JOURNAL OF AIRCRAFT
Vol. 45, No. 6, November–December 2008

Small Aircraft Transportation System, Higher Volume Operations Concept and Research Summary

Brian T. Baxley,* Daniel Williams,† Maria Consiglio,‡ and Cathy Adams‡
NASA Langley Research Center, Hampton, Virginia 23681
and
Terence Abbott§
Booz–Allen and Hamilton, McLean, Virginia 22102

DOI: 10.2514/1.20493

The ability to conduct concurrent, multiple aircraft operations in poor weather at virtually any airport offers an opportunity to increase the rate of flight operations, an improvement in passenger convenience, and the potential to foster the growth of small airports. The small aircraft transportation system, higher volume operations concept will increase capacity at the 3400 nonradar, nontowered airports in the United States where operations are currently restricted to a "one-in, one-out" procedural separation during low visibility or ceilings. The concept's key feature is that pilots maintain their own separation from other aircraft using the air-to-air data link and onboard software within the self-controlled area, an area of flight operations established during poor visibility and low ceilings around an airport without Air Traffic Control services. While pilots self-separate within the self-controlled area, an airport management module located at the airport assigns arriving pilots their sequence based on aircraft performance, position, and Air Traffic Control intent. The higher volume operations concept uses distributed decision making and safe procedures designed to minimize pilot and controller workload and integrates with today's Air Traffic Control environment. This paper summarizes the higher volume operations concept, procedures, research, and results, as well as outlines areas in which future higher volume operations research is required.

I. Introduction

FORMER Secretary of Transportation Norman Mineta recently predicted the tripling of air traffic in the United States in the next 15–20 years and projected the substantial impact that new transportation modes such as jet taxies and unmanned aerial vehicles will have on the character and volume of future traffic. He stated, "The changes that are coming are too big, too fundamental for incremental adaptation. . . . We need to modernize and transform our global transportation system, starting right now." [1] Congress funded the small aircraft transportation system (SATS) program, a partnership between NASA, the National Consortium of Aviation Mobility, and the Federal Aviation Administration (FAA). The program identified several key areas in the forecasted National Airspace System (NAS) of 2010 that needed resolution and, as a result, the SATS higher volume operations (HVO) project was created to address the projected increase in traffic [2]. Although this increase in traffic cannot be supported by the already-saturated 35 major hub airports, the 3400 underused, nontowered, and nonradar airports in the United States could accommodate a significant portion of that increase. Furthermore, using these local airports would also significantly lower the traveler's door-to-door travel time because these facilities are generally closer to their homes than the major hubs [3].

However, a major reason cited for limited services at local airports is the "procedural separation" imposed on aircraft operations when poor weather occurs at these airfields [4]. Arrival and departure operations drop from over 40/h in visual flight rules to around 5/h or less when Air Traffic Control (ATC) needs to increase separation and spacing criteria to compensate for their inability to "see" the aircraft during poor visibility and/or low ceilings. This causes delays and increased fuel consumption, driving up costs.

II. HVO Concept

A. The Higher Volume Operations Solution

One solution is to implement the SATS HVO concept. During poor weather, a block of airspace is established around the airport within which pilots will separate and space themselves from other similar SATS HVO equipped aircraft. A ground-based system provides the pilots their arrival sequence. All participating aircraft within this airspace provide their own separation using a combination of procedures and specialized tools, including localized surveillance data [5].

HVO relies on participating aircraft to broadcast critical flight information, such as their position, heading, airspeed, and projected flight path to other aircraft (e.g., automatic dependent surveillance-broadcast or ADS-B). Flight information is received by all aircraft and displayed to the pilot. The pilot's awareness of this traffic, along with HVO procedures, enables a distributed decision-making environment in which the pilot maintains separation and spacing regardless of low visibility or ceilings (precision approach minimums). Procedures for off-nominal operations (runway change, emergencies, etc.) are covered in another paper [6].

The SATS HVO concept does not depend on a control tower or designated approach times but rather allows the pilot to descend and then follow the preceding aircraft on the instrument approach with appropriate spacing. The pilot uses the onboard equipment to verify that the altitude and location to which his aircraft is descending is free of other traffic. Once adequate spacing behind the preceding aircraft is achieved and can be maintained throughout the approach, the pilot would begin the approach [7].

Presented as Paper 7379 at the Aviation Technology, Integration, and Operations Conference, Arlington, VA, 26–28 September 2005; received 21 October 2005; revision received 27 February 2006; accepted for publication 2 March 2006.

*Small Aircraft Transportation System Higher Volume Operations Project Manager, Aviation Operations and Evaluation Branch, MS 152. Member AIAA.

†Higher Volume Operations, Principle Investigator, Aviation Operations and Evaluation Branch, MS 152. Member AIAA.

‡Higher Volume Operations, Principle Investigator, Crew Systems Branch, MS 152.

§Senior Research Engineer, MS 156A.

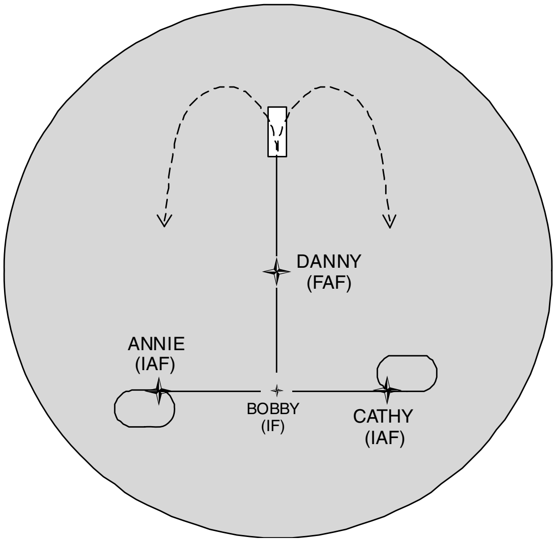

Fig. 1 Plan view of the self-controlled area (SCA).

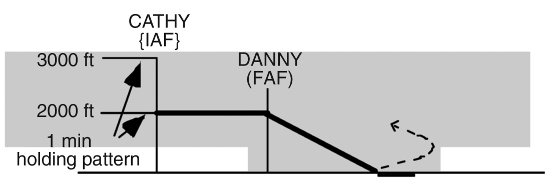

Fig. 2 Profile view of the self-controlled area.

B. Instrument Approach Design

The HVO concept has the potential to work for any type of approach. However, the research team selected the GPS-T configuration because it is the FAA's instrument approach procedure of choice for airports with little or no ground infrastructure. The HVO approach consists of an initial approach fix (IAF), an approach path, and a missed approach procedure to the missed approach holding fix (MAHF) as shown in Fig. 1. A second IAF increases the number of aircraft ready to immediately start the approach, reducing the time between approaches. To minimize the workload, the entire approach and missed approach procedure is contained within the self-controlled area (SCA) (i.e., no frequency change required or transfer of separation responsibility required). These features led to the very unique features of the HVO concept: the IAF and the MAHF are the same, and there is a missed approach procedure to each MAHF. Figure 1 shows ANNIE and CATHY as both the IAFs and MAHFs and the missed approach paths.

