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Conflict Prevention and Separation Assurance in Small Aircraft Transportation Systems

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A multilayer approach to the prevention of conflicts due to the loss of aircraft-to-aircraft separation that relies on procedures and onboard automation was implemented as part of the Small Aircraft Transportation Systems Higher-Volume-Operations concept. 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 were implemented in an aircraft simulation in the Air Traffic Operations Laboratory at NASA Langley Research Center and on the NASA Cirrus SR22 research aircraft.

I. Introduction

THE Small Aircraft Transportation Systems (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 (ATC's) workload or on overall National Airspace System (NAS) structures and principles. HVO procedures were designed for use at nonradar, nontowered airports in near all-weather conditions within a volume of airspace in which 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 because of turns and vertical maneuvers in the en route phase of flight [1]. 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.

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II. SATS HVO Concept Overview

At towered airports, ATCs 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 at and depart 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 in which 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.

The AMM provides landing-sequence information to approaching aircraft via data link on a first-come, first-served 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 because 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., a sequencing function placed in the cockpit). The rationale for this concept and a more in-depth description of the functional structure of the NAS can be found in [2]. Prior applications include the method for separation assurance described in [3], in which 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 data link communication, GPS-based navigation, and a cockpit display of traffic information (CDTI).

Figure 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

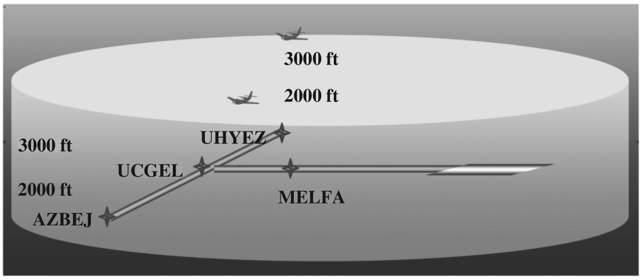

Fig. 1 Generic SCA and approach geometry.

UCGEL, and a final-approach fix MELFA. Two holding altitudes at 2000 and 3000 ft at each of the IAFs are part of the SCA.

Flights for which the 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 between controlled airspace and the SCA for approaches to and departures from a SATS airport. Transition procedures were developed and tested in a simulation experiment that looked at controller's workload and situation-awareness issues [4]. The AMM gives pilots landing sequences as part of entry messages that include the type of entry into the SCA, the 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. Although minor deviations from these rules might 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 the pilot procedures for normal operations and results from preliminary performance studies can be found in [5,6]. The concept of operations included a wide range of procedures for off-nominal conditions that comprise ground-based and onboard equipment failures, emergencies during approach and departures, and SCA reconfiguration due to winds or weather conditions [7]. Limited validation activities for the off-nominal-conditions procedures and required onboard equipage are briefly discussed in the next section.

III. Self-Separation in the SCA

Self-separation in the SCA relies on a multitier 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 during normal operations [8,9]. 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 two human-in-the-loop experiments and a flight test. The first piloted study required pilots to fly the same approach and departure scenarios and compared their workload, situation awareness, and proficiency during normal SATS procedures with those of today's ATC-managed procedures. The study showed that during SATS scenarios situational awareness was increased and workload levels were similar to those during current procedures [10]. In addition, no loss-of-separation conditions were observed because only normal operations were simulated. The same research goals and experiment design were used for a flight test that produced similar results [11]. Off-nominal conditions and mixed VFR and IFR operations were addressed in another human-in-the-loop experiment. The goal was to evaluate pilot performance and workload during landing-priority requests and when transitioning to VFR during approach. Results from the study showed that pilots were able to perform all the assigned tasks proficiently and with no increase in workload, when compared with normal SATS operations. A complete description of the experiment can be found in [12]. Another study addressing some of the pilot-interface issues associated with the use of the onboard automation developed for SATS HVO procedures was collocated with the off-nominal-conditions experiment. The study provided important feedback from pilots about usability, workload, and situation awareness associated with the procedure support functionality implemented as part of the onboard automation and, specifically, about some elements of the interface design. Results from the study are described in [13].

