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Investigating Conformance Monitoring Issues in Air Traffic Control Using Fault Detection Techniques

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Conformance monitoring is a critical function in air traffic control to determine if aircraft are adhering to their assigned clearances so that safety, security, and efficiency can be maintained. Methods are needed to identify undamental conformance monitoring issues, to guide the development and use of new technologies that support the monitoring task, and to evaluate algorithms that could be employed in automated monitoring systems. An analysis framework has been developed to meet these needs based on classical fault detection techniques. Use of the approach for conformance monitoring research is demonstrated using simple implementations of the framework elements and flight-test data from different surveillance systems. Results suggest that significantly more effective conformance monitoring can be conducted in straight and level flight regimes when surveillance provides high-accuracy, high-update-rate, and high-order dynamic state information. In contrast, the use of high-order dynamic states can degrade conformance monitoring performance when aircraft are transitioning from one target state to another (such as at a waypoint or during an altitude change). Intent states offer an opportunity for improved conformance monitoring in these regimes in the future. Implications of these findings for conformance monitoring in air traffic control are discussed.

I. Introduction

A CONFORMANCE monitoring function is required in air traffic control (ATC) to detect any excessive deviations of aircraft from their cleared trajectories that could compromise system operation. This task is often performed by the air traffic controller comparing observations from radar surveillance to their expectations based on the active clearances for each aircraft. If the difference between the observed and expected behaviors exceeds some allowable deviation, then nonconformance can be determined. Because of limited surveillance and workload resources available to the controller, allowable deviations are often based on estimates of the tracking performance of the least capable aircraft types within the system or the widths of airways set by procedures. However, many modern aircraft are capable of significantly better performance, adding to the detection time of a deviation by one of these aircraft if they are held to the reduced standards. This performance issue is shown in Fig. 1 by the cross-track deviations calculated from radar position and flight plan data for two properly conforming commercial aircraft with different equipages. Both were flying the same en route segment a short time apart. The modern aircraft equipped with area navigation (RNAV) and global positioning system (GPS) demonstrates cross-track errors five times smaller than the older aircraft equipped with less sophisticated navigation aid tracking and inertial reference system (IRS) technologies.

Therefore, there is an opportunity to improve conformance monitoring in ATC, as well as significant interest in doing so to promote safe, secure, and efficient system operation. Improvements are potentially enabled through the application of automated tools to support the controller, especially during high workload or high criticality operations. They provide an opportunity to employ automated algorithms that utilize the benefits of advanced communication, navigation, and surveillance (CNS) technologies more fully. For example, algorithms could be designed to account for different aircraft navigational capabilities automatically and to utilize the higher-accuracy, higher-update-rate, and higher-content aircraft state information available in the future through advanced surveillance systems such as automatic dependent surveillance-broadcast (ADS-B).

Decision support tools are already being developed and deployed for conformance monitoring applications.[1] In a fashion analogous to the way controllers perform monitoring, most deployed systems simply flag nonconformance when the observed position deviation of aircraft from its assigned trajectory exceeds a predetermined threshold value.[2,3] It appears that many of these tools do not take full advantage of the opportunities afforded by advanced CNS capabilities, and it is unclear whether they were designed to address the conformance monitoring needs of current and future ATC operating environments adequately.

Hence, general analysis techniques are needed to help identify fundamental conformance monitoring issues in ATC, to guide the development and use of new technologies that support the monitoring task (such as what states should be provided from enhanced surveillance systems), and to evaluate algorithms that could be employed in automated monitoring systems. This paper describes an analysis framework to address these needs based on classical fault detection techniques. Application of the approach for conformance

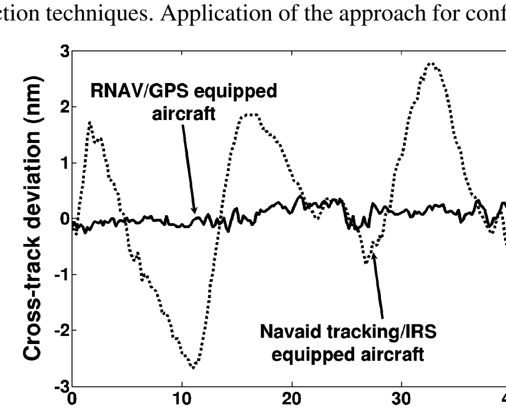

Fig. 1 Comparison of aircraft tracking capabilities.

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monitoring research in ATC is demonstrated by using the framework with flight-test data from different surveillance systems under various representative flight regimes. The key insights of this exercise in terms of technological and procedural implications for conformance monitoring in future ATC environments are discussed in detail.

II. Development of the Conformance Monitoring Analysis Framework

When an aircraft nonconformance is considered as a fault that needs to be detected in the ATC system, classical fault detection techniques[4,5] can be used to create the conformance monitoring analysis framework shown in Fig. 2. A conformance basis acts as the input to the aircraft being monitored in the actual system. A surveillance system provides observed state behaviors of this aircraft, while a conformance monitoring model is run in parallel to develop expected state behaviors for the aircraft when it is properly conforming to the conformance basis. The differences between the observed and expected state behaviors are used in a conformance residual (CR) generation scheme. The characteristics of the resulting residual are used in a conformance decision-making function to determine if the aircraft is conforming or not. Each of the framework elements identified in Fig. 2 is described in detail in the corresponding subsections that follow.

A. Conformance Basis

The conformance basis defines the criteria against which the observed behavior of an aircraft can be monitored. It is a representation of the currently active clearances or procedures that can be monitored against in each of the lateral, vertical, and longitudinal flight domains. Examples are listed in Table 1. The conformance basis for any given monitoring task can be a collection of the sub-elements in the various domains, or just one of them individually. For example, monitoring could be conducted on the union of the conformance basis elements in each flight domain (such as the full active flight plan) or on one of the elements individually (such as only the assigned heading during vectoring operations) depending on the priorities of the task at hand and the information available.

The availability of accurate conformance basis information is a fundamental requirement for the conformance monitoring task. The implications of this are discussed later when the framework is employed for flight-test data analyses.

Table 1 Examples of conformance basis

Example conformance basis	Lateral	Vertical	Longitudinal
Active flight plan	Assigned route	Cruise altitude	Cruise speed
Tactical amendments	Heading vector	Interim altitude	Interim speed
Standard procedures	Standard departure procedures		
	Standard terminal arrival route		
	Localizer signal	Glide slope signal	Approach speed

B. Actual System

The actual system contains the processes occurring in the ATC system relevant to the execution of the conformance basis for the aircraft being monitored. These processes are modeled by a standard feedback representation of the aircraft control system and dynamics, supplemented with upstream pilot and aircraft intent components. Pilot intent represents the intended actions on the part of the flight crew to execute their understanding of the conformance basis, whereas the aircraft intent represents the future behavior of the aircraft as programmed into any autoflight systems. The notion of intent and its relationship to the traditional dynamic states of position, velocity, and acceleration in the ATC domain is formalized in an enhanced surveillance state vector,[6] $X(t)$:

$$X(t) = \left\{ \begin{array}{c} \text{Position} \\ \text{Velocity} \\ \text{Acceleration} \\ \hdashline \text{Current target} \\ \text{Planned trajectory} \\ \text{Destination} \end{array} \right\} \begin{array}{c} \text{Traditional dynamic} \\ \text{states} \\ \\ \text{Defined intent} \\ \text{states} \end{array}$$