To ensure the ability to self-separate even during off-nominal conditions, the maximum number of landing aircraft allowed in the SCA is determined by the total number of IAFs and the associated holding pattern altitudes at those IAFs. In the case shown in Figs. 1 and 2, four arriving aircraft are allowed within the SCA, whether approaching the IAF, in holding at the IAF, on approach, or on missed approach.

C. Generic SCA Design

The airspace surrounding the instrument approach, within which the pilot is responsible for self-separation from other aircraft, is called the SCA. Similar to class C airspace, the SCA can be modified to integrate into the current NAS by tailoring it to be as small as possible, but large enough to allow a pilot to safely fly the approach and self-separate from other aircraft. The SCA described in this paper is a generic 15-n mile radius circle centered over the final approach fix (FAF) and extended vertically from the surface to 3000 ft above ground level (AGL) (Figs. 1 and 2). No work was done to identify the best SCA size or shape, and further research is required to optimize the SCA.

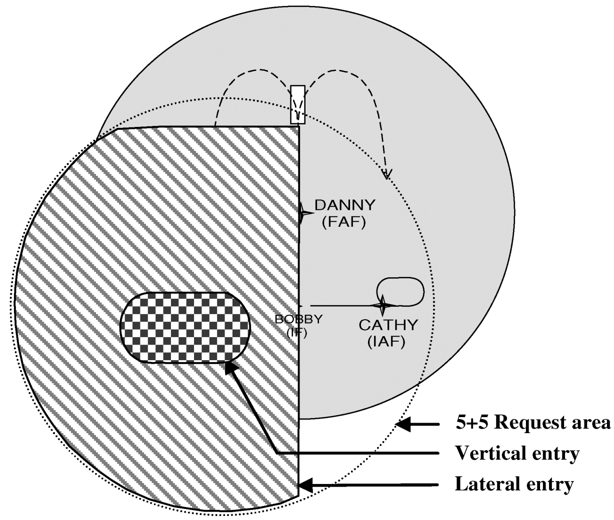

Fig. 3 5 + 5 request, vertical entry, and lateral entry areas for IAF ANNIE.

D. Airport Management Module

The HVO concept uses a ground-based automation system called an airport management module (AMM), which provides sequencing information to arriving pilots. Although typically located at the airport, the AMM is not an automated tower controller, but rather a system that issues sequence information based on predetermined rules using the aircraft's broadcasted flight information. These assignments are based on calculations involving aircraft speed, aircraft position, winds in the terminal area, and missed approach requirements. The AMM sequence assignment process also supports actions and decisions made by ATC by sequencing only those aircraft at the lowest ATC-managed altitude above the SCA, tying the ATC and AMM sequences together (this gives the controller flexibility to resolve issues unknown to the AMM, such as crossing airways, weather, etc.).

1. AMM Operating Assumptions

The AMM assumes the following applies in the SCA:

1) Pilots are responsible for maintaining flight-path separation from all aircraft and the proper sequence and spacing with the leading aircraft.

2) The AMM only provides an arrival sequence. The AMM does not monitor aircraft flight paths for conflicts, provide conflict resolution, or command pilots to descend or commence an approach.

3) Departing aircraft are not sequenced by the AMM. [NOTE: HVO does accommodate departures in a timely manner. See Sec. II.J for more].

4) HVO procedures provide a unique place for every arriving aircraft in the event of a lost voice or data link communication, whether entering the SCA, in holding at the IAF, on approach, or on missed approach.

2. AMM Entry Message Request and Format

When an aircraft is within 5 min of a 5-n mile ring around the IAF, onboard software allows the pilot to request an entry into the SCA from the AMM. This "5 + 5" request ring (shown as a dotted circle in Fig. 3 for IAF ANNIE) creates a "first-come, first-served" arrival sequence that compensates for different arrival speeds and winds aloft (faster aircraft have a larger circle whereas winds aloft shift the circle). Once the onboard software allows the pilot to request an entry, the AMM's response to the pilot request is a "vertical," "lateral," or "stand by" entry message. The entry message format consists of the entry type (vertical or lateral), IAF to proceed to (confirms the IAF requested by the pilot), aircraft to follow (given as the registration number), and MAHF (opposite of preceding aircraft). A sample AMM entry message and subsequent pilot action would be as follows:

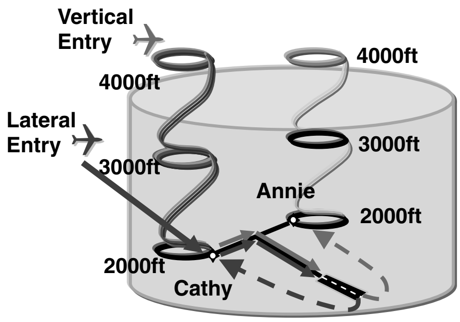

Fig. 4 Pilot operating procedures.

1) Message: Entry: Vertical; IAF ANNIE; Follow N12345; GPS-03 MAHF CATHY.

2) Pilot Response: Inform ATC of entry message from AMM, request descent into SCA, and notify ATC when entering the SCA.

3. AMM Vertical Entry Message Logic

The AMM's default arrival procedure is the vertical entry, in which the pilot proceeds under traditional instrument flight rules (IFR) control to the vicinity of the IAF at the lowest ATC-managed altitude immediately above the SCA. In "the vicinity of the IAF" creates a known and predictable traffic flow from which the pilot would self-separate. For the vicinity of the IAF, the HVO concept selected a "protected holding area" (FAA Order 7130.3A) for the IAF/MAHF holding depicted by the checkered area around ANNIE in Fig. 3. Once the aircraft is within the vicinity of the IAF and a vertical entry message from the AMM is received, the pilot determines the altitude below is clear of other traffic, notifies ATC and receives clearance to depart their airspace, and then descends through the top of the SCA to the lowest available altitude.

NOTE: A pilot receiving a vertical entry must determine that there is no other traffic at 3000 ft AGL; if there is, the pilot must wait. Likewise, a pilot receiving a vertical entry with no other aircraft within the vertical entry area and adequate spacing behind the aircraft to follow can immediately begin the approach; that pilot only enters holding if required to lose altitude (vertical entries with holding shown in Fig. 4).

For a vertical entry message to be generated and sent by the AMM, the following conditions must be met (satisfies requirement for procedural separation for both normal and off-nominal HVO procedures):

1) Less than two aircraft are assigned to that IAF/MAHF (aircraft proceeding to, in holding at, on approach assigned to, or on missed approach to that fix).

2) The requested IAF is not assigned as the MAHF to another aircraft on missed approach.

3) The requested IAF is not assigned as the MAHF to another aircraft on approach and past the initial fix.

4) The requesting aircraft is less than 1000 ft above the top of the SCA (integrates the AMM to ATC).

5) The requesting aircraft must be within the vertical entry area of the IAF.