Because the SATS HVO procedures are based on published instrument approach and departure procedures, the pilot must have onboard IFR navigation systems that provide primary flight guidance. Pilots are expected to adhere to AMM-provided sequences, maintain IFR separation standards (3 n mile lateral and 1000 ft vertical) while using traffic depiction on a moving map display, and conform to the instrument procedure. Should the pilot deviate from the HVO procedure, the onboard primary flight guidance system would show that deviation, and the pilot's role is to correct that error to return to conformance with the procedure. To be certified to fly IFR procedures, pilots must demonstrate proficiency in flying procedures to instrument-rating Practical Test Standards criteria.

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.

The evaluation process of the SATS HVO concept design was composed of different activities of varying depth and rigor. In the beginning, the concept design was subject to multiple iterations based on feedback and advice provided by many subject matter experts. Then formal analysis of the normal operations procedures revealed a couple of instances in which loss of separation could have occurred under certain conditions. Procedures were amended as a result of the study, removing the potential sources of conflicts. The remaining validation activities consisting of piloted experiments, and flight tests revealed some efficiency limitations but not procedure flaws. No further modifications were made to the design because of these evaluation activities. Finally, a comparative study of flight technical-error metrics from the simulation experiment and flight test of normal operating conditions was conducted in an effort to validate the simulation tools. Analysis of results from both activities showed that pilots executed SATS HVO scenarios with equivalent levels of proficiency during flight and simulation [14] henceforth, increasing the confidence in the simulation results.

B. Second Layer: Procedure Support Automation

The second layer in the separation-assurance concept is provided by the 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 nonnormal conditions. The PS functionality is composed 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 missed-approach holding fixes (MAHFs)].

The procedure support advisories are part of an experimental pilot notification tool called the pilot advisor (PA) that uses dynamic

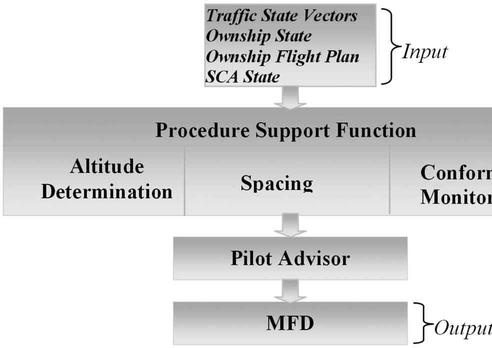

Fig. 2 Functional diagram of the pilot support automation.

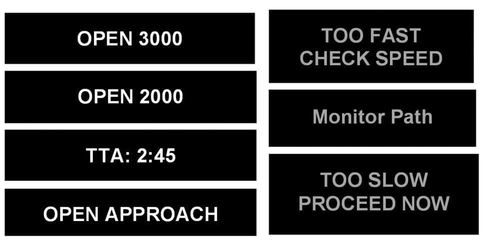

Fig. 3 Examples of pilot advisor conformance-monitoring messages.

messages shown on the multifunction 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 the holding patterns, approach segment, and missed-approach segment. Pilots can perform small corrective maneuvers to fix deviations from the flight path as soon as they are notified by the conformance withol, 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 on the right in Fig. 3.

The design of the conformance-monitoring tool used the concept of a nominal approach path (NAP). The NAP is composed of a containment volume around the approach path and a set of conditions. An aircraft is in conformance with its NAP if the following conditions are satisfied:

1) The 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 segment's CV.

2) The aircraft enters the SCA according to the information received in the AMM entry notification.

3) The aircraft remains within the intended speed profile during all the approach segments.

4) The aircraft performs a missed approach according to procedures, returning to the assigned 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. Figure 3 shows two messages (open 2000 and open 3000) indicating that no traffic is occupying the given altitudes. During normal operating conditions, adherence to procedures guarantees that it is safe to climb to the assigned MAHF, because consecutive approaches are assigned alternating MAHFs. In addition, the AMM entry logic prevents other aircraft from entering the SCA during a missed approach to the same IAF.

This altitude-determination tool was proven to increase pilots' situation awareness and to reduce workload in the human-in-the-loop simulation experiment previously mentioned [13].

