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Initial Efforts Toward Identifying Aviation Alerting System Dissonance

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The potential for conflicting information to be transmitted by different alerting systems is growing as these systems become more pervasive in aerospace. Newly introduced alerting systems must be carefully designed to minimize the potential for and impact of alerting conflicts or dissonance. A methodology for dissonance analysis has been developed recently to provide a foundation for understanding, identifying, and resolving dissonance between alerting systems. One area of application of this method is the proliferation of decision-support systems for air traffic management. With alerts from multiple independently developed alerting systems, pilots and air traffic controllers may have difficulty reconciling dissonant alert information. One example application is the recently proposed airborne conflict management (ACM) system, which must operate in conjunction with existing traffic alert and collision avoidance systems (TCAS). Alerts from ACM should be harmonized with alerts from TCAS and vice versa. As a case study, dissonant operating regions for TCAS and ACM are articulated, and it is shown that in some geometries potentially undesirable TCAS advisories may occur following action taken in response to ACM alerts.

Nomenclature

A_{ij} = region in state space where alerting system i is in jth alert stage
a = distance until closest point of approach between two aircraft
$\boldsymbol{a}$ = alert stage of alerting system
B_{CAZ} = safety buffer distance for airborne conflict management (ACM) collision avoidance zone (CAZ) alert
B_{DMODTA} = safety buffer distance for traffic alert and collision avoidance systems (TCAS) traffic advisories (TA) alert
B_{DMOD} = safety buffer distance for TCAS resolution advisories (RA) alert
B_{PAZ} = safety buffer distance for ACM protected airspace zone (PAZ) alert
b = miss distance between two aircraft
f_{ij} = jth predicate of ith alerting system
r = range between two aircraft
$\dot{r}$ = range rate between two aircraft
S_{jk} = intersection of alert spaces A_{1j} and A_{2k}
T = set of alerting threshold functions
V_r = relative velocity between two aircraft
$\boldsymbol{v}$ = velocity vector
x = distance between two aircraft along aircraft 0 velocity vector
$\boldsymbol{x}$ = complete state vector
y = distance between two aircraft perpendicular to aircraft 0 velocity vector
$\boldsymbol{y}$ = observable state vector
θ = angle between the relative velocity and the bearing between two aircraft
τ = temporal threshold parameter for TCAS RA alert
τ_{CAZ} = temporal threshold parameter for ACM CAZ alert
τ_{PAZ} = temporal threshold parameter for ACM PAZ alert
τ_{TA} = temporal threshold parameter for TCAS TA alert
ϕ = angle between relative velocity and aircraft 0 velocity
χ = angle between aircraft 0 velocity and the bearing between two aircraft

Introduction

WHEN two or more decision-making components of a system are dissonant or conflict with one another, accidents can occur. This was recently demonstrated in July 2002 when two jet transport aircraft collided while over Germany, killing 71 people. Contributing to the accident was a conflicting set of information presented to the flight crew on one aircraft: An air traffic controller using ground-based decision-support tools instructed the pilot to descend while simultaneously the crew received a climb command from an onboard traffic alert and collision avoidance system (TCAS). The flight crew delayed action, then ultimately followed the air traffic control instruction, which was dissonant with the TCAS instructions issued to both aircraft, and a collision occurred. This tragedy highlights a growing concern in automation system development. Because it is costly to redesign and recertify automation completely, new decision-support systems are often independent enhancements layered on top of existing systems. The result is that we are now faced with new safety and design challenges: the need to ensure that multiple independent systems monitoring similar threats operate harmoniously together. Although procedures can be developed to resolve these types of conflicts, for example, TCAS supercedes an air traffic controller, a more thorough understanding of dissonance would greatly aid in predicting, assessing, and mitigating conflicts during the design phase rather than after systems are fielded.

In the 1990s, Pritchett and Hansman explored the concepts of consonance and dissonance between an alerting system's decisions and a human operator's internal model of a threat situation.[1] Their work and observed incidents in the field have shown that a mismatch or dissonance between the human and automation could lead to undesirable behavior from the human including increased delay in taking action, failure to take action at all, or even implementing an action contrary to the automation's command.