6) Simultaneous entries at an IAF are not permitted. If any preceding aircraft entering the SCA has been assigned this IAF, it must have already transitioned into (or beyond) the vertical entry area (protected holding) of that IAF.

4. AMM Lateral Entry Message Logic

If traffic conditions allow, the AMM issues a lateral entry message that allows the aircraft to penetrate from its current position through the top or side of the SCA to expedite starting the approach. An ATC clearance to descend and depart ATC-managed airspace is required as with a vertical entry. If the following lateral conditions are met, the pilot receives a lateral entry message from the AMM (within the diagonal blue stripes in Fig. 3).

In addition to the vertical entry conditions, a lateral entry (see Figs. 3 and 4) requires the following:

1) Aircraft must be within 5 n mile and 5 min of the IAF. (The $5 + 5$ entry request ring uses aircraft ground speed to create a first-come, first-served arrival sequence based on the estimated time of arrival at the appropriate IAF.)

2) The requesting aircraft is on the approach side of the airfield.

3) The requesting aircraft and IAF are on the same side of the extended runway centerline.

4) No other aircraft are assigned to that IAF/MAHF.

5. AMM Standby Message Logic

The AMM will issue the pilot a standby message in the event of the following:

1) The aircraft is within the vicinity of the IAF but the vertical entry criteria has not been met (e.g., two other aircraft are assigned to that IAF/MAHF, an aircraft on approach with that assigned MAHF, etc.).

2) The aircraft is within the lateral entry area but does not meet lateral entry criteria (traffic, etc.).

3) The aircraft is within the 5-n mile plus 5-min request ring of the IAF with no other traffic in the SCA but does not meet other entry requirements (e.g., too high above the SCA, etc.).

E. HVO Arrival Sequence

The arrival sequencing determined by the AMM in the HVO concept orders aircraft as they meet entry requirements. Rather than providing a constantly changing sequence number, the AMM indicates the relative sequence by providing the pilot with the identification ("tail number") of an aircraft to follow. Once the AMM entry message has been received, the pilot confirms via onboard traffic displays that he is sufficiently clear of other traffic already within the SCA and then requests a descent out of ATC-managed airspace into the SCA. ATC approves the descent and advises the pilot that separation services are terminated. The pilot acknowledges and descends into the SCA to the lowest available altitude (see Figs. 4 and 5).

F. Pilot Operating Procedures within the SCA

Pilots will use the following procedures within the SCA (see Figs. 4 and 5):

1) Pilots entering the SCA will descend to the lowest available altitude and continue descending when lower altitudes become available.

2) Pilots only hold at the IAF if required to maintain an appropriate separation behind the preceding aircraft (for either vertical or lateral entries).

3) On a missed approach, pilots will fly to the lowest available altitude at their assigned MAHF.

4) Aircraft operating in the SCA must be able to climb at 300 ft/mile or better.

5) Pilots departing the SCA self-separate from arriving and departing traffic, fly the published departure procedure, and adhere to the ATC clearance to transition back into managed airspace.

G. HVO Arrival Spacing

Pilots continue their descent until they arrive at the initial approach altitude. Before leaving holding and initiating the approach from the IAF, the pilot must determine if the preceding aircraft is sufficiently ahead to provide adequate spacing throughout the approach. SATS HVO aircraft create spacing by holding at the IAF until spacing with the lead aircraft meets specified criteria (dynamically computed by onboard algorithms or a default that the previous aircraft has passed the FAF). A pilot arriving at the IAF with greater than the required spacing behind the preceding aircraft would immediately commence the approach; no turn in holding would be required, although the pilot could elect to do so if other requirements dictated.

Most of NASA Langley Research Center's simulator and flight experiments used onboard algorithms that continuously computed the spacing required to generate a minimum 3-n mile spacing throughout the approach. During the approach, an aircraft would continuously monitor the relative spacing between itself and the

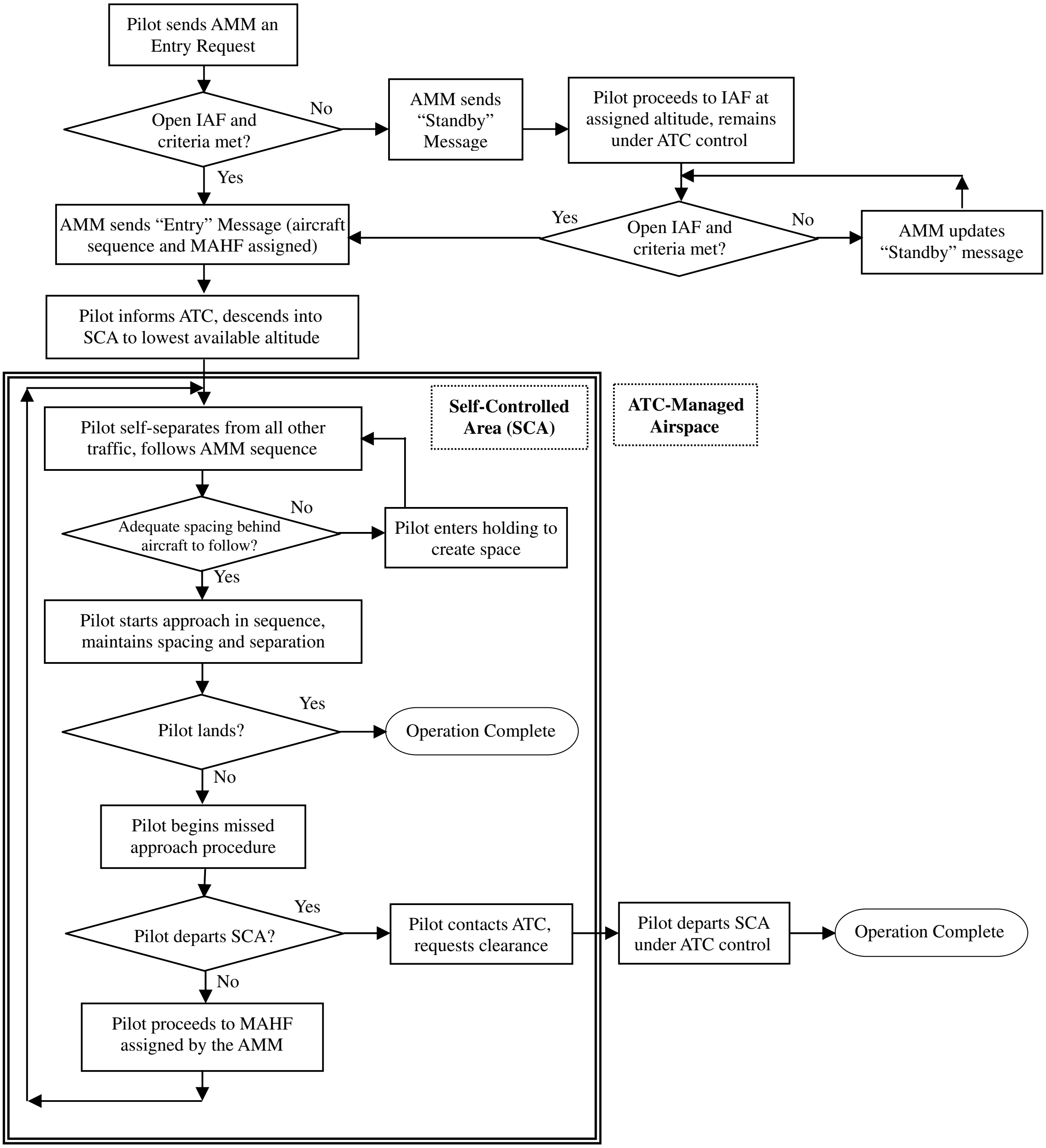

Fig. 5 Flowchart of HVO arrival procedures.

preceding aircraft. If the following aircraft is predicted to get closer than the nominal spacing, the onboard software issues alerts to reduce the approach speed. A comprehensive analysis of the spacing requirements on approach and missed approach was mathematically modeled to verify that the HVO concept met IFR safety standards and the minimum spacing distance [8].