Under this representation, the future behavior of the aircraft is defined by intent at current target, planned trajectory, and destination state levels. These definitions are consistent with the way intent is communicated in the ATC system, how it manifests in aircraft autoflight systems, and how it is defined in the ADS-B specifications for future environments.[7,8] Each intent element in the vector exists at an incrementally higher-order level and produces inputs for the next state in the formalism, just as each element in the actual system representation generates appropriate target states for the downstream elements. One of the advantages of representing the aircraft processes in this manner is that it allows the characteristics of different surveillance environments to be visualized, as shown in Fig. 3 for the cases of the current radar and potential future ADS-B surveillance environments. The set of downward arrows shows where potentially surveillable states could be extracted from various points in the

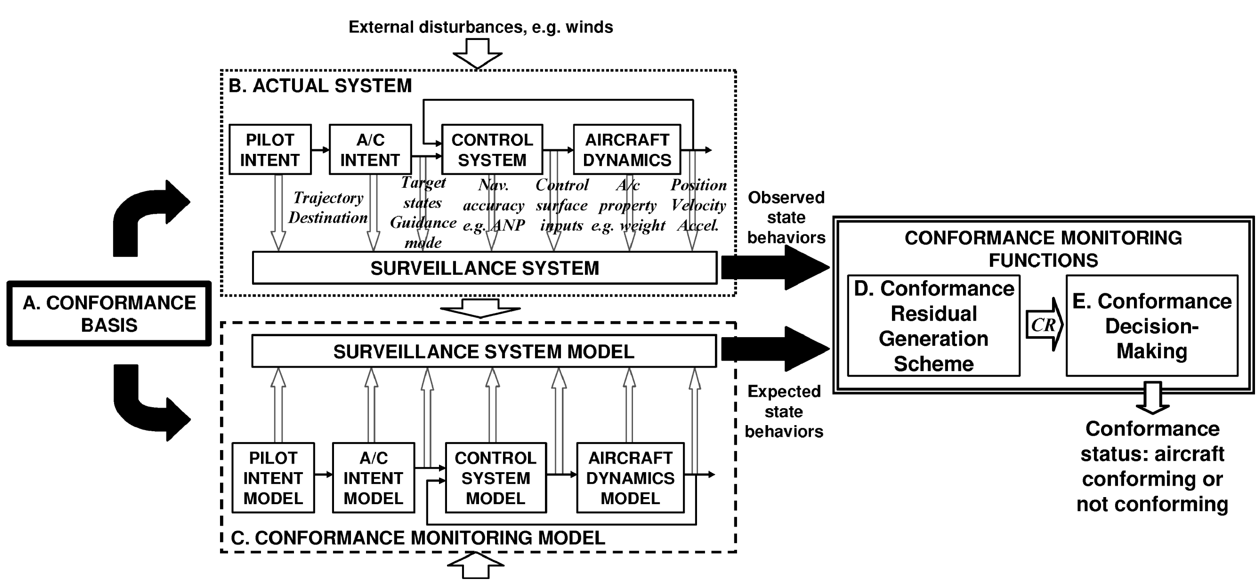

Fig. 2 Conformance monitoring analysis framework.

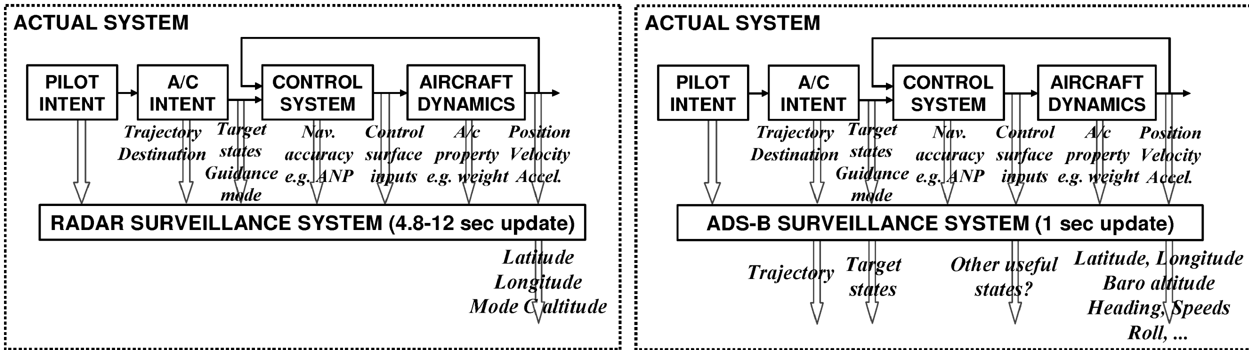

Fig. 3 Representation of radar and ADS-B surveillance environments.

aircraft process representation. Surveillance systems act as filters that allow certain states through with a given accuracy and frequency. For example, traditional radar surveillance systems only provide position and mode C altitude information every 4.8–12 s (depending on the type of ATC radar), whereas an ADS-B surveillance system allows many more dynamic and intent states to be accessible with higher accuracy and frequency. In addition, supporting states such as the actual navigation performance (ANP) of the aircraft could also be provided. Although the use of position or altitude alone allow for simple conformance monitoring criteria that can be readily understood by a human user, additional states could lead to a better understanding of the actual system behavior and, therefore, potentially enhance conformance monitoring capability. This issue is also examined in the application of the framework with flight-test data.

C. Conformance Monitoring Model (CMM)

The conformance monitoring model (CMM) is used to generate expected state values for a conforming aircraft to be compared with those surveilled from the aircraft in the actual system. The states surveilled from the actual system can also be used to help populate or provide inputs to the appropriate CMM elements, as represented by the downward arrow from the actual system to the CMM in the framework.

One of the greatest challenges in exercising the approach is the development of the CMM at a level of fidelity appropriate for the given application. It requires sufficient fidelity to undertake effective conformance monitoring (because errors can be perceived as nonconformance), but should not be so detailed that modeling uncertainty limits performance. A tradeoff is required to determine the fidelity required in the model for the ATC environment being monitored. In this study, low-, medium-, and high-fidelity model classifications were considered, with the primary distinction being the fidelity with which the aircraft dynamics were modeled. This is especially relevant during transitioning flight regimes, for example, at a lateral waypoint or during an altitude change, where the impacts of different dynamic models are most important. In a low-fidelity model, discrete state changes are assumed during transitioning flight, for example, a discrete heading change at a waypoint. In the medium-fidelity model, dynamics are approximated by a curve fit to observed behavior. A high-fidelity model would employ explicit models of the dynamics of the aircraft under the expected environmental conditions, for example, feedback control loops with appropriate transfer functions, loop gains, and disturbance characteristics. The impacts of different CMM fidelities and consequences associated with inappropriate fidelities for a given application are presented in the flight-test data analysis.