In this paper, the focus is on dissonance between two or more automation systems. We define dissonance as a situation in which

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the information (or lack of information) from two or more systems suggest different timing, urgency, or actions be taken regarding a threat. Thus, dissonance may range from obvious cases such as when system A commands a climb but system B commands a descent, to more subtle cases such as when a strategic system with a long look ahead distance does not signal a threat but a shorter-timescale tactical system does indicate a threat. Whether the latter case causes a safety problem or affects the operator's workload or decision making would need to be studied, but this type of dissonance could potentially raise concerns about why the strategic system does not agree with the tactical system.

We have developed a methodology to assist in detecting what states of the air traffic system can produce alerting conflicts or dissonance between different decision-support systems.[2] In brief, our approach involves the following steps.

1) Each alerting system is formally described in terms of how a given state vector is mapped into an alerting system output called an alert stage. Alert stages include a categorization of the level of threat posed by a hazard as well as command or guidance information to the pilot or air traffic controller. Example stages might be no alert, an informational traffic advisory, or an explicit climb command to avoid a collision. Accordingly, in this step, mathematical mapping functions are defined for each alerting system.

2) Sensor and dynamic modeling errors can be introduced to make the mapping of state vectors into alert stages probabilistic rather than deterministic. This step involves modeling uncertainties using probability density functions (PDF) and carrying those PDFs through the mapping functions defined in step 1.

3) A visualization of the alert stage mapping for each alerting system can then be created. This is simply a view of state space in which the different alert stages are demarcated by their boundaries defined by the mapping functions of steps 1 and 2. When uncertainties are present, the view can show contours of probability of a state being in a given alert stage.

4) The two alerting systems are then overlayed to examine potential regions where dissonant alert stages occur simultaneously. This can be done both formally through mathematics and informally through a visual depiction of state space. This new depiction of state space shows regions of intersection between the various alert stages of each alerting system. Thus, one can see how a given state maps into a combination of the alert stages of each system.

5) Each intersection of alert stages must then be examined to determine whether dissonance may exist. This is an area requiring significant future research because it depends heavily on complex human factor issues beyond the scope of this study.

6) The entire system is then assessed to determine how dissonant regions may be mitigated. This may involve modifications to one or more alerting algorithms (thereby changing the mapping of alert stages in the state space), changes in operational procedures to deter the process from entering dissonant regions, additional filtering or prioritization schemes, or enhanced operator training.

To illustrate these steps, we examine a few cases of potential dissonance between a newly proposed airborne traffic separation monitoring system and the existing TCAS.

Example Analysis of Airborne Alerting System Dissonance

TCAS uses range, range rate, altitude, and altitude rate between two aircraft obtained through radio transponder messages. Based on this information, TCAS has two alerting functions: traffic advisories (TA), which direct the crew's attention to a potential threat, and resolution advisories (RA), which provide vertical collision avoidance commands to the crew. The quality of the input information (range, range rate, altitude, and altitude rate) of TCAS limits its ability to make accurate collision predictions beyond approximately 45 s. More strategic maintenance of separation between aircraft would be the function of a different airborne separation assurance system (ASAS). Each type of system has distinct requirements due to different timescales, consequences, and information quality with which to base decisions. Combining ASAS and TCAS components within a single aircraft and between different aircraft will be a challenging problem to ensure that these systems convey consistent information to decision makers.

Recently, an ASAS concept termed airborne conflict management (ACM) has been proposed, and initial concepts and specifications have been drafted by Radio Technical Committee on Aeronautics subcommittee.[3,4] ACM uses an automatic dependent surveillance-broadcast (ADS-B) data link to enable longer lookahead than is possible with TCAS. ADS-B periodically broadcasts aircraft information such as identification, position, velocity, altitude, and the next trajectory change point. This information may enable accurate prediction of traffic conflicts on timescales on the order of minutes. In the initial concept, ACM can include up to three alert levels built around two separation zones called the protected airspace zone (PAZ) and a smaller collision avoidance zone (CAZ). A low-level alert may be issued well before the violation of the PAZ with the intent to allow the crew time to resolve the conflict efficiently. Response to a low-level alert is optional; as such, the alert provides primarily a cue that a conflict may need to be resolved in the near future, but is not an urgent signal that action is required immediately. If the conflict remains unresolved, a PAZ alert will be issued. A maneuvering response should then be initiated with a minimum of delay. If the conflict is still not resolved, a CAZ alert is ultimately issued when immediate action is required to avoid a near miss.