H. HVO Separation

The HVO concept uses a three-tiered approach to allow pilots to assume the responsibility for separation from appropriately equipped aircraft within the SCA [9].

1) Procedural Separation: Pilots flying today follow procedures to ensure separation between aircraft, for example, in the event of lost two-way radio communication (Federal Aviation Regulations 91.185). *A central tenet of the HVO concept is that the procedures must provide procedural separation of aircraft at all times.* The HVO research team maintains that when aircraft are flying in instrument metrological conditions (IMC) in uncontrolled airspace, it is imperative that all aircraft have a specific location (e.g., clearance limit fix) in the event of lost two-way communication. This requirement heavily influenced the development of the AMM entry message logic described earlier and is a major factor in flow inefficiencies for arriving aircraft (spacing varies from 3 to 8 n mile).

2) Procedural Support: The HVO team developed an onboard pilot advisor (PA) as a second-tier system that takes inputs from an altitude determination tool, a spacing tool, and a conformance monitor to provide procedural support for the pilot. The PA selects and displays the highest priority message on a display to provide assistance and guidance to the pilot (example shown in white text in top right of Fig. 11): a) when the next lowest altitude is available to the pilot (OPEN: 2000), b) when the approach can be started and the required spacing maintained (TTA: $1 + 22$), and c) whether the pilot is flying in conformance to the instrument approach flight path (MONITOR ALT).

3) CD&A: The third tier is onboard algorithms that constantly monitor the conformance of the ownship and other aircraft to HVO procedures, determine potential conflicts, and issue alerts as required.

I. HVO Missed Approach

An aircraft entering the SCA with no aircraft to follow will be given an MAHF that is the same as the aircraft's original IAF. Aircraft following other aircraft will be assigned the MAHF point opposite of the preceding aircraft as part of their SCA entry message. Because approach spacing must consider the potential loss of separation while two aircraft are on a common path, alternating missed approach paths reduces the distance along which the second aircraft must maintain the required IFR spacing (3-n mile spacing must only be maintained from the IAF to the missed approach point, or MAP). This becomes especially noticeable when there is a performance difference between two aircraft, as in a faster aircraft following a slower aircraft.

Just as with an instrument approach today, if a missed approach is required, pilots may begin a climb to the missed approach altitude at any point along the instrument approach path before the MAP, but may only turn to the MAHF after crossing the MAP. Aircraft on a missed approach climb to the lowest available holding altitude, simplifying the transition to begin another approach.

Should only one missed approach path or IAF/MAHF be available (weather, airspace constraints, terrain, etc.), the HVO concept and the AMM logic still function but with larger spacing requirements and therefore slower rates of operation. Without the ability to alternate missed approach paths, the pilot must now maintain IFR spacing from not only the IAF to the MAP, but also from the MAP back to the IAF/MAHF. A faster aircraft following a slower aircraft would need to increase the time gap between aircraft by delaying their start of the approach (more time in holding at the IAF).

J. HVO Departure Sequence and Spacing

Before departing a SATS airfield, pilots file a standard IFR flight plan and receive a clearance, potentially including release and clearance void times [10]. When ready for takeoff, the pilot ready for a takeoff would determine that the time is still within the ATC clearance window, that there are no aircraft past the FAF or on the runway, and that there is sufficient spacing behind the previous departure (3 n mile to the opposite departure fix, 10 n mile to the same fix as shown in Figs. 6 and 7). Onboard displays and software aid the pilot in making this determination. HVO employs two departure paths, which reduce the spacing requirement.

An earlier version of the HVO concept had the AMM sequence departures as well as arrivals. However, it was determined during concept development that gaps in the arrival flow caused by procedural requirements and pilot variances creates enough space for departures without the AMM having to sequence them. Removing the requirement to schedule departures significantly reduced the complexity of the AMM.

Gaps in the theoretical maximum arrival flow (3 n mile between aircraft over the runway threshold) are generated for several reasons, to include 1) the speed differential of aircraft (slow behind fast), 2) pilots not commencing approach at the earliest time possible (flight-path geometry, pilot not ready, etc.), and 3) AMM logic closing an IAF to new entries due to other aircraft on the approach or missed approach.

K. HVO Minimum Equipment Requirements

Key to the HVO concept is the ability to transmit and receive GPS-quality information, the ability to display that information, onboard software to support the pilot, and a two-way data link with the AMM. Here is an initial list of required equipment:

1) Aircraft: an IFR approach-certified GPS receiver, an ADS-B transmission and reception of aircraft information, an AMM messaging data link, a cockpit display of traffic information (CDTI), and onboard conflict detection and alerting capability. Also desirable is a pilot advisor providing HVO altitude, spacing, and conformance information.

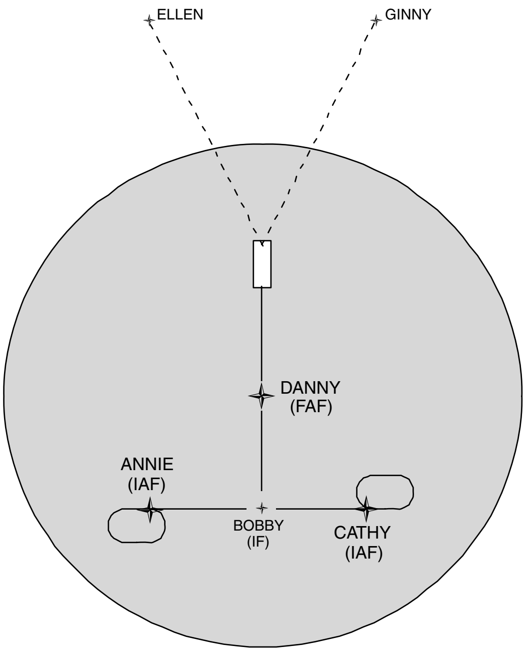

Fig. 6 HVO departure procedure.

