Conflict Prevention and Separation Assurance Method in the Small Aircraft Transportation System

Maria Consiglio[*], Victor Carreño[†], and Daniel Williams[‡]
NASA Langley Research Center, Hampton, VA 23681

And

César Muñoz[§]
National Institute of Aerospace, Hampton, VA 23666

Abstract

A multilayer approach to the prevention of conflicts due to the loss of aircraft-to-aircraft separation which relies on procedures and on-board automation was implemented as part of the SATS HVO Concept of Operations. The multilayer system gives pilots support and guidance during the execution of normal operations and advance warning for procedure deviations or off-nominal operations. This paper describes the major concept elements of this multilayer approach to separation assurance and conflict prevention and provides the rationale for its design. All the algorithms and functionality described in this paper have been implemented in an aircraft simulation in the NASA Langley Research Center's Air Traffic Operation Lab and on the NASA Cirrus SR22 research aircraft.

Nomenclature

ADS-B = Automatic Dependent Surveillance - Broadcast
AMM = Airport Management Module
ATOL = Air Traffic Operations Lab
CDA = Conflict Detection and Alerting
CDTI = Cockpit Display of Traffic Information
CV = Containment Volume
HVO = Higher Volume Operations
IAF = Initial Approach Fix
IFR = Instrument Flight Rules
IMC = Instrument Meteorological Conditions
NAP = Nominal Approach Path
PA = Pilot Advisor
PS = Procedure Support
MAHF = Missed Approach Holding Fix
NAP = Nominal Approach Path
NAS = National Airspace System
PA = Pilot Advisor
PS = Procedure Support
SATS = Small Aircraft Transportation Systems
SCA = Self Controlled Area
VFR = Visual Flight Rules
VMC = Visual Meteorological Conditions

---

[*] Research Engineer, Crew Systems Branch, 24 West Taylor St., Hampton 23681/MS152.
[†] Research Engineer, SCASB, MS 130, NASA Langley RC, Hampton, Virginia, Member, AIAA.
[‡] Research Engineer, Aviation Operations and Evaluation Branch, MS 152, Member, AIAA.
[§] Senior Research Scientist, Formal Methods Team, 100 Exploration Way, Hampton, Virginia.

I. Introduction

THE Small Aircraft Transportation (SATS) Higher Volume Operations (HVO) concept was developed to increase access to thousands of public use airports in the United States by increasing the rate of operations at these facilities without a major impact on the air traffic controller’s workload or on overall National Airspace System (NAS) structures and principles. HVO procedures were designed for use at non-radar, non-towered airports in near all-weather conditions within a volume of airspace where pilots have the responsibility for maintaining safe separation from other traffic.

The notion of *conflict prevention* was established as a design goal of the SATS HVO concept. The conflict prevention foundation that researchers used to develop the HVO concept means that by design, pilots should always have a safe place to be in the Self-Controlled Area (SCA). Should an HVO pilot stray beyond the constraints of the HVO procedure, then advisories and alerting would increase appropriately in intensity and frequency to cue the pilot to return into conformance with the procedure. Previous uses of the term “conflict prevention” include a technique that alerted pilots of potential short-term conflicts as a result of turns and vertical maneuvers in the en-route phase of flight [18]. A multilayer approach to separation assurance and the prevention of conflicts due to the loss of aircraft-to-aircraft separation is an explicit part of the SATS HVO Concept of Operations design that uses both procedures and onboard automation. The multilayer system gives pilots support and guidance during the execution of normal operations and advance warning in case of procedure deviations or off-nominal operations.

II. SATS HVO Concept Overview

At towered airports, air traffic controllers (ATC) provide sequencing and separation for all Instrument Flight Rules (IFR) and participating Visual Flight Rules (VFR) aircraft. They control aircraft on the runway and in the controlled airspace immediately surrounding the airport. They coordinate the sequencing of aircraft in the traffic pattern and direct aircraft on how to safely land and depart at and from the airport. Conversely, at airports without control towers and radar coverage, IFR flights are limited to one operation at a time during instrument meteorological conditions. SATS HVO procedures rely on the establishment of a volume of airspace around designated airports referred to as a SCA where air traffic management functions are distributed between pilots and a ground based automated system called the Airport Management Module (AMM). Within the SCA, pilots are expected to fly according to SATS-HVO operational procedures and to accept responsibility for separation.