Several issues relate to the interoperability between TCAS and ACM. One set of concerns arise when TCAS and ACM are both installed on the same aircraft. TCAS measures relative range, altitude, and bearing, whereas ACM receives the broadcast state vector and intent. The different surveillance sources may result in two targets that need to be merged or fused on displays.[5] The different surveillance methods used by TCAS and ACM may also produce different threat projections between the same targets. Whereas ACM alerts will protect a much larger minimum separation than TCAS, in some geometries the enhanced accuracy of ADS-B may allow ACM to determine that no PAZ or CAZ threat exists while TCAS still predicts a threat. As such, TCAS may issue alerts when ACM sees no urgent conflict. This may cause a problem if pilots have become accustomed to receiving urgent ACM alerts before TCAS alerts. Further research is necessary into the human factors implications of situations like this in which shorter-timescale alerts are issued before longer-timescale alerts. An additional source of concern would be transitioning from a lateral maneuver, which might be preferable during the resolution of a PAZ alert, to a vertical maneuver commanded by TCAS. More study is warranted on the ability of pilots to make this transition from lateral to vertical maneuvers and on the potential impact to safety if the transition is not carried out. Finally, it would be preferable to not experience TCAS alerts at all if an ACM advisory is being followed properly. A second group of issues relates to cases where TCAS is installed on one aircraft but ACM is installed on another. In this case, the two systems may issue different resolution advisories at different times. A problem exists if in certain geometries these resolutions are not coordinated or compatible, leading to a loss of separation.

Because specifications for both TCAS and ACM have been published, they serve as a convenient illustrative example for analysis here. Note, however, that ACM is still under development, and so the following analysis should be interpreted as a preliminary study. The intent is to demonstrate how dissonance analysis can be performed and how the analysis translates into potential mitigation strategies.

Aircraft Encounter Kinematics

To simplify the case study, the analysis of TCAS and ACM is limited here to only horizontal-plane motion where the two aircraft are coaltitude and converging. A similar analysis could be performed for more complex three-dimensional cases.

Several kinematic parameters are required for the mathematical description of TCAS and ACM. Figure 1 shows two aircraft (labeled 0 and 1) in the horizontal plane using Cartesian coordinates oriented along and perpendicular to the aircraft 0 velocity vector. This choice of frame is arbitrary and simplifies the kinematic equations. The aircraft are a distance x and y apart along the two axes in this

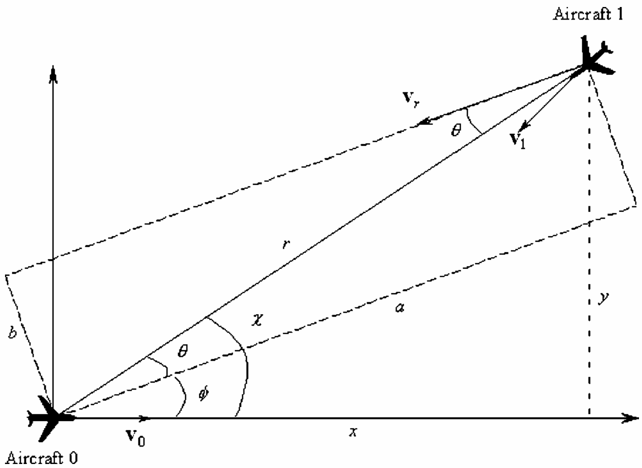


Fig. 1 Horizontal plane kinematics.