D. Conformance Residual Generation Scheme

The CR provides a quantification of the difference between the aircraft states observed from the actual system and those expected based on the CMM. There are a large number of residual generation functions that can be employed and tailored for different conformance monitoring applications. Indeed, the development of effective residual generation schemes is still a fertile topic in fault detection fields. To demonstrate the application of the approach in the ATC domain, a simple scalar residual generation scheme is presented for use in the later flight-test data analysis. It has the following form:

$$\mathrm{CR} = \sum \mathrm{WF}_x \cdot \boldsymbol{f}(\boldsymbol{x}_{\mathrm{obs}}, \boldsymbol{x}_{\mathrm{CMM}}) = \left(\sum \frac{|\boldsymbol{x}_{\mathrm{obs}} - \boldsymbol{x}_{\mathrm{CMM}}|}{2\sigma_x} \right) \Big/ \boldsymbol{n}$$

Here, $\boldsymbol{x}$ is a useful surveilled state, $\boldsymbol{x}_{\mathrm{obs}}$ is the observed value for each of those states from the actual system, $\boldsymbol{x}_{\mathrm{CMM}}$ is the expected value of the state from the CMM, $\boldsymbol{f}(\boldsymbol{x}_{\mathrm{obs}}, \boldsymbol{x}_{\mathrm{CMM}})$ is a function applied to the observed and expected state values, and WF_x is a weighting factor for each state component. A variety of different functions and WF strategies can be employed to develop a residual with the characteristics desired for a given application. The sample scheme above takes the absolute difference between the observed and expected state and normalizes it by an amount based on the standard deviations observed in each state σ_x during nominal conforming flight. The sum of each state component is then averaged over the number of states $\boldsymbol{n}$ used to generate the residual. Normalization of states based on standard deviations observed during nominal operation is an extension of the required navigation performance (RNP) philosophy,[9] which defines 95% probability (or 2σ for normally distributed variables) containment limits on the cross-track position state during nominal operation. When the residual is weighted in this way, it has the desirable property of automatically accounting for different aircraft navigational performance. Note that if multiple states are used simultaneously in a residual, for example, position *and* heading, this scheme combines the effects observed in each state into a scalar value. If knowledge of the separate behaviors in each state were required or preferred, alternative schemes could easily be developed to present the conformance behavior of each state independently, or to define a vector residual whose components were defined by each state behavior.

E. Conformance Decision Making

Once a CR has been generated, the decision-making process involves a determination of whether the residual behavior is characteristic of a conforming aircraft or not. The simplest and most commonly employed technique is to use a threshold on the CR with values above the threshold implying nonconformance. The threshold setting can vary as a function of many parameters, such as flight regime, environmental conditions, or the desired decision sensitivity, all of which are issues to be discussed later.

III. Assessing Performance of Conformance Monitoring

Conformance monitoring performance can be defined by various figures of merit, such as time-to-detection, correct detection/false alarm probabilities, simplicity, and cost. The properties required of a monitoring system and, therefore, the appropriate figures of merit to assess its performance, vary depending on the ATC application and environment of interest. The two figures of merit pursued further here are time-to-detection (TTD) of a true nonconformance and

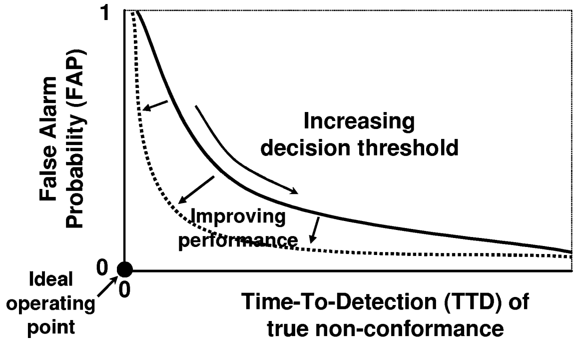

Fig. 4 FAP/TTD figures of merit.

false alarm probability (FAP) of alerting when an aircraft is actually conforming. These two figures of merit typically trade against each other as the decision threshold is varied, as shown schematically in Fig. 4. This is analogous to an inverse system operating characteristic curve, widely used for alerting system design,[10] to examine the tradeoff between false alarm and correct detection probabilities.

The characteristics of the chosen forms of the analysis framework elements result in a specific performance curve in the FAP/TTD space. Varying the placement of the decision threshold causes the operating point to move along the curve, allowing the impact of different surveillance systems, CMM, and CR generation schemes to be evaluated. Higher-performance designs possess curves closer to the ideal operating point of instantaneous detection with no false alarms located in the lower left corner of the FAP/TTD space. The curves can also be used to establish the threshold position that puts the operating point of a design closest to this ideal.

IV. Application of the Conformance Monitoring Analysis Framework in ATC

A. Methodology

The framework was used to analyze data from two flight tests of an experimental configuration Boeing 737-400 aircraft. During the flight tests, radar-based data were archived from the Federal Aviation Administration host computer system (HCS): this dataset represents current ATC surveillance capabilities. Aircraft-based data were also archived from the onboard ARINC 429 databus and GPS, providing states that could potentially be available in future surveillance environments such as through the ADS-B system. The relevant states archived from each of these two surveillance sources are listed in Table 2.

The flight tests included a number of intentional nonconformance behaviors conducted with the agreement of ATC. The data, therefore, provide an opportunity to examine conformance monitoring issues under different surveillance environments and flight regimes. In addition, the data can be used with different implementations of the analysis framework to examine effects of conformance basis uncertainty, CMM fidelities, and CR generation schemes. The following sections present key results from straight flight and waypoint transitioning flight in the lateral domain; and in level flight and altitude transitioning flight in the vertical domain. Longitudinal domain conformance monitoring is not explicitly considered here.

B. Lateral Conformance Monitoring During Straight Flight

To investigate lateral conformance monitoring involving a deviation from straight flight, the nonconformance scenario shown in Fig. 5 was analyzed.

The scenario started with 10 min (600 s) of nominal flight (segment 1), where the aircraft flew the assigned flight plan route. The pilot then initiated an intentional deviation phase (segment 2) where the aircraft turned left off of the flight plan course by 10 deg until a cross-track deviation of approximately 3 nm from the flight plan route had been achieved. At this time a recovery phase (segment 3) of flight returned the aircraft to the flight plan trajectory. This scenario was analyzed using the conformance monitoring analysis framework. The conformance basis was defined by the route segment of the HCS flight plan route identified in Fig. 5. A low-fidelity CMM was initially used for simplicity: the expected states were determined from an assessment of what they would be for a perfectly conforming aircraft with no disturbances, that is, cross-track position, $L_{CMM} = 0$ nm; heading angle, ψ_{CMM} = the route segment track angle corrected for wind; and roll angle, $\phi_{CMM} = 0$ deg because no turning was expected. The CR generation scheme used the weighted absolute differences of each state component described earlier. To investigate the use of different state combinations and surveillance environments, CRs were generated using cross-track position only (CR_L), representative of criteria used by most tools today; combined position and heading ($CR_{L\psi}$); and combined position, heading, and roll ($CR_{L\psi\phi}$) states from both the radar and aircraft data sources, according to the following equations:

Table 2 Flight-test data

Category	Radar-based data (6 s update[a])	Aircraft-based data (1 s update)
Dynamic states	Time	Time
	Latitude	Latitude
	Longitude	Longitude
	Altitude (mode C transponder)	Altitude
	Ground speed (HCS-derived)	Ground speed
		Calibrated airspeed
		Vertical speed
	Heading angle (HCS-derived)	Heading angle
		Track angle
		Roll angle
Intent states	Assigned altitude (when present)	Flight management system (FMS) desired track angle
		FMS distance to active waypoint
	Active flight plan route	FMS destination estimated time of arrival

[a]Each enroute ATC radar rotates once every 12 s, but the HCS information updates on a 6-s cycle.

$$CR_L = WF_L|L_{obs} - L_{CMM}|$$

$$CR_{L\psi} = (WF_L|L_{obs} - L_{CMM}| + WF_\psi|\psi_{obs} - \psi_{CMM}|)/2$$

$$CR_{L\psi\phi} = (WF_L|L_{obs} - L_{CMM}| + WF_\psi|\psi_{obs} - \psi_{CMM}| + WF_\phi|\phi_{obs} - \phi_{CMM}|)/3$$

The WFs for each state were based on twice the standard deviation of each state's error observed in the surveillance data during the nominal flight phase (segment 1), such that the residual was tailored to the tracking performance of the aircraft used in the flight trials. The resulting WFs and CRs are presented in Fig. 6.