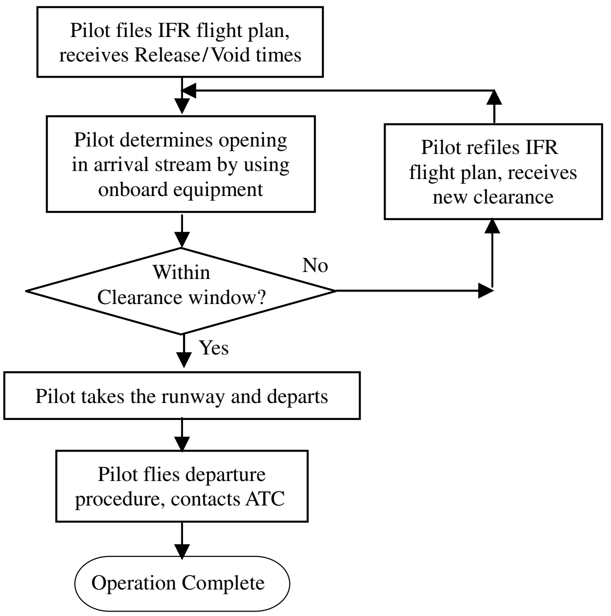

Fig. 7 Flowchart of HVO departure procedures.

2) Airports: weather reporting, an AMM, a ground-based ADS-B transceiver, and data link capability.

L. Mixed Equipage Operations

HVO aircraft can separate from other HVO aircraft in the SCA but cannot separate themselves from aircraft not transmitting ADS-B state data. To retain the level of safety that procedural separation provides (both in today's procedures and the proposed HVO concept), it is necessary to separate nonequipped aircraft from SATS aircraft during HVO. That is, all HVO aircraft must land before a nonequipped aircraft departs ATC's airspace, and all nonequipped aircraft must land before an HVO aircraft enters the SCA. Although not as efficient as HVO, this procedure does produce a faster rate of flight operations than today's procedures. For example, assume six

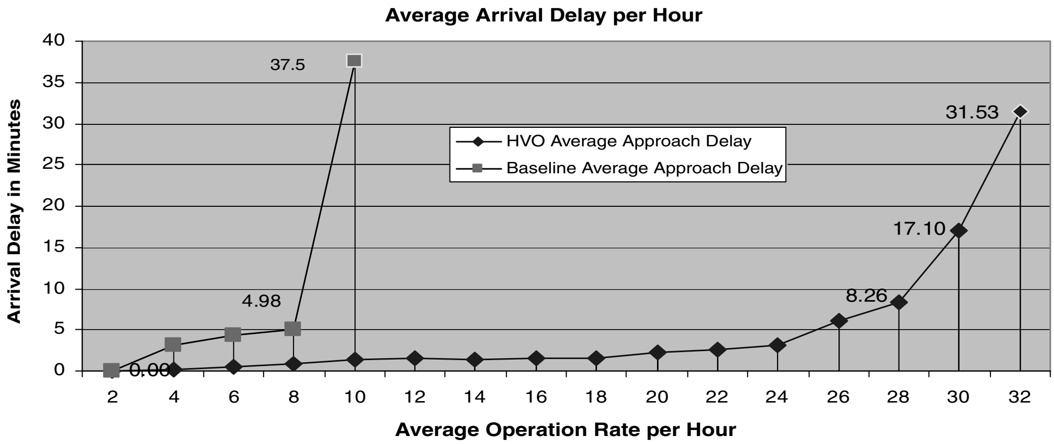

Fig. 8 Throughput study results.

aircraft arrive at an airport at approximately the same time but only the first three aircraft are equipped for HVO. The nonequipped aircraft still reap the benefits that the HVO aircraft provide by having approximately 20 fewer minutes in holding than they would otherwise (10 min savings between the first and second aircraft, another 10 min savings between the second and third aircraft; therefore, the fourth aircraft can start its approach at least 20 min earlier).

III. Study and Experiment Results

This section of the paper provides a summary of the studies, simulations, and flight experiments done in support of the HVO concept. Included are formal methods studies to ensure a complete accounting for all states and transitions between those states, batch studies to determine throughput, conflict detection and alerting studies of the appropriate algorithms and warning criteria, and human-in-the-loop simulation and flight experiments to determine the safety and usability from a subject pilot's and subject controller's perspective.

A. Formal Methods Studies

Early in the development of HVO, a formal methods analysis was conducted using nondeterministic, asynchronous mathematical models of the operational concept. This study found that the procedure was safe for all nominal operations, for example, there are no procedural deadlocks (all aircraft in the SCA eventually land or depart) and no loss of separation, and there is always an available altitude for aircraft on missed approach [11]. Several concept changes were incorporated based on that research, the most important being modifications to missed approach procedures [12].

B. Throughput Batch Studies

Using the simulation batch mode, multiple runs were investigated for both today's procedures (baseline) and the HVO concept (SATS) using an equal number of arriving and departing aircraft per hour from multiple points with varying approach speeds. Initial studies indicate that the HVO concept results in a three- to fourfold increase in the rate of flight operations [13]. Figure 8 shows eight operations per hour (four arrivals and four departures) using today's procedures results in a 5 min average delay, whereas HVO procedures can support 26 operations with the same average delay. This batch study closely correlates with the results of the linked NASA–FAA simulation experiment described in Sec. III.D.

C. Conflict Detection Studies

HVO uses a concept whereby an aircraft that is within the containment volume of an instrument approach to the declared destination would include as part of its ADS-B message that it is in conformance. This allows proximate aircraft to use state-plus-intent

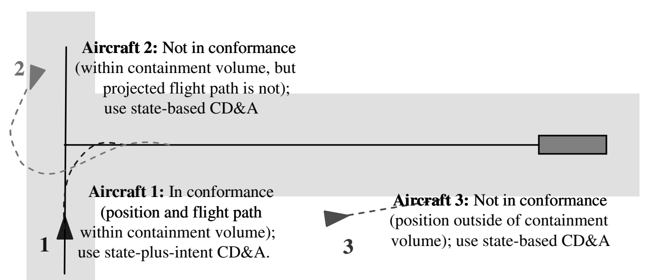

Fig. 9 CD&A based on conformance to flight path.

algorithms in determining traffic conflicts between aircraft (aircraft 2 and 3 can infer that aircraft 1 will make a right turn onto final in Fig. 9 because it is in conformance). Should the aircraft's position or flight path not be within the containment volume, the transmitted data field in the ADS-B message would state that aircraft is not in conformance. At that time, all other aircraft would revert to state-based algorithms of that aircraft's flight path (linear projection of that aircraft's current position) to determine if there is a potential conflict between the two aircraft (aircraft 2 and 3 in Fig. 9 are not in conformance, aircraft 1 uses state-based CD&A to determine their potential for conflict). (Detailed information about the conflict detection used in SATS HVO can be found in Consiglio et al. [14] and Appendix B of Abbott et al. [7].)

