots are often not cost effective, and that useful results can be obtained with fewer pilots [15,16]. Hodgkinson points out that although seven pilots is a desired number, between three and six is acceptable for evaluation [17]. Pilots ranging from low-time with instrument ratings, up to high-time with flight instructor ratings were used. A preflight briefing was given to the pilots before the evaluation, in which the pilots were instructed on operating at the airport, performing holding patterns, and the spacing protocol. Each pilot was able to practice using the avionics and flying to the airport before the evaluation.

Tables 2 and 3 contain the aircraft type, cruise speed, pilot experience level, distance to IAF, and intended IAF for the human factors testing scenarios (Cases IV–VII). They are similar to those used for Cases I–III except for differences in initial conditions (position, airspeed, altitude, IAF), and the substitution of a Cessna 182 for the Piper Cub. The changes were intended to remove previous pilot bias toward the conduct of the flights because Scenario 1 was used to train pilots on SCA procedures, and the substitution of a faster aircraft permitted the testing to be accomplished more quickly. For Scenario 2, Case IV does not use automated spacing, and Case V uses the automated spacing. For Scenario 3, Case VI does not use automated spacing, and Case VII uses the automated spacing. To determine the number of test runs which are appropriate, Wilson and Riley recommend that if three pilots agree reasonably after three long-look evaluation runs, then the objective is achieved. If the pilots do not agree reasonably, then another three evaluation runs should be added [15]. Following this procedure, three runs without automated spacing were conducted with good pilot agreement, and this was followed by three runs with automated sequencing, for a total of six. Test cases were run on multiple days, and after each run the pilots assigned Bedford ratings to each flight phase and filled out a situational awareness questionnaire. Pilots also gave suggestions and comments to a test coordinator, who also kept records of test times.

Table 1 Scenario 1 (Cases I–III) aircraft cruise speeds and initial positions

Aircraft type	Cruise speed, kn	Distance to IAF, n miles	Intended IAF
Mooney 201	180	20	RAZVY
Cessna 172	125	22	RAZVY
Commander 700	150	20	LOUIE
Piper Cub	80	16	LOUIE

VII. Results

A. Revised Sequencing

The Case I scenario using the original SATS sequencing rules produced a THT of approximately 38 min. A large percentage of this holding time is due to faster aircraft holding while waiting for the slower aircraft that have not even arrived in the SCA. When the Case I conditions are repeated using the new sequencing rule, the THT was reduced to 23 min. This 15 min savings translates into a 39.4% reduction in THT. The dramatic reduction is a result of the delayed sequencing that prevents slow aircraft from being assigned

Table 2 Scenario 2 (Cases IV–V) aircraft cruise speeds and initial positions

Aircraft type	Pilot experience, h, plus rating	Cruise speed, kn	Distance to IAF, n miles	Intended IAF
Mooney 201	1100[a,b]	170	28	LOUIE
Cessna 172	125[c]	110	18	RAZVY
Commander 700	370[a,b]	150	15	RAZVY
Cessna 182	150[a]	135	17	LOUIE

[a]instrument rated. [b]certified flight instructor. [c]noninstrument rated.

Table 3 Scenario 3 (Cases VI–VII) aircraft cruise speeds and initial positions

Aircraft type	Pilot experience, h, plus rating	Cruise speed, kn	Distance to IAF, n miles	Intended IAF
Mooney 201	1100[a,b]	170	15	RAZVY
Cessna 172	125[c]	110	20	LOUIE
Commander 700	370[a,b]	150	25	RAZVY
Cessna 182	150[a]	135	20	RAZVY

[a]instrument rated. [b]certified flight instructor. [c]noninstrument rated.