The residuals are plotted relative to the time of the start of the deviation, so that negative times correspond to the nominal flight phase of the scenario and positive times correspond to times after the deviation has commenced. By using a threshold-based decision-making strategy, the proportion of CR values above a given threshold in the negative time region was used as the observed FAP, whereas the TTD was calculated from the first update time after the CR exceeded the threshold in the positive time region. The FAP/TTD curves for each surveillance case presented in Fig. 7 were generated by varying the placement of the threshold.

The aircraft-based data curves are observed to be steeper, indicating a higher signal-to-noise ratio relative to the radar-based data. The results also show the significantly better performance associated with access to aircraft-based data relative to the radar-based data due to the higher accuracy/higher update rate in the former. This is indicated by the location of parts of the aircraft-based curves nearer to the ideal operating point. Realistic minimum detection times (found from the point at which each curve first increases from zero false alarms) were 5–15 s with the aircraft-based data compared to 60–85 s possible with the radar data. In addition, for both surveillance sources, access to the higher-order dynamic states

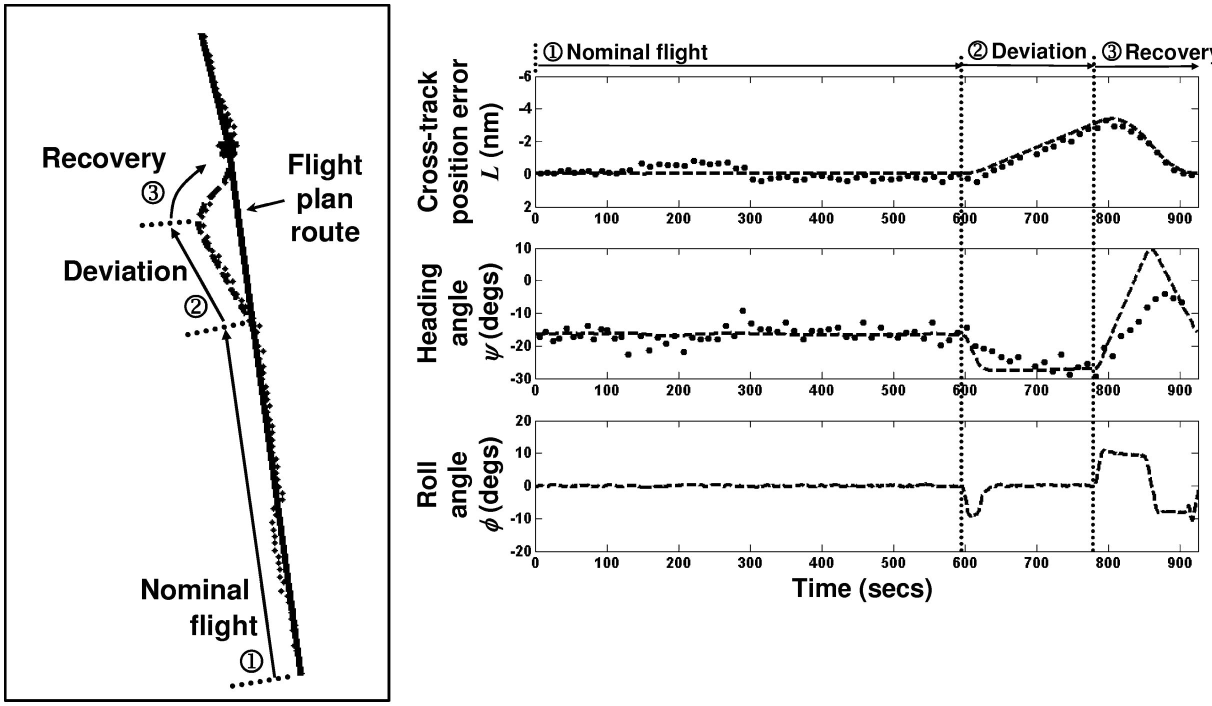

Fig. 5 Straight flight nonconformance scenario: ●, radar-based data and - - - -, aircraft-based data.

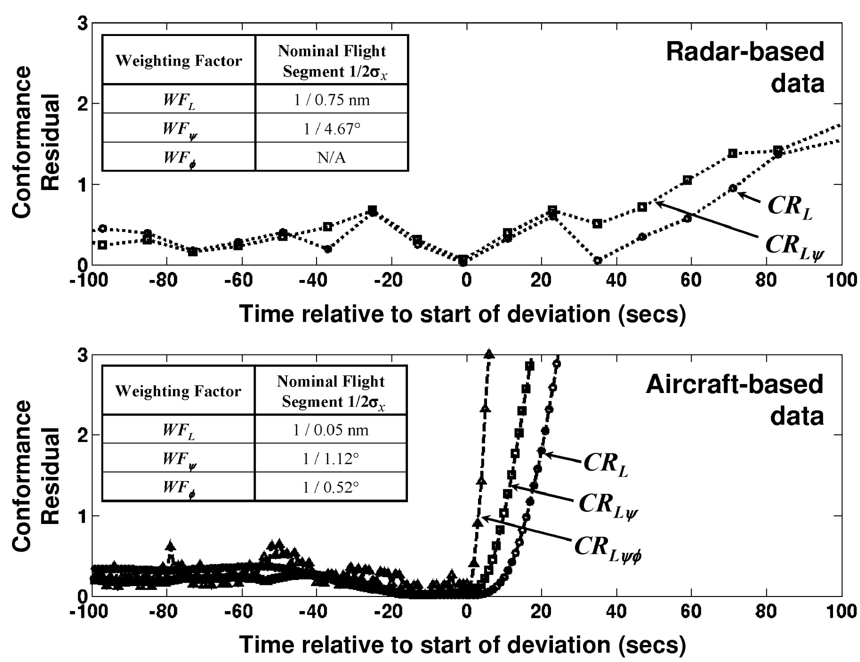

Fig. 6 Straight flight scenario CRs.

(heading and roll in this case) was observed to shorten the detection times significantly relative to the position-only results due to the lead information provided by these states. During straight flight, the higher-order states were not expected to vary, permitting a simple, low-fidelity CMM to be effective because the deviation was readily detected when the observed states did start to change. It is reasonable to expect similar general conclusions as these with other aircraft types (because the residual generation scheme automatically accounts for tracking performance) and other nonconformance scenarios (such as different heading angle deviations) during straight flight regimes. However, in more dynamic scenarios, such as during turbulence or maneuvering flight where the higher-order states are expected to change, it is harder to define the expected values accurately. The implications of this are discussed in the context of the lateral transitioning flight scenarios considered next.