One study of the HVO procedures and state-based versus state-plus-intent CD&A indicated a significant decrease in false alarms (alert or alarm issued without subsequent violation by the aircraft) with the state-plus-intent CD&A algorithms compared with the state-only CD&A [14]. Table 1 illustrates the performance of the CD&A algorithm for different configurations of the SCA, where D is the diameter in nautical miles around the aircraft, H is the height in feet, T_c is the look-ahead time for a caution, and T_w is the look-ahead time for a warning. The figure summarizes for each configuration the average ratio of false alarms compared with the total number of alerts. The smaller the ratio, the more effective the logic is to avoid false alarms. The hybrid logic is consistently better than the state-only logic in the first four configurations. For instance, for a small protected zone and short look-ahead times (configuration 4), only 10% of the alarms issued by the hybrid logic are false alarms. For the same configuration, the amount of false alarms issued by the state-only algorithm is 59%. In all configurations, the average ratio of false alarms issued by the hybrid logic is less than 50%, and it decreases as the protected zone is reduced and the look-ahead times are shortened. Except for the case of a very small protected zone and very short look-ahead times, the average ratio of false alarms issued by the state-only algorithm is always greater than 50%.

Table 1 Conflict detection false alarm rates

	Configuration	CD&A	False alarm ratio
1	$D = 3, H = 750, T_c = 120, T_w = 30$	Hybrid	49%
		State	69%
2	$D = 3, H = 750, T_c = 45, T_w = 20$	Hybrid	32%
		State	58%
3	$D = 1, H = 300, T_c = 120, T_w = 30$	Hybrid	30%
		State	61%
4	$D = 1, H = 300, T_c = 45, T_w = 20$	Hybrid	10%
		State	59%
5	$D = 0.35, H = 400, T_c = 35, T_w = 20$	Hybrid	0%
		State	0%

D. Simulation Experiments

Four simulation experiments using pilot and controller subjects were conducted at NASA Langley's Air Traffic Operations Laboratory (ATOL) and at the FAA's William J. Hughes Technical Center Target Generation Facility (TGF).

1. *HVO-2 (Normal Operations)*

The primary objective of this experiment was to validate the HVO concept of operations. Fifteen low-time instrument-rated pilots flew two replicates of ten scenarios (five scenarios using today's procedures (baseline) and the same five scenarios using HVO procedures) to answer these two questions:

1) "Can pilots safely and proficiently fly an airplane while performing HVO procedures?"

2) "Do pilots perceive that the workload while performing HVO procedures is no greater than flying using today's system?"

The first four scenarios for both the baseline and HVO operations consisted of the pilot flying in various phases of flight with virtual traffic, and the fifth scenario for both procedural types replaced the virtual traffic with the other three subject pilots to create a live, linked simulation.

Results based on the flight technical error (FTE) analysis and workload assessments indicate little difference in pilot performance for altitude control in either simulation. The FTE analysis examined airspeed, altitude, and lateral path control of the pilot flying both the baseline and HVO procedures and found that the pilots performed statistically better relative to airspeed and lateral deviation using HVO procedures [15]. The workload assessment was accomplished using a Wilcoxon test with a modified Cooper–Harper rating scale ("1" being very easy to "10" being an impossible task), and these results show that, at a statistically significant level, the evaluation pilots reported lower workload ratings when flying SATS HVO scenarios than when flying current day baseline scenarios [16].

2. *HVO-3a (Pilot Advisor)*

In January 2005, the NASA HVO research team conducted an experiment with 16 evaluation pilots. The ATOL was used over a two-day period to evaluate four groups of four subjects, all low-time instrument-rated pilots. These pilots were run through a series of scenarios to determine the requirement for a PA that provided information on altitudes available for the pilot, conformance to the selected flight path, and conflict detection. Results from the pilot surveys indicate that, although not required, the PA was highly desired for use in HVO procedures. Furthermore, the pilot workload was lower and the situation awareness was higher with the PA than without [17].

3. *HVO-3b (Off-Nominal Operations)*

Immediately after the pilot advisor study, there was a simulation experiment to examine two of the HVO procedures developed to address off-nominal operations (runway changes, change in arrival sequence, etc.) and equipment malfunctions (radio failure, etc.) [18]. The same pilots were presented various off-nominal scenarios. The subjective workload assessments given by the pilots indicated that there was no difference in the pilot workload for a normal HVO procedure and the tested off-nominal HVO procedures [19]. In other words, the use of data-linked displays offset the additional cognitive requirements to safely fly HVO procedures.

4. *Air Traffic Controller Experiments*

The principle objective of this simulation was to determine the viability of the SATS HVO concept from an air traffic controller's point of view. Using the TGF, controllers were brought in from the Washington Air Route Traffic Control Center and from the Philadelphia Terminal Radar Approach Control facilities. Three simulation experiments were conducted: 1) the terminal sector, 2) the en route sector, and 3) the linked en route sector (controllers at the FAA Technical Center linked live to pilots at NASA Langley). Twelve current controllers participated (four in each phase) and each controlled four scenarios that replicated today's procedures, HVO procedures, today's traffic load, and the predicted traffic load in 2010.

In all three simulations, the controllers were able to hand off aircraft quicker (much faster arrival rate) with the HVO concept compared with today's procedures and generally had decreased workload (Fig. 10). The FAA study used during-test and post-test feedback to assess workload based on a rating of 1 being the lowest and 7 being the highest workload. (In the linked experiment, controllers and pilots regularly landed all six HVO aircraft within 35 min, but using today's procedures only landed three aircraft after 55 min.) The HVO concept was generally well received by the subject controllers. The two primary areas identified for further research were the tailoring of the size and shape of the SCA to meet airspace constraints and the handling of nonequipped aircraft [20].

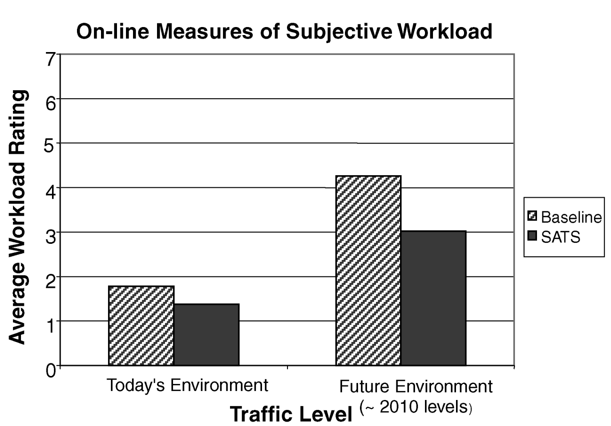

Fig. 10 Philadelphia controller results.