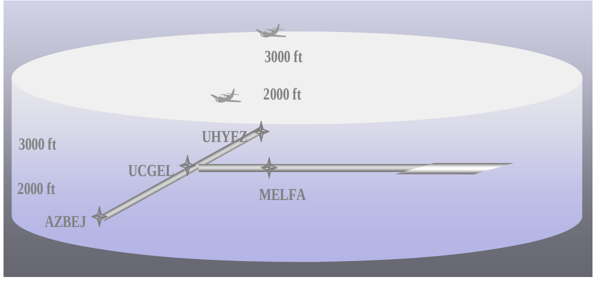


Figure 1. Generic SCA and Approach Geometry

The AMM provides landing sequence information to approaching aircraft via datalink on a first-come first-serve basis. The AMM acts as a ground based arbiter that centralizes the decision making function of “who goes first” without trying to make efficiency based inferences or give pilots instructions or clearances. This division of responsibilities between the cockpit (airborne separation) and the AMM (ground based sequencing) is fundamental to this concept since it enables the development of automated tools for these two functions: a distributed airborne separation function and a centralized sequence arbitration function. The AMM only retains the function that by its nature requires complete knowledge of the entire system and would therefore be very difficult to implement as a distributed entity (i.e., sequencing function placed in the cockpit). The rationale for this concept as well as a more in depth description of the functional structure of the National Airspace System (NAS) can be found in [5]. Prior applications include the method for separation assurance described in [1], where a concept of operations is presented that includes a similar division of air traffic management functions.

Aircraft separation in the SCA is based primarily on pilot procedures and supporting procedure automation in the cockpit. Minimum aircraft equipage includes Automatic Dependent Surveillance - Broadcast (ADS-B), air-ground datalink communication, GPS based navigation and a Cockpit Display of Traffic Information (CDTI).

Fig. 1 shows a diagram of a generic SCA and a SATS HVO approach path based on a GPS “T” approach consisting of two Initial Approach Fixes (IAF), AZBEJ and UHYES, an Intermediate FIX UCGEL and a Final Approach Fix MELFA. Two holding altitudes at 2000 and 3000 feet at each of the IAFs are part of the SCA.

Flights whose destination is a SATS airport must file an IFR plan indicating one of the IAFs as a fix in the route. Pilots must request ATC permission to transition from controlled airspace into the SCA after receiving an entry message from the AMM [4]. The AMM message includes the type of entry into the SCA, missed approach holding fix assignment and lead aircraft identification. Pilots must identify their lead aircraft on the CDTI and maintain proper spacing from it throughout the operation.

The SATS HVO concept relies on pilots complying with procedures, communicating their intentions and maintaining some degree of synchrony during operations. While minor deviations from these rules may have no negative effects, major procedure violations can be significant. A detailed description of the SATS HVO concept is out of the scope of this paper, but can be found in [2, 3 and 6].

III. Self-Separation in the SCA

Self-separation in the SCA relies on a multi-tier approach that includes three logically independent layers: procedural separation, Procedure Support (PS) automation and Conflict Detection and Alerting (CDA). A key element in the SATS HVO separation assurance concept is the logical independence of the three layers that prevents a failure at one level from affecting a lower level. This important design property must be preserved during implementation to maintain the safety of the system.

A. First Layer: HVO Procedures

The SATS HVO procedures represent the first layer of separation assurance. They were designed to be both simple and robust and have been formally proven to provide safe separation to approaching and departing aircraft [11, 12]. The formal verification process guarantees that if all participating pilots in the SCA comply with procedures, no loss of separation conflicts can occur. Pilot procedures were also validated in human-in-the-loop experiments and flight test, where it was shown that pilots were able to perform them proficiently and with no increased workload as compared to today's procedures [7, 8, 10, and 17]. Pilots reported increased situational awareness and no loss of separation conditions were observed. Key elements of the pilot procedures are: adhering to AMM provided sequence, maintaining IFR separation standards (3nm lateral and 1000 ft vertical) while using traffic depiction on a moving map display, and conforming to the instrument procedure.

Because the SATS HVO procedures are based on published instrument approach and departure procedures, the pilot must have on-board IFR navigation systems that provide primary flight guidance. Should the pilot deviate from the HVO procedure, the on-board primary flight guidance system would show that deviation and the pilot's role is to correct that error to return to conformance to the procedure. In order to be certified to fly IFR procedures, pilots must demonstrate proficiency in flying procedures to instrument-rating practical test standards criteria.

In order for pilots to violate the first layer of separation assurance, they must violate sequence, or spacing, or exceed the level of acceptable navigation guidance deviations.