Finally, the requirement for an accurate conformance basis implies that the benefits associated with enhanced surveillance of aircraft states can only be realized with accurate knowledge of the waypoints defining the route segment being flown. For automated conformance monitoring, this requires that any route amendments verbally communicated from a controller to a flight crew must be properly updated in the automation system. This does not always occur in the present system, when the active route in the HCS may not include some verbal route amendments[11] as a result of workload, procedure design, or controller-automation interface limitations. Enhancing the reliability of conformance basis information is another

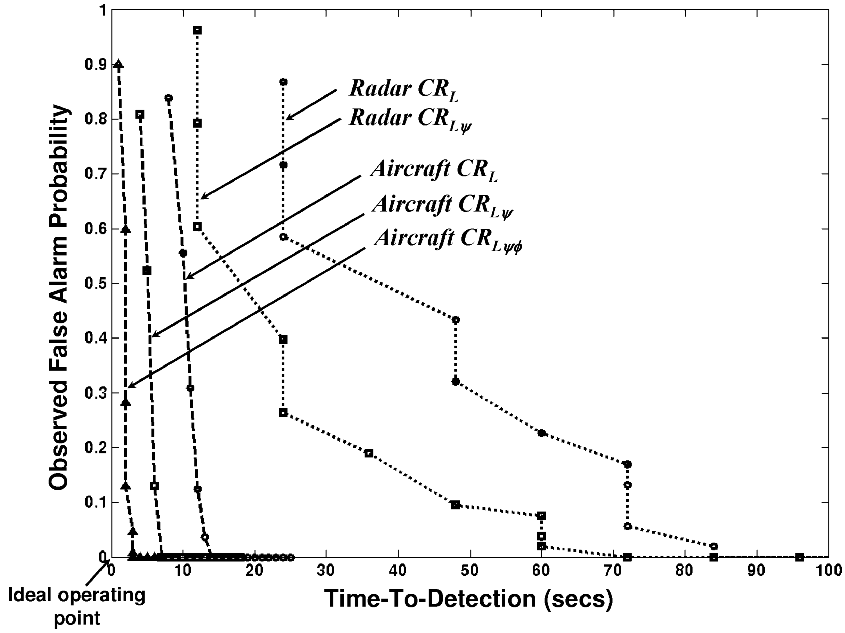

Fig. 7 Straight flight scenario figures of merit.

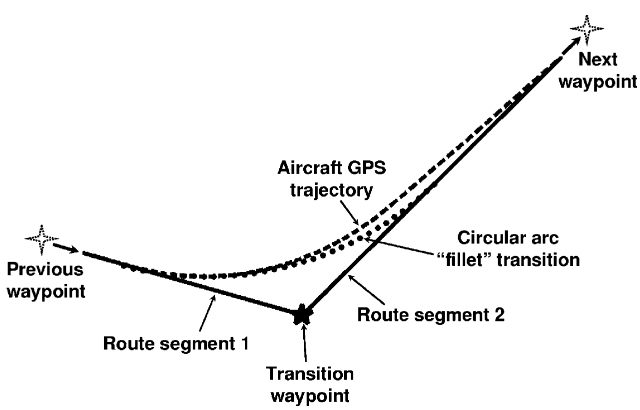

Fig. 8 Waypoint transition conformance scenario.

area where enhanced communication and surveillance systems, such as datalink and ADS-B, could add significant benefits in the future.

C. Lateral Conformance Monitoring During a Waypoint Transition

To contrast the lateral straight flight scenario, conformance monitoring was analyzed under two maneuvering scenarios involving waypoint transitions. In the first scenario, the challenges associated with lateral conformance monitoring at a waypoint transition, even for a conforming aircraft, are disscused. The second scenario investigated how these challenges affect the detection of an actual nonconformance event that occurs during a waypoint transition.

1. *Scenario 1: Conforming Behavior at a Waypoint Transition*

It is common for a lateral flight plan to be simplified by straight-line segments joining the waypoints that define the assigned route. This simplification was found to be appropriate for conformance monitoring along the route segments (as in the preceding analysis), but implies that a low-fidelity CMM contains a discrete heading change at the waypoint transitions between the route segments. In reality, aircraft exhibit gradually changing heading and roll states to accomplish the transition such that higher-fidelity CMMs may be required for effective conformance monitoring at these times. This issue is examined in the waypoint transition scenario shown in Fig. 8 for the case of a properly conforming aircraft.

Figure 8 shows the flight plan route based on straight-line route segments between the waypoints. These segments govern the expected aircraft states predicted by a low-fidelity CMM. Figure 8 also shows a simplified "fillet" approximation to the transition trajectory based on a circular arc. The use of a circular arc as an approximation to a transition trajectory has been established in the RNP minimum aviation system performance standards (MASPS)[9] and is supported by the provision of a turn radius parameter in the ADS-B MASPS.[7] The characteristics of this arc are defined in the RNP MASPS in terms of a radius of curvature and initiation point as a function of aircraft speed, transition angle, and maximum aircraft bank angle resulting from empirical analysis of nominal aircraft behaviors. Therefore, by the standards of the CMM fidelity classifications described earlier, this can be considered a medium-fidelity CMM. Finally, a high-fidelity CMM was also investigated to model the transition dynamics more completely using feedback control loop representations of heading and roll states with commercial aircraft characteristics. This scenario, therefore, provides an opportunity to examine the impacts of different CMM fidelities and their tailoring for the conformance monitoring task being undertaken.

CRs were generated using the same scheme and WFs as used in the straight flight scenario, but this time state expectations from both the low- and medium-fidelity CMMs were used during the transition. The resulting CRs using aircraft-based position alone (CR_L) are presented in Fig. 9: similar characteristics were displayed by the residuals using higher-order states and the radar-based data, but they are omitted for clarity.

Recalling that these are the CRs for a properly conforming aircraft, the increased residuals in the vicinity of the waypoint transition are dominated by errors in the CMM rather than nonconformance on the part of the aircraft. The errors at the transition are reduced by switching from a low- to a medium-fidelity model, but they are not eliminated because the circular fillet is not a perfect representation of the aircraft dynamics during the maneuver. Given these errors in the CMM, larger decision thresholds are required during the transition period to achieve a given false alarm performance, as shown in Fig. 9. For the low-fidelity CMM, a transition region threshold value of approximately 10 times the nontransition region value is required in order to achieve an equivalent false alarm performance, whereas it is approximately 3 times the nontransition region value for the medium-fidelity CMM. The placement and width of the transition region where the thresholds are increased is an indication of the expected initiation time and duration of the transition maneuver, respectively. The CMMs used here were tuned to match the parameters of the actual maneuver accurately. In practice, there can be significant variability in how the transition is executed by different aircraft types and autoflight systems, resulting in spikes in the CR (especially

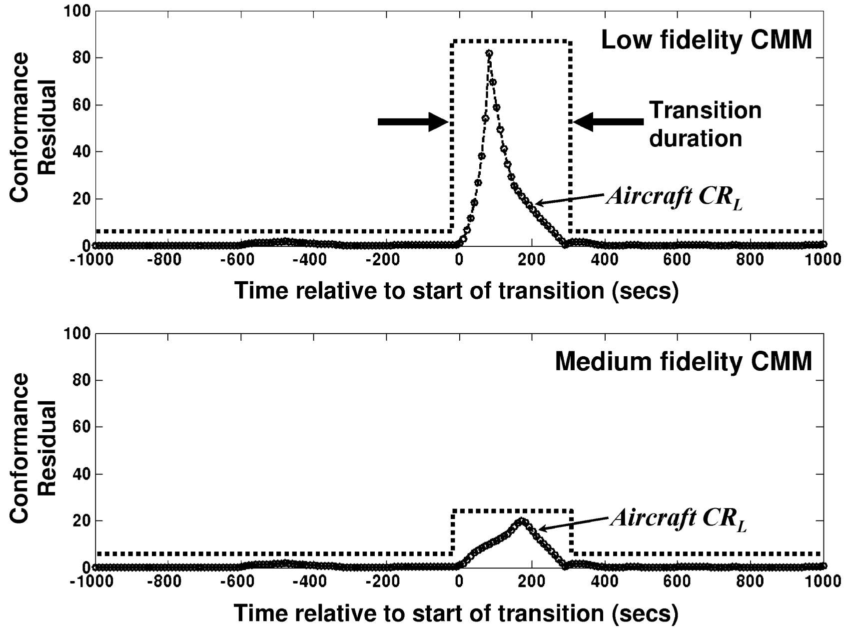

Fig. 9 Waypoint transition conformance scenario residuals and thresholds.