frame and have velocity vectors $\boldsymbol{v}_0 = [v_{0x}, 0]^T$ and $\boldsymbol{v}_1 = [v_{1x}, v_{1y}]^T$. The relative position of the aircraft can also be expressed in terms of their range r and bearing χ:

$$r = \sqrt{x^2 + y^2} \tag{1}$$

$$\chi = \tan^{-1}(y/x) \tag{2}$$

The relative velocity between aircraft is

$$V_r = \sqrt{(v_{1x} - v_{0x})^2 + v_{1y}^2} \tag{3}$$

which can be expressed in terms of the range rate

$$\dot{r} = -V_r \cos\theta \tag{4}$$

where

$$\theta = \chi - \phi \tag{5}$$

and

$$\phi = \tan^{-1}[v_{1y}/(v_{1x} - v_{0x})] \tag{6}$$

Finally, the distance until the closest point of approach a and the miss distance b are given by

$$a = r\cos\theta \tag{7}$$

$$b = r\sin\theta \tag{8}$$

Formal Description of TCAS and ACM

In the case of TCAS and ACM analysis here, the state vector $\boldsymbol{x}$ represents the complete two-dimensional position and velocity vectors of each aircraft involved. The analysis to follow neglects issues such as accelerating or maneuvering aircraft, sensor filtering dynamics, or threats that suddenly appear at close range; the assumption is that both aircraft have been monitored for a sufficient time that variance in the state estimates have reached steady state.

Consider a situation in which both ACM and TCAS are implemented on aircraft 0 in Fig. 1. The complete state vector is not available to the alerting system logic, but is observed through a set of sensors. The resulting information that is observable to each alerting system is included in the vector $\boldsymbol{y}$. For TCAS (system 1), $\boldsymbol{y}$ is a vector including the range and range rate between two aircraft (again, considering the horizontal plane only):

$$\boldsymbol{y}_1 = [r, \dot{r}]^T = \left[\sqrt{x^2 + y^2}, -V_r\cos\theta\right]^T \tag{9}$$

In contrast, ACM (system 2) uses a more complete set of state vector components:

$$\boldsymbol{y}_2 = [x, y, v_{0x}, v_{1x}, v_{1y}]^T \tag{10}$$

ACM is able to observe the complete kinematic relationship in Fig. 1 but TCAS only has access to range and range rate, which significantly limits the degree to which TCAS can predict the evolution of the encounter between aircraft. When the information in $\boldsymbol{y}$ is used, each alerting system applies a set of threshold functions or other logic, T, to map the situation into an alert stage $\boldsymbol{a}$. The alert stage specifies the level of threat or urgency level according to that alerting system.

TCAS has three main alert stages.

Stage 0 indicates no threat. Traffic is shown on a map display using a white diamond symbol that also indicates its altitude and whether it is climbing or descending. No additional information is provided; $\boldsymbol{a}_1 = 0$.

Stage 1 indicates a TA. A master caution light is illuminated in amber, the traffic icon changes to a yellow circle on the traffic display, and an aural "Traffic, Traffic" alert is issued in the cockpit; $\boldsymbol{a}_1 = 1$.

Stage 2 indicates an RA. A master warning light is illuminated in red, the traffic icon changes to a red square on the traffic display, an aural resolution command is issued (such as "Climb! Climb!"), and the required climb angle or climb rate is shown on a cockpit display; $\boldsymbol{a}_1 = 2$.

The converging, horizontal-plane TCAS alerting thresholds are based on four parameters: B_{DMOD}, B_{DMODTA}, τ, and τ_{TA}. Here τ and τ_{TA} are threshold parameters with units of time for RA and TA alerts. B_{DMOD} and B_{DMODTA} are safety buffer distances for RA and TA alerts. At its core, the RA threshold can be defined as[6]

$$r < (B_{\text{DMOD}} - \tau\dot{r}) \Leftrightarrow \text{RA alert} \tag{11}$$

If an RA is not issued, a TA occurs when the following is satisfied:

$$r^2 < (B_{\text{DMODTA}})^2 - r\dot{r}\tau_{\text{TA}} \Leftrightarrow \text{TA alert} \tag{12}$$