B. Second Layer: Procedures Support Automation

The second layer in the separation assurance concept is provided by the Procedure Support (PS) automation, which includes a set of tools that provide pilot advisories, based on the traffic conditions and AMM entry information.

PS functionality provides help and guidance specifically related to the immediate task required by the operation. These advisories aid pilots during normal operating conditions, advise them in cases of minor deviations and non-normal conditions. The PS functionality is comprised of onboard conformance monitoring, approach spacing and altitude determination tools. The conformance monitoring tool advises pilots of altitude, speed and path deviations during all holding patterns, approach segments, and missed approach segments. The spacing tool provides in-trail spacing advisories and approach initiation time. The altitude determination tool identifies open holding altitudes at the IAFs (or MAHF).

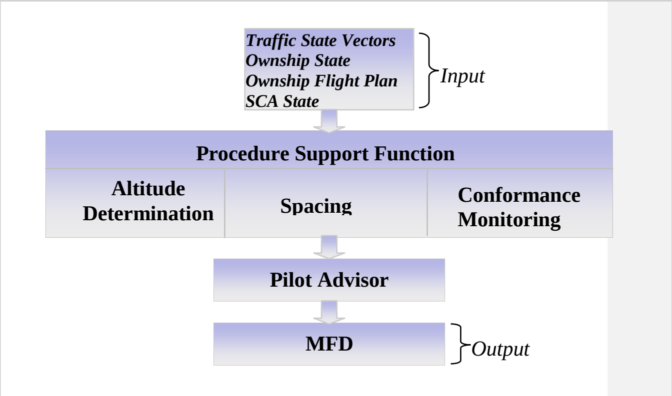


Figure 2: Functional Diagram of the Pilot Support Automation

The procedure support advisories are part of an experimental pilot notification tool called the Pilot Advisor (PA) that uses dynamic messages shown on the Multi-Function Display (MFD). A functional diagram of the PS logic is depicted in Fig.2.

1. *Conformance Monitoring Tool*

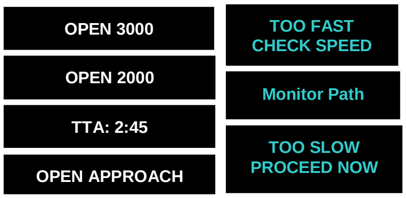
The conformance monitoring function checks if the aircraft satisfies all the conditions for the current phase of the procedure: lateral path, altitude and speed profile deviations are monitored during holding patterns, approach segment and missed approach segment. Pilots can perform small corrective maneuvers to fix deviations from flight path as soon as they are notified by the conformance tool, even before these deviations are predicted to cause traffic conflicts. The conformance status is also broadcast to all participating aircraft via an on-condition ADS-B message. The PA issues pilot notifications indicating conformance deviations based on the output from the conformance monitoring function. A subset of conformance monitoring messages displayed by the PA is shown in blue in Fig. 3.

The design of the conformance monitoring tool used the concept of a Nominal Approach Path (NAP). The NAP is comprised of a containment volume around the approach path and a set of conditions. An aircraft is in conformance to its NAP if the following conditions are satisfied:

- Aircraft remains within the lateral and vertical boundaries of the approach Containment Volume (CV).[**] The CV is defined by a lateral and vertical error that limits the accepted deviation of an aircraft from its nominal trajectory. A CV is defined for all segments of the approach and holding patterns. During a missed approach, pilots must remain outside of the approach segments' CV.
- Aircraft enters the SCA according to the information received in the AMM entry notification.
- Aircraft remains within intended speed profile during all the approach segments.
- Aircraft performs a missed approach according to procedures, returning to the assigned Missed Approach Holding Fix (MAHF).

2. *Altitude Determination Tool*

According to the SATS HVO approach procedure, aircraft entering the SCA or flying a missed approach procedure must proceed to the lowest available altitude at the requested/assigned IAF/MAHF. The Altitude Determination tool verifies traffic conditions and notifies pilots of the available altitudes. Fig. 3 shows two messages ("open 2000" and "open 3000") indicating that no traffic is occupying the given altitudes. This function was proven to increase pilot's situation awareness and reduce workload as shown in [9].