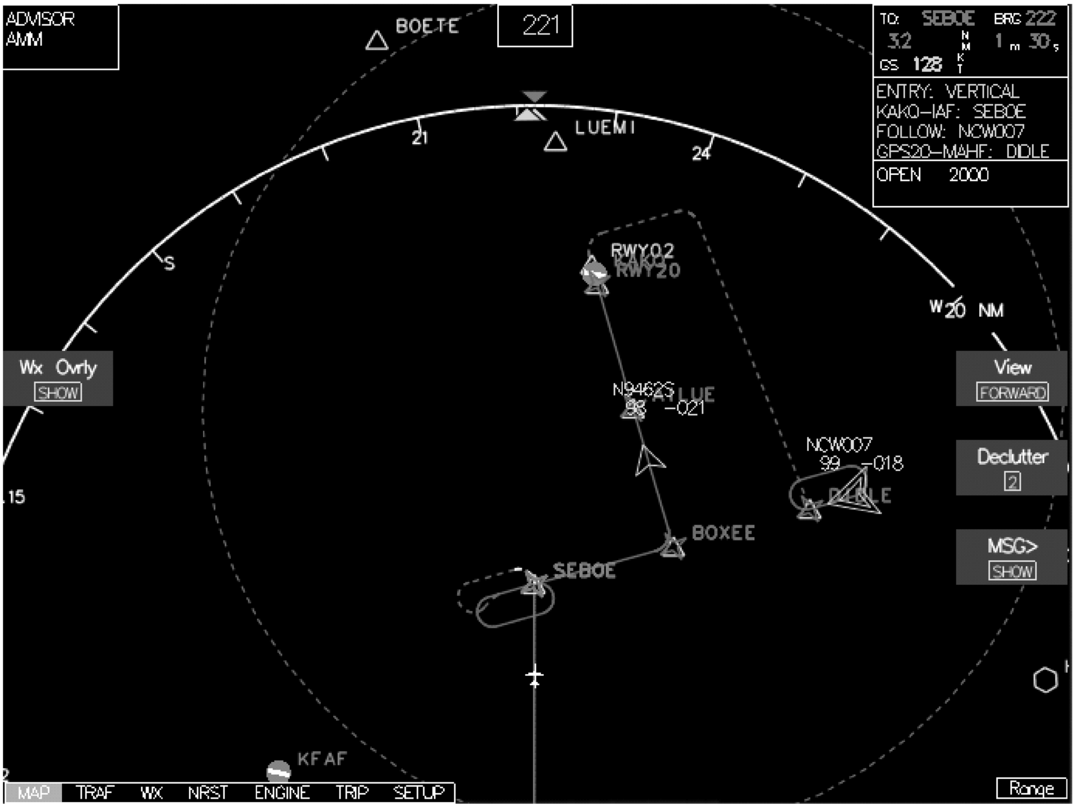

Fig. 11 HVO-2 multifunction display used in NASA Cirrus-22 aircraft.

This FAA report also includes suggested phraseology for the transition from managed to nonmanaged airspace.

E. Flight Experiments

Flight experiments were also conducted at NASA Langley with a Cirrus SR-22. Other flight experiments were also conducted by the Southeast SATSLab and the North Carolina and Upper Great Plains SATSLab [21].

1. HVO-1 (Self-Separation and Sequencing)

From November 2003 through January 2004, NASA Langley examined whether pilots could hand fly an aircraft using a CDTI to self-separate and sequence their own aircraft from other similarly equipped aircraft. Six general aviation low-time pilots (less than 350 h) flew scenarios to evaluate if they could maintain separation and spacing behind the preceding aircraft and maintain the proper landing sequence.

Analysis of the results indicates that there was no difference in the pilots' flight-path deviation or airspeed, nor did the pilots report an increase in workload. Even more significantly, during the 48 test runs, no pilot violated the separation requirements or landed out of sequence [22].

2. HVO-2 (Normal Operations)

From July through October 2004, NASA Langley conducted flight experiments to validate the results of the normal operations simulation experiment in a Cirrus SR-22. The 12 subject pilots in this experiment had participated in the normal operations simulation experiment (discussed in Sec. III.D) and flew two replicates of six different approach scenarios. The flight experiment used the same procedures, software and displays, and approach scenarios as the simulation experiment.

The 12 evaluation pilots reported a lower workload and higher situation awareness. The flight technical error (FTE) results for the lateral, vertical, and airspeed deviation were comparable for HVO procedures versus today's procedures, despite having the additional requirements to separate, space, and sequence their own aircraft while in IMC. The FTE analysis examined the airspeed, altitude, and lateral path control of the pilot flying both baseline and HVO procedures and found that the pilots performed statistically better relative to airspeed and lateral deviation using HVO procedures (FTE improvement when flying HVO was 1 kn of airspeed, no change in altitude, and an 0.04-n mile improvement in lateral path control) [23]. The workload assessment was accomplished using a Wilcoxon test with a modified Cooper–Harper rating scale (1 being very easy to 10 being an impossible task), and these results show that, at a statistically significant level, the evaluation pilots reported lower workload ratings when flying SATS HVO scenarios than when flying current-day baseline scenarios. Furthermore, there were no violations of separation and spacing requirements, nor did any pilot land in an improper sequence [15].

The display software shown in Fig. 11 was used in both the simulation and flight experiments. Shown is the NASA Cirrus as an aircraft icon, whereas chevrons represent other traffic and the traffic to follow is the double chevron to the right. The "entry" message from AMM is at the top right of the display, whereas a solid line shows the instrument approach and a dotted line is used to show the assigned missed approach path. This particular figure was taken during an actual flight research scenario with the pilot entering the terminal area from the bottom of the screen and with traffic to follow on the right side of the display approaching the opposite IAF.

IV. Future Research

A. Normal and Off-Nominal Procedures

More research into HVO procedures by a range of experts is required. More efficient operations can be realized by analyzing parameters used to allow entrance into the SCA (when an IAF is closed to new traffic to accommodate aircraft on missed approach) and adjusting them within the constraints established by procedural safety.

B. Conflict Detection and Alerting

Research is required to determine the acceptable rate of false alarms and the appropriate containment volume and look-ahead time in a terminal area. It may be possible that state-based alerting algorithms would be sufficient in this operating environment. However, the intent-based approach seems to be much more viable, robust, and accurate.

C. Mixed Equipage Operations

During the SATS2005 Technical Demonstration held at Danville, Virginia, most of the six SATS aircraft were able to see nonparticipating aircraft on their certified Garmin cockpit displays. The information on non-SATS equipped aircraft came from the FAA's SAFEFLIGHT 21 system, which sends radar data to the FAA Technical Center in Atlantic City, New Jersey, then retransmits the information in a TIS-B format that the Garmin Universal Access Transceiver can read. These new technologies may afford possibilities for mixed equipage operations.

D. Other Implementation Issues

1) Altitudes or IAF/MAHF constraints. Airspace requirements, overlaying instrument approaches to other airfields, terrain, and weather all create situations in which the full, generic HVO concept cannot be implemented. Initial experiment results indicate that, even when there is only one IAF and one altitude at that IAF, that pilot and controller workload is less and the rate of operations is slightly higher than today's procedures.

2) Optimize the SCA. The size of the SCA would be significantly reduced if there was no requirement that the missed approach path remain within the SCA. However, it is believed that ATC workload would be substantial.

3) Optimized instrument approach designs. Further research should examine other configurations and how to handle circling approaches.

4) Airspace activation. How will the SCA be turned on or off, and who will activate it?