Even though TCAS operates with only r and $\dot{r}$ as states, its thresholds can be rewritten in terms of the more general state parameters from Fig. 1. This facilitates comparison with ACM later. From Eq. (12), the TA threshold equivalently lies in state space according to the following equation:

$$a^2 + b^2 < (B_{\text{DMODTA}})^2 + V_r\tau_{\text{TA}}a \tag{13}$$

or

$$(a - V_r\tau_{\text{TA}}/2)^2 + b^2 < (B_{\text{DMODTA}})^2 + (V_r\tau_{\text{TA}}/2)^2 \tag{14}$$

Thus, aligned in a new (a, b) Cartesian coordinate frame in Fig. 1 (along and perpendicular to the relative velocity vector), the TA threshold is a circle centered on $(V_r\tau_{\text{TA}}/2, 0)$ with radius

$$\sqrt{(B_{\text{DMODTA}})^2 + (V_r\tau_{\text{TA}}/2)^2}$$

In a similar manner and coordinate system, the criterion for an RA [Eq. (11)] can be rewritten as

$$(a - V_r\tau/2)^2 + b^2 < B_{\text{DMOD}}\sqrt{a^2 + b^2} + (V_r\tau/2)^2 \tag{15}$$

The alert stage sets for TCAS can then be formally defined by a threshold function T_1 using the following notation:

$$T_1 = \begin{cases} f_{11} : (a - V_r\tau_{\text{TA}}/2)^2 + b^2 < (B_{\text{DMODTA}})^2 + (V_r\tau_{\text{TA}}/2)^2 \\ f_{12} : (a - V_r\tau/2)^2 + b^2 < B_{\text{DMOD}}\sqrt{a^2 + b^2} + (V_r\tau/2)^2 \\ A_{10} = \bar{f}_{11} \cap \bar{f}_{12} \\ A_{11} = f_{11} \cap \bar{f}_{12} \\ A_{12} = f_{12} \end{cases} \tag{16}$$

Each set A_{ij} represents a region in state space where alerting system i is in alert stage $\boldsymbol{a}_j$. The extent of each set is defined by a combination of predicates f_{ij} that evaluate to true or false as shown in Eq. (16). For example, if predicate f_{11} is true but f_{12} is false, then the state lies in the region A_{11} and a TA is issued ($\boldsymbol{a}_1 = 1$). If the

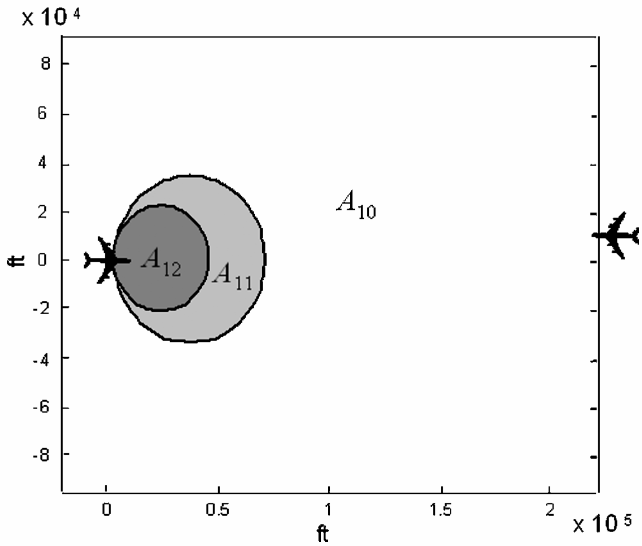


Fig. 2 Example TCAS threshold function and alert stages, opposite direction aircraft at 500 kn each: A_{10} = no alert, A_{11} = TA, and A_{12} = RA.