OPEN 3000

OPEN 2000

TTA: 2:45

OPEN APPROACH

TOO FAST
CHECK SPEED

Monitor Path

TOO SLOW
PROCEED NOW

Figure 3: Examples of Pilot Advisor Conformance Monitoring Messages

3. *Spacing Tool*

The Spacing tool provides an approach initiation time for aircraft entering the SCA based on the position of the leading aircraft and the speeds and type of aircraft involved. The tool includes two main functions: a planning function and a real-time spacing error function. The planning function computes the delay time for the trailing aircraft required to maintain a minimum distance between itself and the leading aircraft on approach. The trailing aircraft must remain in holding until the indicated delay has elapsed. The real-time function is a state-based tool that computes the nominal distance and time errors associated with the two aircraft positions relative to their planned trajectories. Its output is used to provide appropriate pilot advisories indicating potential spacing violations. The spacing function logic is based on the notion of "active spacing" developed in [15] for precision approaches. Each of the two aircraft may use independent approach profiles with the constraint that the final approach segment points must be the same. Dissimilar approach speeds are allowed. Fig. 3 shows two PA massages based on the Spacing tool: "TTA: 2:25" advises the pilot to initiate the approach in 2 minutes and 25 seconds, at which time the message "open approach" will would be shown.

4. *The Pilot Advisor (PA)*

The pilot advisor function prioritizes advisory messages from the various support tools. Input to the procedure support function includes traffic and ownship position vectors, ownship flight plan, AMM sequence information and the SCA traffic state. The pilot advisor selects the appropriate advisory message to be shown to the pilot from the procedure support function based on the current phase of flight. This PA window is displayed when there are active

---

[**] The CV envelopes navigation deviation error, so a pilot deviating to the edge of the CV is already aware of this condition due to information from the on-board navigation system.

pilot advisory messages. A complete description of the PA functionality can be found in [9, 16]. The procedure support function and the PA represent a second layer of safety in the SATS HVO concept helping pilots to perform normal procedures and providing advisories to correct minor deviations.

C. Third Layer: Conflict Detection and Alerting

The third layer is provided by the Conflict Detection and Alerting (CDA) logic, which is also part of the onboard automation. The CDA concept was designed to address cases of procedure violations or off-nominal conditions. It is based on a combination of state vector and procedure-based intent information. CDA symbology is displayed on the CDTI, which is part of NASA's experimental MFD.

The CDA was designed to provide conflict awareness to aircraft within the SCA during off-nominal conditions such as procedure violations and emergency operations. The CDA logic is based on a hybrid method that uses a combination of both ADS-B state vector and intent information to predict any loss of separation while minimizing false alarms. The method uses the concept of NAP conformance as part of the prediction logic. The NAP, as described earlier, represents the *implicit intent* of all participating aircraft in the SCA [14]. The intent of pilots flying HVO is procedure based and therefore known to all participating aircraft in the SCA. Pilots are expected to fly the approach path, keep appropriate spacing during approach and departure operations and maintain their intended speed profiles.

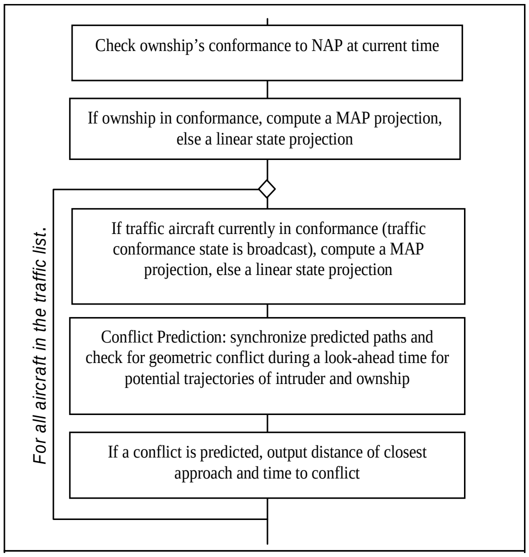


Figure 4. Hybrid Conflict Detection Logic

1. Conflict Detection

The pair-wise conflict detection logic selects different trajectory projections techniques depending on whether the aircraft is in conformance or not. An aircraft in conformance is expected to remain in its approach path; therefore, its predicted path is projected to be along the approach path. This is referred to as NAP path projection. Such assumption cannot be made for an aircraft out of conformance; therefore, its path can only be projected along its current state. This is referred to as state based path projection. This hybrid conflict detection scheme was developed to reduce false alarms that otherwise frequently occur in terminal areas. False alarms can have an adverse effect on pilots in that they may ultimately ignore real conflicts. Preliminary simulation studies [13] have shown that this hybrid approach outperforms state based only methods with regards to false and missed alerts. In addition, the technique was successfully implemented and used in human in the loop simulations and flight tests with very low incidence of false alerts during these tests.