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 types 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. Figure 3 shows two messages based on the spacing tool: "TTA: 2:25" advises the pilot to initiate the approach (time to approach) in 2 min and 25 s, at which time the message "open approach" will would be shown.

4. Pilot Advisor

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 pilot advisory messages. A complete description of the PA functionality can be found in [13]. 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 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 [16]. 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.

[¶]The CV envelopes navigation deviation error, and so a pilot deviating to the edge of the CV is already aware of this condition, because of information from the onboard navigation system.

Table 1

Alert level	Severity level	Purpose	Traffic symbols	Pilot actions
0	Nonadvisory	Information only	Hollow cyan chevron	——
1	Advisory	Pilot awareness	Filled cyan chevron	Pilot monitors the separation and may need to adjust the lateral or vertical path and/or speed according to the situation.
2	Caution	Pilot awareness	Hollow amber chevron within a circle	Pilot monitors the situation. Action is likely required to adjust the lateral or vertical path and/or speed according to the situation. A lateral, vertical, or combination maneuver may have to be initiated.
3	Warning	Require pilot action	Filled red chevron within a circle, plus an aural alert	Immediate evasive maneuver is required: either lateral, vertical, or both.

1. Conflict Detection

The pairwise conflict-detection logic selects different trajectory-projection techniques based on whether the aircraft is in conformance. 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 projection. Such an 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 [17] have shown that this hybrid approach outperforms state-based-only methods with regard 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. The CDA design was not the object of the piloted studies; therefore, specific data were not collected on traffic alerts, and pilots were instructed to perform their assigned tasks.

2. Conflict Alerting

The conflict-alerting algorithm developed for SATS HVO employs a multistage asymmetrical alerting scheme. Multistage refers to the use of three levels of alerts, advisories, cautions, and warnings that are based upon the time to conflict. Asymmetrical alerting involves selecting the order and time at which pilots are notified of an impeding conflict based on a pairwise, inherently simultaneous, conflict detection. More details on the conflict-alerting logic and implementation can be found in [17].

A. Asymmetrical Alerting. The alerting system was designed to be configurable so that the time at which pilots are notified of impending loss-of-separation conflicts can be manipulated for experimental studies. Although 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 with be notified first so that 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 ongoing research.

B. Multilevel Alerting. The increasing levels of alerting severity are advisory, caution, and warning and are based on the predicted time to loss of separation. Values for the different time-to-conflict conditions that will trigger the multiple alert levels are configurable in the current implementation. All alerts are shown in the traffic display on the MFD. The different alert levels and required pilot actions are described in Table 1. Alerts remain on display as long as the conflict exists. Alerts are upgraded or downgraded based on the detection-function output.

Figures 4–8 show five frames captured during a simulation run that exercises the conflict-detection and alerting logic. The five successive snapshots show a traffic conflict caused by an aircraft that deviates from its holding pattern, ignoring guidance and advisories, and initiating the approach ahead of time. For the simulation test, the configuration values for the three alert levels were 120 s for the advisory severity time, 60 s for the caution severity time, and 30 s for the warning severity time. In every case, the times represent the predicted time to loss of separation, which was configured as 3 n mile for lateral separation and 1000 ft for vertical separation. In addition, no alerting delay was configured for conforming or leading aircraft; in other words, the alerting was symmetric and both aircraft in a conflict saw the corresponding alerts at the same time. The features of the experimental MFD that are relevant for this example are labeled in the figures and their role is explained in each case.

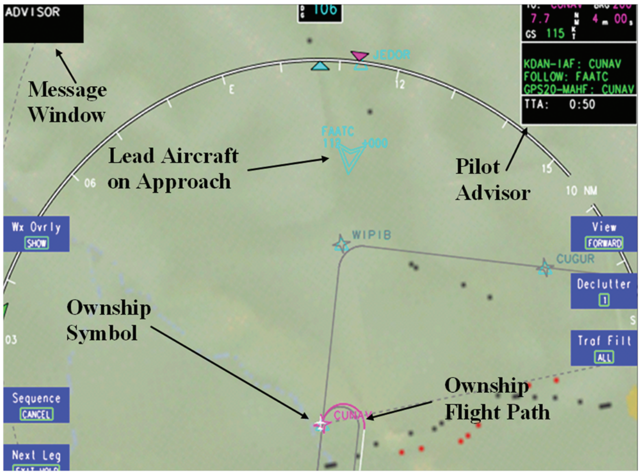

Fig. 4 Nonadvisory traffic symbol: the ownship pilot is still in conformance; the ownship flight path indicates the current leg in magenta and the next leg in white.