5) Runway selection. How will the AMM receive this information, and who will notify the pilots?

6) Controller visibility into the SCA. If traffic within the SCA is visible to the controller, it may require competing cognitive processing and imply controller responsibility for separation. However, lack of visibility may lessen the controller's situation awareness or reduce efficiency [24].

7) Multiple runway operations. Research has not yet been conducted into airfields with multiple runways.

8) Safety and hazard analysis. A safety and hazard analysis of the HVO concept needs to be conducted.

9) Equipment. What will be the minimum equipment and level of complexity needed for a pilot and an aircraft to fly and operate within the SCA?

10) Training. A training program and requirements for both pilots and controllers need to be set. It is critical that both pilots and controllers understand that the responsibility for separation and spacing within the SCA belongs to the pilot in the HVO concept [25].

V. Conclusions

The ability to operate multiple aircraft in poor weather at virtually any airport offers a unique opportunity for significant air transportation growth and a major improvement in passenger convenience. This is accomplished by establishing an area around an airport within which the pilot is responsible for separation, sequencing, and spacing using data-linked flight data from other aircraft. Improved situation awareness provided by modern displays allows pilots to assume self-spacing and self-separation responsibilities. This augmentation of existing flight procedures combined with the use of new information and cockpit display technologies for a distributed responsibility for separation is the core of the HVO concept.

The SATS HVO concept emphasizes integration with current and near-term NAS operations, procedural simplicity, and minimal workload change for pilots and controllers. The SCA described is a starting point for additional designs and analyses; no attempt was made to optimize the size or shape of the proposed airspace. Research conducted to date received positive feedback from both pilots and controllers and indicates that a fourfold increase in the rate of flight operations is possible at small airports during poor weather. This capability to overcome the limitation of one-aircraft-in, one-aircraft-out operations during poor weather removes a major obstacle to operations at underused small airports.

References

[1] Transportation Secretary Mineta, speech to the Aero Club of Washington, D. C., 27 Jan. 2004.

[2] Holmes, B., Durham, M., and Tarry, S., "Small Aircraft Transportation System Concept and Technologies," *Journal of Aircraft*, Vol. 41, No. 1, Jan.–Feb. 2004, pp. 26–35.

[3] Viken, S., and Brooks, F., "Demonstration of Four Operating Capabilities to Enable a Small Aircraft Transportation System," *24th Digital Avionics Systems Conference*, Oct. 2005, p. 16.

[4] Conway, S., and Consiglio, M., "A Method of Separation Assurance for Instrument Flight Procedures at Non-Radar Airports," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, Aug. 2002.

[5] Jones, K., Williams, D., Consiglio, M., Adams, C., and Abbott, T., "IFR Operations at Non-Towered, Non-Radar Airports: Can We Do Better Than One-At-A-Time?," AIAA Paper 2003-2874, 2003.

[6] Baxley, B., Williams, D., Consiglio, M., Adams, C., and Abbott, T., "The Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) Off-Nominal Operations," AIAA Paper 2005-7461, Sept. 2005.

[7] Abbott, T., Consiglio, M., Baxley, B., Williams, D., Jones, K., and Adams, C., "Small Aircraft Transportation System, Higher Volume Operations Concept," NASA TP 2006-214512, Sept. 2005.

[8] Munoz, C., and Dowek, G., "Formal Verification of Spacing Properties of an Air Traffic Management Concept," Network in Computer Algebra Workshop, July 2005.

[9] Consiglio, M., Carreno, V., Williams, D., Munoz, C., and Abbott, T., "Conflict Prevention and Separation Assurance in the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) Concept of Operations," AIAA Paper 2005-7463, Sept. 2005.

[10] *Aeronautical Information Manual*, Federal Aviation Administration, Washington, D. C., 2005, Chap. 5-2-4.

[11] Munoz, C., Dowek, G., and Carreno, V., "Modeling and Verification of an Air Traffic Concept of Operations," *International Symposium on Software Testing and Analysis*, July 2004, pp. 175–182.

[12] Dowek, G., Munoz, C., and Carreno, V., "Abstract Model of the SATS Concept of Operations: Initial Results and Recommendations," NASA TM-2004-213006, 2004.

[13] Consiglio, M., and Williams, D., "Preliminary Validation of the SATS HVO Concept," *24th International Council of the Aeronautical Sciences*, International Council of the Aeronautical Sciences, Oct. 2004.

[14] Consiglio, M., Munoz, C., and Carreno, V., "Conflict Detection and Alerting in a Self Controlled Terminal Airspace," *24th ICAS*, International Council of the Aeronautical Sciences.

[15] Williams, D., Consiglio, M., Murdoch, J., and Adams, C., "Flight Technical Error Analysis of the SATS HVO Simulation and Flight Experiments," *24th Digital Avionics Systems Conference*, Oct. 2005, p. 12.

[16] Consiglio, M., Williams, D., Murdoch, J., and Adams, C., "SATS HVO Concept Validation Experiment," AIAA Paper 2005-7314, Sept. 2005.

[17] Adams, C., Consiglio, M., and Conway, S., "The Pilot Advisor: Assessing the Need for a Procedural Advisory Tool," *24th Digital Avionics Systems Conference*, Oct. 2005, p. 8.

[18] Abbott, T., Consiglio, M., Baxley, B., Williams, D., and Adams, C., "Small Aircraft Transportation System, Higher Volume Operations Concept: Off-Nominal Operations," NASA TM 2005-213914, Sept. 2005.

[19] Consiglio, M., Conway, S., and Adams, C., "SATS HVO Procedures for Priority Landings and Mixed VFR/IFR Operations at Non-Towered, Non-Radar Airports," *24th Digital Avionics Systems Conference*, Oct. 2005, p. 8.

[20] Magyarits, S., Racine, N., and Hadley, J., "Air Traffic Control Feasibility Assessment of Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO)," U.S. Department of Transportation/Federal Aviation Administration CT-05/26, May 2005.

[21] Kelly, W., Valasek, J., Wilt, D., Deaton, J., Alter, K., and Davis, R., "The Design and Evaluation of a Traffic Situation Display for a SATS Self Controlled Area," *24th Digital Avionics Systems Conference*, Oct. 2005, p. 12.

[22] Murdoch, J., Ramiscal, E., McNabb, J., and Bussink, F., "Flight Experiment Investigation of General Aviation Self-Separation and Sequencing Tasks," NASA TP-2005-231539, May 2005.

[23] Williams, D., Murdoch, J., and Adams, C., "The Small Aircraft Transportation System Higher Volume Operations Flight Experiment," AIAA Paper 2005-7421, Sept. 2005.

[24] Lohr, G., Williams, D., Baxley, B., and Abbott, T., "Integrating SATS HVO into the National Airspace System," AIAA Paper 2005-7313, Sept. 2005.

[25] Conway, S., Williams, D., Adams, C., Consiglio, M., Murdoch, J., "Flying SATS Off-Nominal Airport Operations: Training, Lessons Learned, and Pilots' Experiences," AIAA Paper 2005-7422, Sept. 2005.