2. Conflict Alerting

The conflict alerting algorithm developed for SATS HVO employs a multi-stage, asymmetrical alerting scheme. Multistage refers to the use of three levels of alerts, advisories, cautions and warnings; which are based upon the time to conflict. Asymmetrical alerting involves selecting the order and time in which pilots are notified of an impeding conflict based on a pair-wise inherently simultaneous conflict detection. More details on the conflict alerting logic and implementation can be found in [13].

- Asymmetrical Alerting

The alerting system was designed to be configurable so the time at which pilots are notified of impending loss of separation conflicts can be manipulated for experimental studies. While two aircraft running the conflict alerting algorithm can detect a conflict simultaneously, the time at which pilots are alerted can be delayed depending on certain conditions. In particular, this alerting method permits a conflicting aircraft that is out of conformance to be notified first so it can make trajectory and speed adjustments to correct its course before the conforming aircraft is notified. The same logic can be applied to a trailing aircraft on approach that, if notified first, can make speed adjustments to avert potential conflicts. Resolution advisories to potential loss of separation conflicts are not automated in the current system and are part of on going research.

- Multilevel Alerting

The increasing levels of alerting severity are advisory, caution, and warning and are based on the time to conflict. Values for the different time to conflict conditions that will trigger the multiple alert levels are configurable. All alerts are shown in the traffic display on the MFD. The pilot actions for the different alert levels are as follows:

Level 0 Alert: Non-Advisory: Information only. The ownship symbol is white and non-advisory traffic is shown as hollow cyan chevron symbols.

Level 1 Alert: Advisory: Pilot Awareness, pilot monitors separation and may need to adjust lateral or vertical path and or speed according to the situation. Advisory traffic is a cyan filled chevron symbol.

Level 2 Alert: Caution: Pilot Awareness, pilot monitors situation and action is likely required to adjust lateral or vertical path and or speed according to the situation. Lateral, vertical or a combination maneuver may have to be initiated. Advisory traffic symbol is an amber hollow chevron with a circle around.

Level 3 Alert: Warning: Immediate evasive maneuver required, vertical, lateral or both. Advisory traffic symbol is a red filled chevron with circle around plus an aural alert.

Alerts will remain on display as long as the conflict exists. Alerts are upgraded or downgraded based on the detection function output. Figure 5 shows four successive snapshots of a traffic conflict caused by an aircraft that deviates from its holding pattern, initiating the approach ahead of time. The pilot ignored the first PA message "Monitor path" and continued on approach. The conflict alert level went from advisory (not shown) to caution and warning before the pilot took corrective action and returned to its path. The alert level reverted to caution and advisory as the likelihood of a conflict was reduced.

Figure 5: Multi-level Alerting During Approach Sequence

IV. Summary

SATS HVO includes a unique approach to airborne conflict prevention and separation assurance that assists the pilot in a non-towered, non-radar, terminal environment. This method considers the procedural constraints of this environment and uses nominal approach path to determine if the pilot is "in conformance" with the SATS HVO procedures. HVO supports the pilot by a robust system that prevents conflicts by design and procedural support advisories, and in the event of procedural violations, provides conflict detection and alerting to cue the pilot to return into conformance with the procedure.

A multilayer approach to the prevention of conflicts due to the loss of aircraft-to-aircraft separation which relies on procedures and on-board automation was implemented as part of the SATS HVO Concept of Operations. The multilayer system gives pilots support and guidance during the execution of normal operations and advance warning for procedure deviations or off-nominal operations. The major concept elements of this multilayer approach to separation assurance and conflict prevention include the HVO procedures themselves; procedures support automation, and conflict detection and alerting. All the algorithms and functionality described in this paper have been implemented in aircraft simulation experiments in the NASA Langley Research Center's Air Traffic Operation Lab and on the NASA Cirrus SR22 research aircraft for flight test. Results from multiple research activities, including human-in-the-loop simulation experiments and flight tests, indicate the conflict prevention function of the HVO concept is crucial, especially during off-nominal operations. Further investigations into the effects of varied conflict geometries, alerting parameters, and procedural resolutions are ongoing and the subject of future publications.

Acknowledgments

The authors would like to thank Terence Abbott, author and developer of the Spacing Tool and a member of the SATS HVO concept development team for his invaluable contributions to this project. In addition, James Sturdy and Kumar Subramanian who developed most of the CDA and PA functionality implemented both in the ATOL simulation software and on the NASA Cirrus SR22 research aircraft. We would like to extend our thanks to Sheila Conway and Brian Baxley for their thoughtful remarks in reviewing this paper.