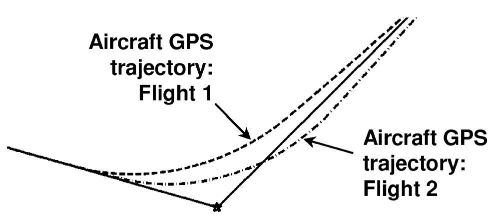

Fig. 10 Waypoint transition ground tracks.

when higher-order states are used) if they are different from those expected.

The use of high-fidelity CMMs was also considered to further reduce the CR errors at the transition. However, the transition dynamics contained so much variability that the high-fidelity models were unreliable. Figure 10 shows an example of the differences between the GPS ground tracks over the two flight tests for the same transition. These differences are possibly due to dissimilar aircraft properties, for example, weight; environmental conditions, for example, winds; or guidance mode, for example, autopilot vs manually flown, between the two flights. Hence, even if a high-fidelity CMM were developed that accurately predicted the transition trajectory for flight 1, it would have significant errors if applied to flight 2, unless it contained sufficient fidelity to capture all of the key variables causing the differences in observed behavior and accurate information on each of these key variables were available. Models of such high fidelity are generally impractical to develop for a wide range of normal ATC operations, although they may be required for some specialized conformance monitoring tasks where detailed transition conformance monitoring is essential.

With the low-fidelity CMM being ineffective due to modeling errors perceived as nonconformance and the high-fidelity CMM containing too much variability to be reliable, a medium-fidelity model appears to be most appropriate in this case. The errors introduced by the incomplete dynamics model and uncertainty in the transition maneuver implies that there is significant uncertainty in the conformance basis at waypoint transitions, which, in turn, hinders conformance monitoring efforts. These uncertainties could be reduced through procedural and technological approaches. Procedurally, the size of the transition region could be made large enough to account for the expected range of transition maneuver behaviors across the aircraft types within the system. However, this would increase the size of the transition region where conformance monitoring capability is reduced due to the larger thresholds. Alternatively, aircraft could be required to fly some type of standard transition, where the initiation point and duration are predetermined, although this may not be possible for all aircraft types. An alternative technical approach is to make parameters defining how the aircraft will execute the available maneuver (such as turn radius and initiation point calculated in an autoflight system) available to the ground through advanced surveillance, so that they can be known before the transition is executed, as has been suggested for the ADS-B message set in the case of the turn radius.

2. *Scenario 2: Nonconforming Behavior at a Waypoint Transition*

Because of the requirement for larger thresholds at transitions just identified, there are significantly greater challenges to detecting actual nonconformance events at transitions relative to the stable straight flight environment. This is illustrated through a transition nonconformance scenario involving a sequence of waypoints (WPs) shown in Fig. 11.

In this scenario, the aircraft was expected to fly to WP3 after WP2, but instead flew toward WP4, resulting in a route segment with a 10 deg heading difference from that expected. This scenario, therefore, involves a 10 deg heading nonconformance at a transition point, allowing the results to be compared directly with the 10 deg heading nonconformance from the straight flight segment described previously.

Figure 12 presents the FAP/TTD results for this scenario when the same CMMs and CRs as in the preceding section are used. Only the curves corresponding to the aircraft-based data are shown, and the results from the straight flight scenario are also included for comparison.

These results show that the larger thresholds required in the transitioning domain significantly increase the TTD of the 10 deg nonconformance during the transition. Minimum detection times of 5–15 s in the straight flight region with a low-fidelity CMM increase to 120–140 s in the transition region with a medium-fidelity CMM and to 225–250 s with a low-fidelity CMM. These results also show that the benefits associated with using higher-order states observed in the straight flight scenario are reduced, or, in some cases, even negated in the transitioning case. This is evident in the low false alarm regions of the transition results in Fig. 12, where the medium-fidelity curves using position, heading, and roll angle states are further from the ideal operating point than those that use only position and heading. In the case of the low-fidelity CMM, the best performance is

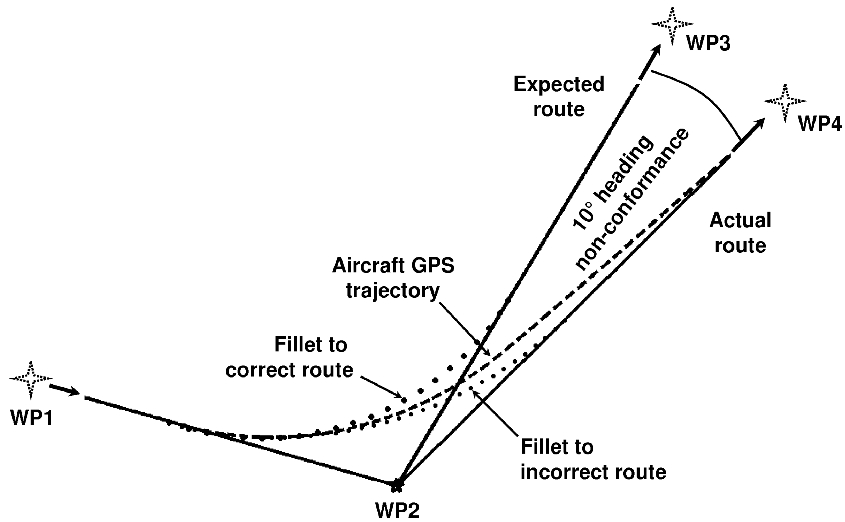

Fig. 11 Waypoint transition nonconformance scenario.