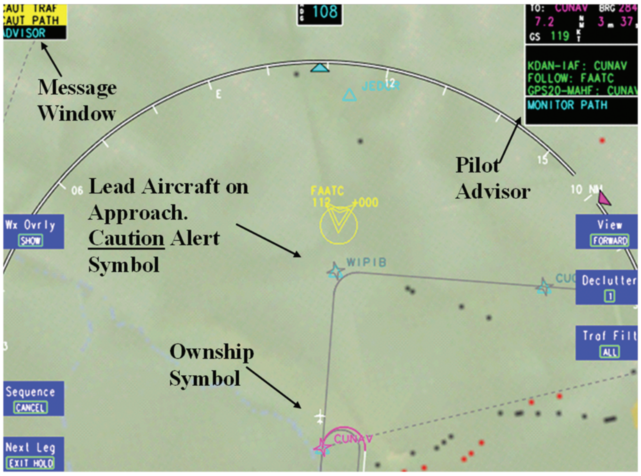

Fig. 5 Caution traffic-alert symbol: the ownship pilot is out of conformance.

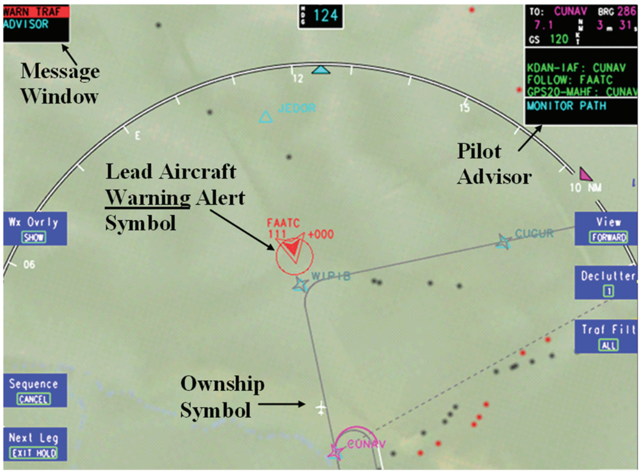

Fig. 6 Warning traffic-alert symbol: the ownship pilot is out of conformance.

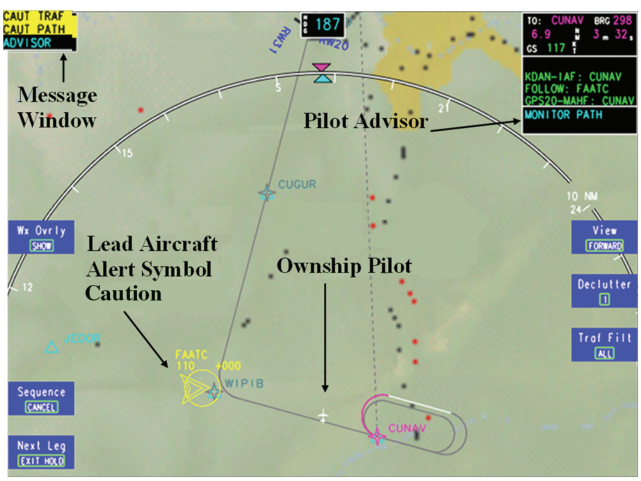

Fig. 7 Caution traffic-alert symbol downgrade: the ownship pilot turns back to hold but is still out of conformance; the lead aircraft begins the turn on final approach.