References

[1] Conway, S. and Consiglio, M., "A Method of Separation Assurance for Instrument Flight Procedures at Non-Radar Airports", AIAA Guidance, Navigation and Control Conference, August 2003, Monterrey California.

[2] Abbott T., Jones K., Consiglio M., Williams D., and Adams C., "Small Aircraft Transportation System, Higher Volume Operations Concept: Normal Operations", NASA/TM-2004-213022.

[3] Abbott T., Consiglio M., Baxley B., Williams D., and Conway S., "Small Aircraft Transportation System, Higher Volume Operations Concept: Off-Nominal Operations, NASA/TM-2005-213914.

[4] Magyarits S., Racine, N., Hadley, J., "Air Traffic Control Feasibility Assessment of Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO)," DOR/FAA/CT-05/26, May 2005

[5] Conway, S., and Consiglio, M., "Towards a Functionally Formed Air Traffic System-of-Systems", International Conference on Systems, Man and Cybernetics, October 10-12, 2005, (To appear)

[6] Williams D., Consiglio M., Murdoch J., and Adams C., "Preliminary validation of the Small Aircraft Transportation Systems Higher Volume Operations (SATS HVO) Concept", Proceedings of the 24th International Congress of the Aeronautical Sciences", August 2004, Yokohama, Japan.

[7] Williams, D., Consiglio, M., Murdoch, J., and Adams, C., "Flight Technical Error Analysis of the Small Aircraft Transportation System Higher Volume Operations (SATS HVO) Simulation and Flight Experiments", Proceeding of the 24th Digital avionics Systems Conference, October 30th, November 3rd, 2005. Arlington VA.

[8] Consiglio, M., Conway, S., Adams, C., and Syed, H., "SATS HVO Procedures for Priority Landings and Mixed VFR/IFR Operations at Non-Towered, Non-Radar Airports", Proceeding of the 24th Digital avionics Systems Conference, October 30th, November 3rd, 2005. Arlington VA.

[9] Adams, C., Consiglio, M., Conway, S., and Syed, H., "The Pilot Advisor: Assessing the Need for a Procedural Advisory Tool", Proceeding of the 24th Digital avionics Systems Conference, October 30th, November 3rd, 2005. Arlington VA.

[10] Williams, D., Murdoch, J., Adams C., "The Small Aircraft Transportation System Higher Volume Operations (SATS HVO) Flight Experiment using NASA's Cirrus SR22". Aviation Technology Integration and Operations Conference, 26 - 28 Sep 2005, Hyatt Regency Crystal City, Arlington, Virginia., AIAA 2005-7421

[11] Munoz, C., Dowek, G., and Carreno V., "Modeling and Verification of an Air Traffic Concept of Operations", Software Engineering Notes, Proceedings of International Symposium on Software Testing and Analysis, ISTTA 2004, Boston, Massachusetts, 2004.

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

[13] Consiglio, M., Munoz, C., and Carreno, V., "Conflict Detection and Alerting in a Self-Controlled Terminal Area", Proceedings of 24th International Congress of the Aeronautical Sciences, ICAS 2004, Yokohama, Japan, 2004.

[14] Carreno, V., and Munoz, C., "Implicit Intent Information for Conflict Detection and Alerting", Proceedings of the 23rd Digital Avionics Systems Conference, Salt Lake City, Utah, 2004.

[15] Abbott T., "Speed Control Law for Precision Terminal Area In-Trail Self Spacing", NASA/TM-2002-211742

[16] Adams C., Murdoch J., Consiglio M., and Williams D., "Incorporating Data Link Features into a Multi-Function Display to Support Self-Separation and Spacing Tasks for General Aviation Pilots" International Journal of Applied Ergonomics (to be published)

[17] Consiglio, M., Williams, D., Murdoch J., and Adams, C., "SATS HVO Normal Operations Concept Validation Simulation Experiment", Proceedings of the Aviation Technology Integration and Operations Conference, 26 - 28 Sep 2005, Hyatt Regency

Crystal City, Arlington, Virginia, AIAA 2005-7314

[18] Ballin, M., Hoekstra, J., Wing, D. and Lohr, G., "NASA Langley an NLR Research of Distributed Air/Ground Traffic Management", NASA-AIAA-2002-5826