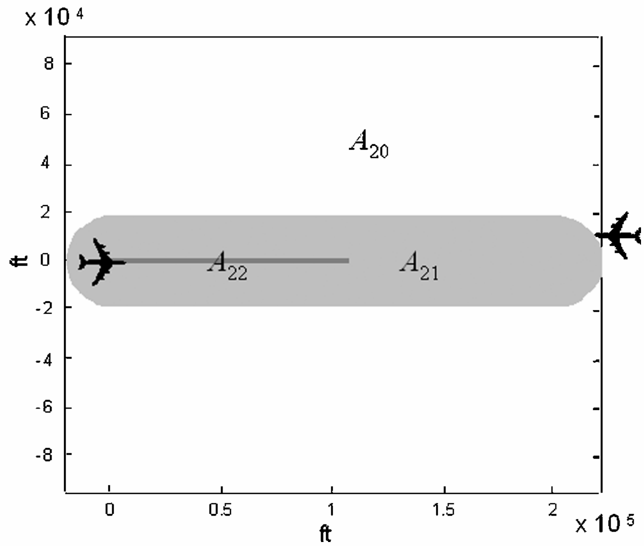


Fig. 3 Example ACM threshold function and alert stages, opposite direction aircraft at 500 kn each: A_{21} = PAZ alert and A_{22} = CAZ alert.

conditions were such that the state was in region A_{12}, then an RA would be issued. Finally, if the state was in region A_{10}, then no alert would be issued from TCAS.

The formalized TCAS threshold function and alert stages can be visualized for a given aircraft encounter situation. Figure 2 shows one example case for two aircraft heading in opposite directions, each at 500 kn. The two alert threshold regions are then shown to scale in the relative frame of one aircraft, with threshold parameter values set assuming the encounter occurs at an altitude of 20,000 ft (Ref. 6). A given type of alert will occur as the intruder aircraft enters each of the circular regions shown.

Switching now to ACM, we focus on the higher two alert stages: the PAZ alert ($\boldsymbol{a}_2 = 1$) and the CAZ alert ($\boldsymbol{a}_2 = 2$). As already mentioned, a low-level alert of ACM provides extended time to allow the crew time to plan, choose, and coordinate the best course of action to remove the conflict, which is expected to be the normal usage of ACM. Thus, the higher level alerts (PAZ and CAZ) of ACM function more similarly to TCAS alerts. Remember, however, that the TCAS alert stages carry different meanings than the ACM stages. For example, $\boldsymbol{a}_1 = 2$ means that an RA is issued from TCAS, whereas $\boldsymbol{a}_2 = 2$ means that a CAZ alert is issued from ACM. The actions the pilot should take in each case may be significantly different.

The thresholds for ACM are based on four parameters, B_{PAZ}, B_{CAZ}, τ_{PAZ}, and τ_{CAZ} (Ref. 4). Similar to TCAS, τ_{PAZ} and τ_{CAZ} are threshold parameters with units of time for PAZ and CAZ alerts; B_{PAZ} and B_{CAZ} are safety buffer distances for PAZ and CAZ alerts:

$$\left[a - \sqrt{(B_{\text{CAZ}})^2 - b^2}\right]\Big/V_r < \tau_{\text{CAZ}} \Leftrightarrow \text{CAZ alert} \tag{17}$$

If there is no CAZ alert, then a PAZ alert is issued according to

$$\left[a - \sqrt{(B_{\text{PAZ}})^2 - b^2}\right]\Big/V_r < \tau_{\text{PAZ}} \Leftrightarrow \text{PAZ alert} \tag{18}$$

With ACM, A_{20} corresponds to a no-alert or low-level alert condition, A_{21} corresponds to a PAZ alert, and A_{22} represents the space where a CAZ alert is issued. These regions are formally defined by the threshold function T_2:

$$T_2 = \begin{cases} f_{21} : \left[a - \sqrt{(B_{\text{PAZ}})^2 - b^2}\right]\Big/V_r < \tau_{\text{PAZ}} \\ f_{22} : \left[a - \sqrt{(B_{\text{CAZ}})^2 - b^2}\right]\Big/V_r < \tau_{\text{CAZ}} \\ A_{20} = \bar{f}_{21} \cap \bar{f}_{22} \\ A_{21} = f_{21} \cap \bar{f}_{22} \\ A_{22} = f_{22} \end{cases} \tag{19}$$