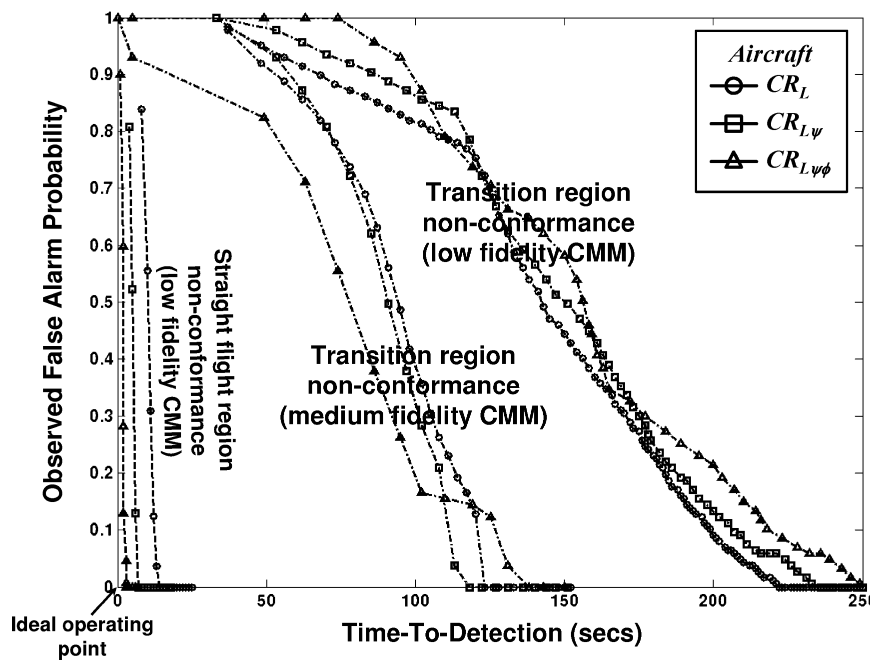

Fig. 12 Waypoint transition nonconformance scenario figures of merit.

associated with position alone. At these times, the modeling errors and noise in the higher-order states are so large as to produce worse performance than curves that just use the lower-order states. Again, this shows the importance of choosing a CMM at a fidelity appropriate to the monitoring task.

Advanced surveillance systems such as ADS-B hold the promise of enabling intent states to also be made available for conformance monitoring purposes. This could have a particular benefit in transitioning flight regimes where access to the current target or trajectory level intent states could allow rapid detection of any nonconformance by the presence of discrepancies between the observed and expected intent values. The focus is shifted from dynamic state conformance monitoring to intent state (autoflight programming) conformance monitoring. For example, nonconformance could be detected as soon as the commanded heading was input to the autopilot if current target intent states were observable, or as soon as the incorrect waypoint was programmed into the FMS if the trajectory level intent states were observable. These states are resident in the aircraft autoflight system and could potentially be downlinked in future surveillance environments. These benefits are limited only to the degree that there can be uncertainty as to whether the aircraft is in a flight guidance mode to follow the programmed intent (they would not be useful, or even potentially available, if the aircraft was being manually flown) and that there is sufficient capability and bandwidth in the surveillance system to make the required states available.

D. Vertical Conformance Monitoring During Level Flight

In order to illustrate the application of the analysis framework for vertical conformance monitoring during level flight, a scenario involving an unscheduled descent from an assigned altitude was examined, as shown in Fig. 13. A flight-path angle state was calculated for the aircraft-based data case from the vertical speed, V_{VS} and ground speed, V_{GS} states available from the databus. CRs using combinations of altitude, A and flight-path angle, γ states were generated of the same form used in the lateral case, according to:

$$\mathrm{CR}_A = \mathrm{WF}_A |A_{\mathrm{obs}} - A_{\mathrm{CMM}}|$$

$$\mathrm{CR}_{A\gamma} = (\mathrm{WF}_A |A_{\mathrm{obs}} - A_{\mathrm{CMM}}| + \mathrm{WF}_\gamma |\gamma_{\mathrm{obs}} - \gamma_{\mathrm{CMM}}|)/2$$

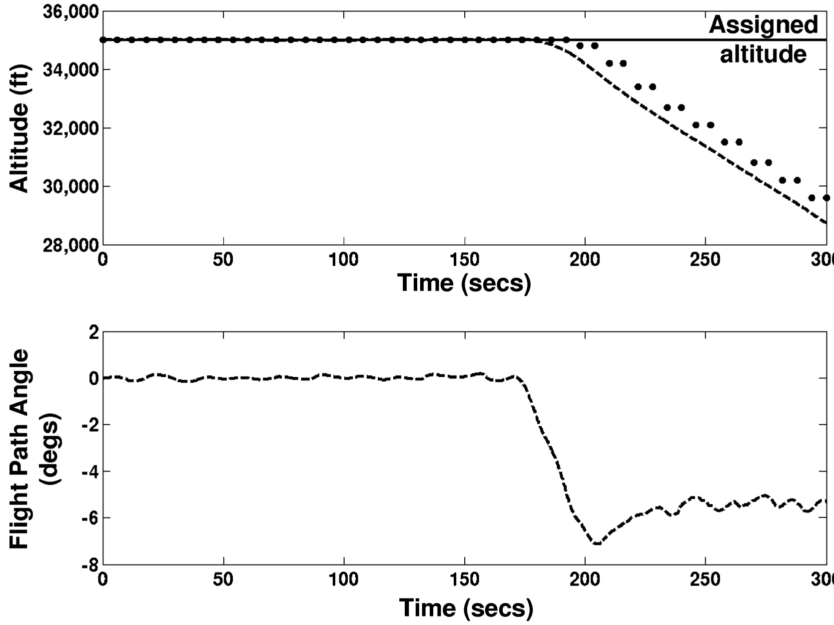

Fig. 13 Level flight nonconformance scenario: ●, radar-based data and – – –, aircraft-based data.

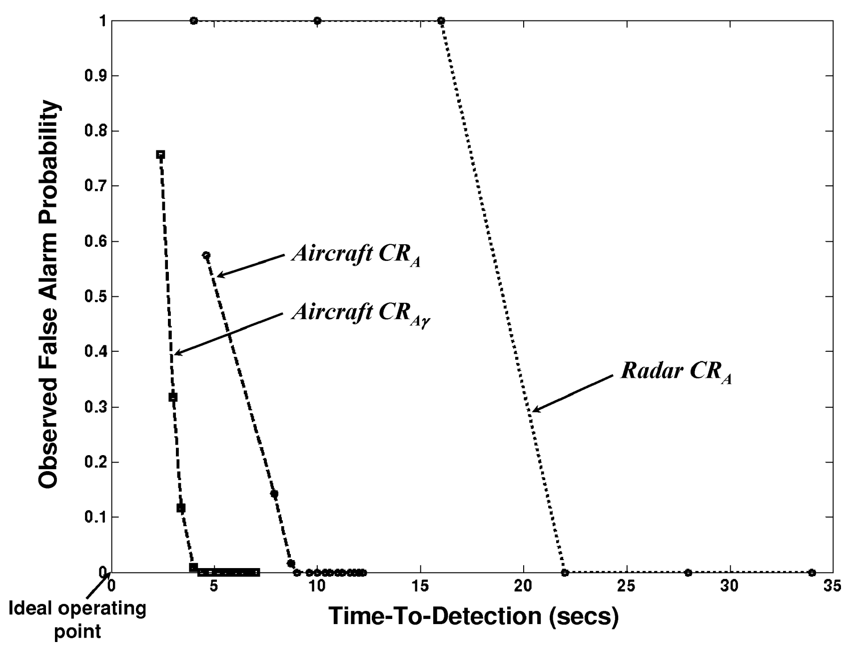

Fig. 14 Level flight nonconformance scenario figures of merit.

Conformance monitoring during level flight relies on an accurate conformance basis derived from a properly updated assigned altitude in the automation system. A low-fidelity vertical CMM was used where the expected states were defined by a perfectly conforming aircraft, that is, $A_{\mathrm{CMM}} = 35{,}000$ ft and $\gamma_{\mathrm{CMM}} = 0$ deg. As before, WFs for the states were based on twice the observed standard deviations in the radar and aircraft-based data during the nominal (conforming) part of the flight. The resulting FAP/TTD figures of merit were generated from the CRs and are shown in Fig. 14.