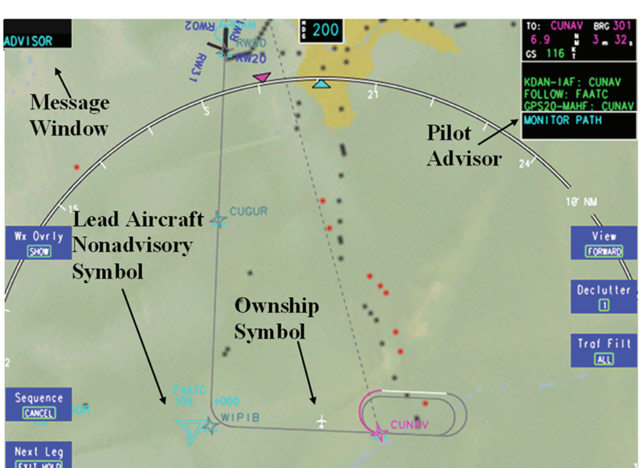

Fig. 8 Nonadvisory traffic symbol downgrade: the ownship pilot is turning back to the path but is still out of conformance.

At the beginning of the sequence in Fig. 4, there are two aircraft in the SCA; the ownship pilot, always shown in white, is expected to turn at the CUNAV IAF following the magenta line of the flight path. The lead aircraft, shown as a hollow cyan double chevron (a nonadvisory level), has initiated the approach and is expected to turn on final approach at the WIPIB intermediate fix. The function of the message window on the top left corner of the MFD is to capture the attention of the pilot, reinforcing the most critical recent change in the MFD; in this case, the advisor message indicates that there is a new advisory in the PA window. The time-to-approach (TTA) message tells the pilot to hold for no less that 50 min to preserve safe spacing from its lead aircraft. At this point, both aircraft are in conformance with their NAPs.

In Fig. 5, the ownship pilot deviated from guidance and ignored the PA message that advised to remain on hold for 50 min. Because of that maneuver, the ownship is out of conformance and the PA displays a monitor-path massage. The alert level is upgraded to caution, indicating a predicted loss-of-separation conflict within the next 90 s. The first alert level, advisory, is never triggered because the conflict is detected when the ownship deviated from its intended path, at which point the two aircraft were already too close. A solid cyan advisory alert would have been shown if the predicted conflict had been detected within 120 s but more than 90 s in the future.

In Fig. 6, the ownship pilot continues on approach in violation of procedures (the trailing aircraft must maintain safe separation from its lead) and ignoring path guidance and PA advisories. The alert level is upgraded to warning, indicating that a loss-of-separation conflict is predicted within the next 30 s. The severity of the predicted conflict is reinforced by the message window and an aural alert.

In Fig. 7, the ownship pilot begins to turn back to holding as the lead aircraft begins to turn on final approach. The alert level is downgraded to caution. The ownship aircraft is still out of conformance and the message window and the PA are informing the pilot of the condition.

In Fig. 8, the ownship pilot continues to turn back to holding but remains out of conformance and the alert level is downgraded to nonadvisory. The ownship pilot must return to holding until there is sufficient spacing to initiate the approach.

IV. Conclusions

SATS HVO relies on a unique approach to airborne conflict prevention and separation assurance that assists the pilot in nontowered, nonradar terminal environments. This multilayer approach considers the procedural constraints of this environment and uses the notion of a 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, it provides conflict detection and alerting to cue the pilot to return into conformance with the procedure.

Prevention of conflicts due to the loss of aircraft-to-aircraft separation relies on procedures and onboard automation and 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: procedure support automation, and conflict-detection and alerting.

All the algorithms and functionality described in this paper were implemented in aircraft simulation experiments in the Air Traffic Operations Laboratory at NASA Langley Research Center and on the NASA Cirrus SR22 research aircraft for flight tests. Although the evaluation process of the HVO procedures is not complete, results from multiple research activities (including human-in-the-loop simulation experiments and flight tests) are very positive, indicating that the multilayer method of separation assurance gives pilots an increased degree of situation awareness during normal operating conditions. Further research is necessary to address off-nominal conditions and the CDA logic and interface. Further investigations into the effects of varied conflict geometries, alerting parameters, and procedural resolutions are ongoing and the subject of future publications.

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