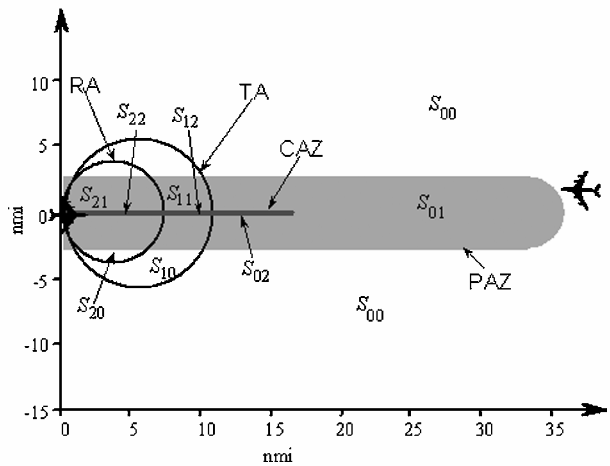


Fig. 4 Example TCAS and ACM thresholds, opposite direction aircraft at 500 kn each.

With the same encounter situation that was shown in Fig. 2, the formalized ACM threshold function and alert stages can be visualized in Fig. 3, with threshold parameter values set assuming the encounter occurs at an altitude of 20,000 ft (Ref. 4).

Equations (16) and (19) then give a formal basis by which a given state can be translated into an alert stage for each system. When combinations of alert stages are compared between the two systems, conditions leading to dissonance can be identified.

Conditions for Dissonance

Having set up the basic alert stage regions in state space, we can now analyze the two systems together. There are nine possible combinations of alert spaces between TCAS and ACM. Each combination of alert spaces is denoted S_{jk} where $S_{jk} = A_{1j} \cap A_{2k}$. For example, a region in state space where TCAS is in stage 1 and ACM is in stage 0 would be $S_{10} = A_{11} \cap A_{20}$.

A more convenient way of visualizing these regions is to plot the four alert stages for the two systems, TA, RA, PAZ, and CAZ, for a given aircraft encounter situation. Figure 4 shows the same encounter situation and same threshold parameter values as were shown in Figs. 2 and 3. ACM is designed to provide an earlier warning of traffic than TCAS. Should this happen, there is probably no perceived dissonance from the pilot's point of view, even when alert stage differences exist between ACM and TCAS. Therefore, alert spaces S_{00}, S_{01}, and S_{02} are not dissonance spaces. If the opposite occurred, however, there may be perceived dissonance because the pilot may not understand why ACM does not rate the traffic as an urgent threat while TCAS does.

For example, a TCAS RA without any prior urgent ACM alert conditions may be perceived as dissonant if pilots become accustomed to ACM alerts occurring before TCAS alerts. This condition is represented by the set $S_{20} = A_{12} \cap A_{20}$, or, equivalently, in terms of predicates

$$S_{20} = f_{12} \cap \bar{f}_{21} \cap \bar{f}_{22} \tag{20}$$

In terms of the specific state values involved, and because the CAZ threshold is always within the PAZ threshold, Eq. (20) can be rewritten as

$$\left\{(a - V_r\tau/2)^2 + b^2 < B_{\mathrm{DMOD}}\sqrt{a^2+b^2} + (V_r\tau/2)^2\right\}$$
$$\cap \left\{\left[a - \sqrt{(B_{\mathrm{PAZ}})^2 - b^2}\right]\Big/ V_r > \tau_{\mathrm{PAZ}}\right\} \tag{21}$$

As Fig. 4 shows, the PAZ region extends well in front of the CAZ, TA, and RA regions. This is intentional, to provide the pilots ample time to respond to a potential conflict well before severe maneuvering is required. The CAZ is a significantly thinner region, also extending farther forward than the TA or RA. In this situation, however, note that the TA and RA thresholds do extend laterally beyond the CAZ and PAZ regions. If an intruder were to enter the S_{10} or S_{20} regions, dissonance could be perceived if the pilot was concerned why a PAZ alert did not accompany or precede the TCAS alert. Although regions S_{10} and S_{20} appear to be relatively small in Fig. 4, they do extend between 3 and 6 n mile laterally and cover an area over 16 n mile^2. Note also that the diagram in Fig. 4 does not show the region in which an ACM low-level alert occurs. Such an advisory may be enough to prevent any dissonance should a TCAS TA or RA subsequently occur. However, it is also possible that dissonance may still occur if the pilot does not receive the higher-level ACM alerts before TCAS. Determining what conditions may lead to dissonance from a human factors point of view warrants careful study in the future.