Results similar to the lateral deviation scenario are observed. The higher-quality/higher-update-rate aircraft-based data are associated with more rapid detection of the vertical deviation relative to the radar case. Realistic detection times of 8 s with the aircraft altitude data are compared to 22 s with the radar altitude data. In addition, the higher-order dynamic state (flight-path angle) provides added lead time, decreasing the minimum aircraft-based detection time to 4 s when it is used in the residual. The primary differences from the lateral case are that the radar-based altitude data (based on mode C transponder data that is discretized to the nearest 100 ft) allow only a binary decision about the conformance status of an aircraft with either 100% or 0% false alarms. Additionally, there is higher tracking accuracy in the vertical domain relative to the lateral as demonstrated by the use of a weighting factor of 1/50 ft on the altitude compared to 1/300 ft on the cross-track position. This results in a higher sensitivity in the vertical domain to a deviation of a given amount.

E. Vertical Conformance Monitoring During Altitude Transitions

Conformance monitoring during vertical transitions is the most challenging of the environments in the current ATC system because there is poor knowledge of the trajectory to be flown and, hence, poor conformance basis information during the transition. This is analogous to the problems discussed in defining the lateral transition path, but it is compounded by the presence of a large number of

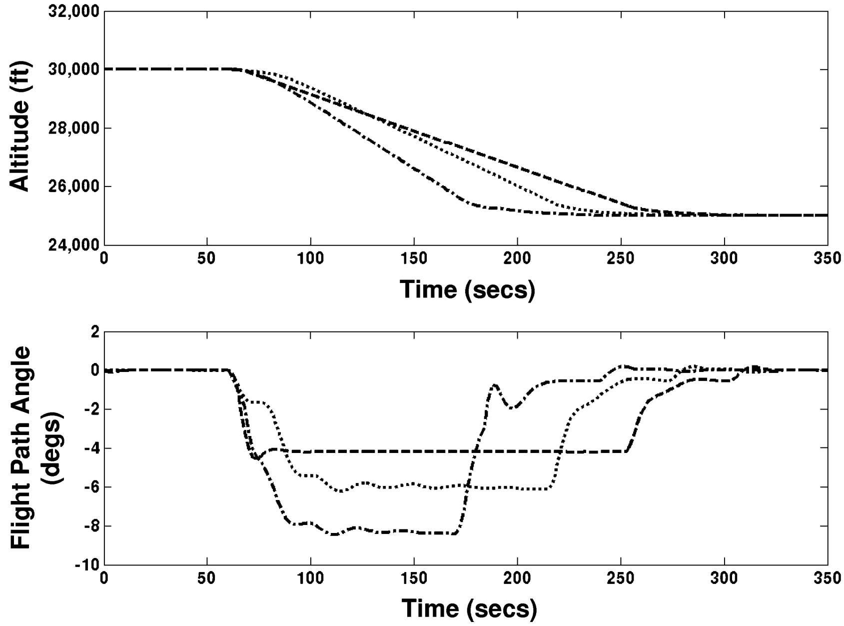

Fig. 15 Simulated altitude transition dynamic states: – – –, V/S mode (−1500 ft/min); . . . . , FLCH mode; and –·–, FLCH mode + speedbrakes.

vertical automation modes[12]; greater dependence on aircraft weight, aerodynamic configuration, and thrust setting; higher sensitivity to atmospheric property forecast errors, in the wind and temperature profiles used by the FMS to calculate optimal trajectories; and the common use of clearances in the form of simple altitude crossing restrictions at a downstream fix that can be met in many different ways.

Some of these challenges are demonstrated in a vertical transition scenario flown in a simulator. It comprised straight and level flight at 30,000 ft for 1 min, followed by a descent to 25,000 ft, under the following conditions: 1) vertical speed (V/S) autoflight mode with descent commanded at −1500 ft/min, 2) flight-level change (FLCH) autoflight mode with the descent profile calculated by FMS, and 3) FLCH autoflight mode with speedbrakes deployed.

Each of these scenarios represents a realistic approach to flying the descent in the ATC system. The first two cases highlight the impacts of flying the descent through different vertical automation modes, whereas the speedbrake case shows the effects of a different aerodynamic configuration. The resulting vertical states archived for one simulation run for each condition are shown in Fig. 15.

This illustrates the significant uncertainty in the path flown during the vertical transition and, therefore, the uncertainty in the conformance basis and/or CMM, despite the same nominal start/finish altitudes and initiation point. In the actual ATC system, the vertical transition initiation point may also be highly uncertain depending on how the pilot intends to fly the descent, compounding the trajectory uncertainty still further. Because of the fundamental requirement for an accurate conformance basis, these issues severely limit the conformance monitoring performance that can be achieved. This is the case even if enhanced surveillance provides accurate information on the aircraft's altitude and flight-path angle states because the expected value for each of these states is still unclear. In the current ATC system, these challenges are handled by blocking off columns of airspace around vertically transitioning aircraft, thereby removing the requirement for accurate conformance monitoring during these flight regimes. However, this is an inefficient use of airspace. In the future, the downlink of FMS-computed vertical transition intent trajectories could be used to define the conformance basis, which would allow dynamic states to be used for improved conformance monitoring and more efficient airspace usage.

V. Conclusions

The tailoring of classical fault detection concepts for conformance monitoring research in ATC has been described. Simple implementations of the analysis framework have been used with flight-test data to demonstrate the insights that can be gained from its use. Given that the approach is based on a classical fault detection framework, it is readily adaptable for use with alternative or more sophisticated techniques to tailor it for specific conformance monitoring applications.

The results showed that more effective conformance monitoring can be conducted in straight and level flight environments when surveillance systems provide high-accuracy, high-update-rate, and high-order dynamic states. These findings were contrasted with the greater conformance monitoring challenges during periods when an aircraft transitions from one target state to another, such as at a waypoint or during an altitude change, because the modeling challenges in these cases make it difficult to separate nonconformance behavior from small errors in model dynamics and maneuver timing. As a result, larger decision thresholds are required during transitioning flight that add to the detection time for nonconformance when only dynamic states are available. However, access to intent states could be highly beneficial at these times to improve conformance monitoring, as long as the aircraft is flying in an autoflight-coupled mode, that is, not being flown manually.

The framework composition and the results also highlighted the fundamental importance of accurate conformance basis knowledge in each flight regime. Improvements enabled by enhanced aircraft surveillance are only realizable under conditions where accurate knowledge of the conformance basis exists. Improvements to the definition and surveillance of the conformance basis in future ATC environments is, therefore, as important as the enhanced surveillance of traditional aircraft states if more effective conformance monitoring is to be enabled.

These findings have significant implications for future ATC system design, both procedurally and technologically. Procedurally, complete updating of clearances at all times in automation systems could be introduced, whereas advanced technologies such as datalink hold promise for the more reliable capture of clearances and, therefore, of the conformance basis. The introduction of advanced surveillance systems that can provide the beneficial dynamic and intent states to a monitoring tool hold significant potential for allowing improved conformance monitoring in future ATC environments. In transitioning environments where only dynamic states are available the larger thresholds required imply that ATC procedures should generally not require rapid detection of nonconformances at transition points, for example, by keeping aircraft widely separated at these points. If rapid detection is essential to a particular ATC operation, accurate modeling of the aircraft transition dynamics is needed. This could be achieved either through the development of sophisticated high-fidelity modeling techniques or through standardization in how transition maneuvers are to be flown. In each case, this helps to make the conformance basis definition more reliable and, therefore, to make conformance monitoring more effective.

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