Table 4 Cases I–III results, total holding time improvements

Test case	Functionality	THT, min	THT savings, min	Reduction from Case I	Reduction from Case II
I	Current SATS sequencing and spacing	38	——	——	——
II	Revised sequencing	23	15	39%	——
III	Revised sequencing and automated approach spacing	12	26	68%	47%

Table 5 Cases IV–VII results, average Bedford ratings by flight phase

Flight phase	Pilot self spacing	Automated spacing
Pre-SCA	2.63	2.67
SCA	2.38	2.25
Holding (IAF)	3.13	2.42
Final approach	3.00	2.92

the early arrival spots when they are still far from the SCA. With the new delayed sequencing the time spent waiting for aircraft to arrive at the SCA is kept to a minimum. These results are presented in Table 4.

B. Combined Revised Sequencing and Approach Spacing

Case III uses the same scenario conditions as Cases I and II, but adds the revised approach spacing. With four aircraft in the scenario and the first arrival not having to hold, the THT was reduced from 23 min down to 12 min compared with Case II (a time savings of 11 min), and from 38 min down to 12 min compared with Case I (a time savings of 26 min). Thus, adding an automated spacing capability to the existing revised sequencing reduced THT by 68% compared with the nominal procedure, and by 47% compared with revised sequencing only. These results are presented in Table 4.

C. Rudimentary Human Factors

Average Bedford ratings are shown in Table 5 for each flight phase of Cases IV–VII, and are separated based upon the type of spacing used. For all flight conditions except holding at the IAF, the averages are very close between cases with and without automated spacing. During the portion of the flight where the pilots hold at the IAF they rated their workload, on average, 0.7 lower with automated spacing. Although this value does not indicate a significant change in pilot workload, the Bedford scale results do show that the automated spacing did not produce an increase in pilot workload. Based upon the Bedford scale results, the automated spacing did reduce pilot workload when making the decision to begin the approach. However, the low ratings suggest that the pilots were probably not stressed enough during the testing in either case, with or without automated spacing, and therefore, future testing should introduce additional tasks or distractions to further determine the workload required for the spacing task.

The pilot questionnaire data was also broken down by type of spacing. Each pilot's perceived understanding of their automated spacing for Levels 1, 2, and 3 was generally rated as "Good" for cases both with and without automated spacing in all flight phases. The most germane information on the questionnaire came from the free-form pilot comments. Pilot concerns focused on two specific items. First, flashing noncritical collision warnings were found to be distracting during the approach and landing phases. Aircraft that had previously landed and were clear of the runway were detected by the software as possible collisions for the next aircraft in the landing sequence. These were displayed as a large flashing area on the pilot display. Although it was not observed to directly impact pilot performance, anecdotal evidence suggests that this distraction probably impaired situational awareness. Second, display clutter precluded the proper interpretation of other aircraft positions and altitudes in cases where two aircraft were at similar positions but different altitudes. In these cases, the tail number and altitude displayed for each aircraft overlapped, making the information unreadable. Pilots also generally commented that the information they were presented was not quite sufficient, and expressed a desire to have information on the aircraft that they were following and the sequence of all aircraft operating in the SCA. Collectively, these results indicate that improvements in the avionics display to eliminate the flashing noncritical collision warnings, reduce display clutter, and add the sequence information for all aircraft in the SCA would be beneficial.

D. Pilot Tracking Performance

Aircraft state data was collected for each aircraft while performing the scenario shown in Table 2 without automated spacing (Case IV) and with automated spacing (Case V) repeated twice. The ground tracks of all aircraft are shown in Figs. 7–9, with the GPS T and SCA boundaries superimposed. These figures suggest that the low-time pilots of the C172 and C182 show some improvement in maintaining the desired ground track when using automated spacing, particularly in the holding patterns that are tighter and less ragged for both of the automated spacing cases. The more experienced pilots did not show any appreciable improvement in tracking performance.

VIII. Conclusions

This paper expanded upon research currently being conducted on aircraft operations in instrument conditions at airports without air

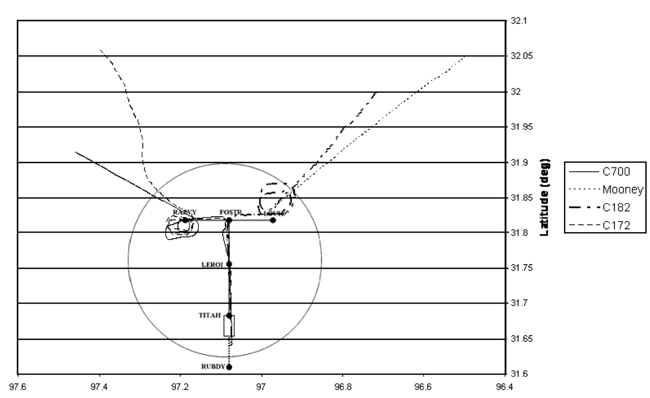

Fig. 7 Case IV: ground tracks (baseline).

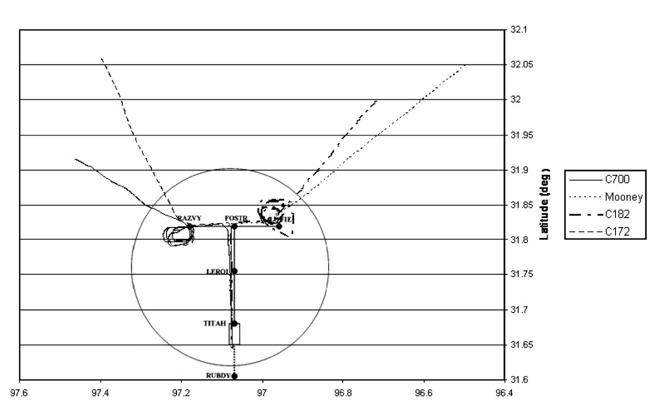

Fig. 8 Case V, Run 1: groundtracks.

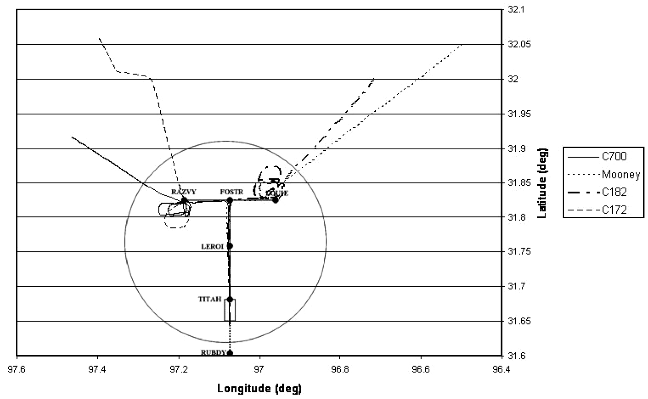

Fig. 9 Case V, Run 2: groundtracks.

traffic control. New automated approach spacing rules, and revised sequencing rules were implemented and evaluated for the purpose of reducing holding times. THT was used as the metric for validation of the new rules. To evaluate these capabilities, both agent-based batch type simulations and real-time human-in-the-loop multiple pilot simulations were performed. Human factors techniques were applied to obtain a rudimentary understanding of the benefits of automated spacing.

Based on the results presented in this paper, it is concluded that by changing the sequencing procedure to assign airspace entries once the aircraft are closer to the airport, potential bottlenecks can be avoided and holding times reduced. This revised sequencing procedure reduced THT by 39.4% compared with the nominal sequencing procedure. Adding automated spacing to the revised sequencing procedure reduced THT even further, producing reductions of 68% compared with the nominal procedure, and 47% compared with revised sequencing procedures only. Pilot human factors performance using the Bedford ratings show that at least for the holding portion of flight where the decision is made to begin the approach, pilots rated their workload, on average, as 0.7 lower using the automated spacing. Despite this small change, the average pilot workload was not increased due to the addition of the automated spacing. Finally, automated sequencing was observed to provide some improvement in pilot tracking performance for the low-time pilots. Taken together, these changes show promise for significant holding time reductions that result in potential fuel and monetary savings, and can help make the self-controlled airport a safe and viable transportation alternative.

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