To estimate the likelihood of such dissonance occurring, assume the two aircraft are traveling in opposite directions within the same airway (with a maximum lateral offset of 4 n mile) and that the relative lateral position of the two aircraft is uniformly distributed. The probability of dissonance with a TCAS TA but without an ACM PAZ alert is then approximately 0.25, and the probability of dissonance with a TCAS RA but without an ACM PAZ alert is approximately 0.12.

Sensor Error Effects

A diagram such as Fig. 4 can be useful for examining where dissonance may occur between two systems solely due to differences in their decision-making logic. Dissonance may also arise due to sensor errors that distort the actual states of the aircraft. A method for examining the effect of sensor error on dissonance has also been developed and is described in Ref. 2. Here, we only briefly discuss how sensor error can be injected into the analysis. Essentially, sensor error causes a given state to be observed with a different value according to some PDF. Without sensor error, a state in state space is mapped deterministically into one of the alert stages A_{ij}. With sensor error, a state instead maps into each alert stage with some probability. We can recast this problem as one in which the boundaries of the alert stages are probabilistic rather than deterministic. A diagram such as Fig. 4 could then be modified to show, for a given state in state space, the probability that the state lies within a given alert stage region.

To illustrate the potential impact of sensor error, a simplified analysis of TCAS measurements was performed. TCAS uses an alpha–beta tracker to produce a filtered estimate of range and range rate.[6] The alpha–beta tracker is a recursive estimator similar to a Kalman filter but with constant filter gains. Range measurements are typically obtained with a standard deviation of approximately 30 ft, which when filtered translates into steady-state standard deviations of approximately 18 ft in range and 6 ft/s in range rate for constant-speed aircraft. If two aircraft are flying in opposite directions with some lateral offset at 260 kn each, the range rate is reduced from that in Fig. 4 such that the TCAS TA region lies entirely within the ACM PAZ. There is then no dissonant region S_{10}. A closeup of the area in which the TCAS TA and PAZ boundaries are closest for this example is shown in Fig. 5. The addition of normally distributed sensor error causes the TCAS TA boundary to become probabilistic, and instead will lie somewhere between the dashed lines shown with probability 0.99. Thus, because of the alerting system logic alone, there would be no potentially dissonant region S_{10} in this case, but sensor error makes it such that there is some probability of a state lying in the region S_{10}. Note that the effect of sensor error is quite small here, extending only approximately 0.1 n mile laterally. This example does serve to illustrate the basic concept behind incorporating sensor error into the dissonance analysis. In other cases, it may be possible that sensor error dominates the potential for dissonance and that logic differences between two systems are not a major contributor to dissonance.

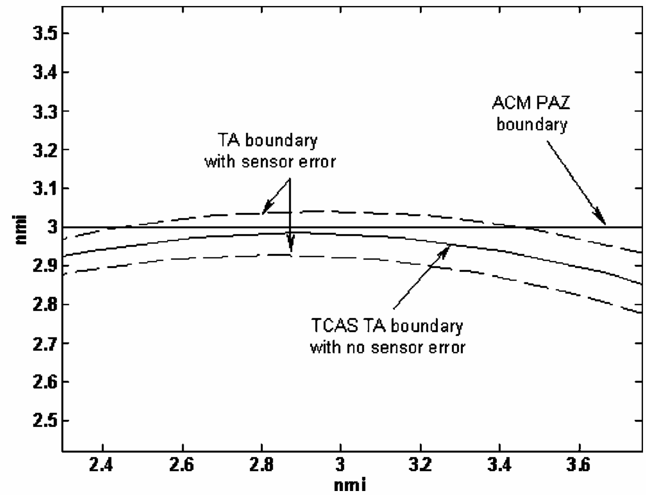


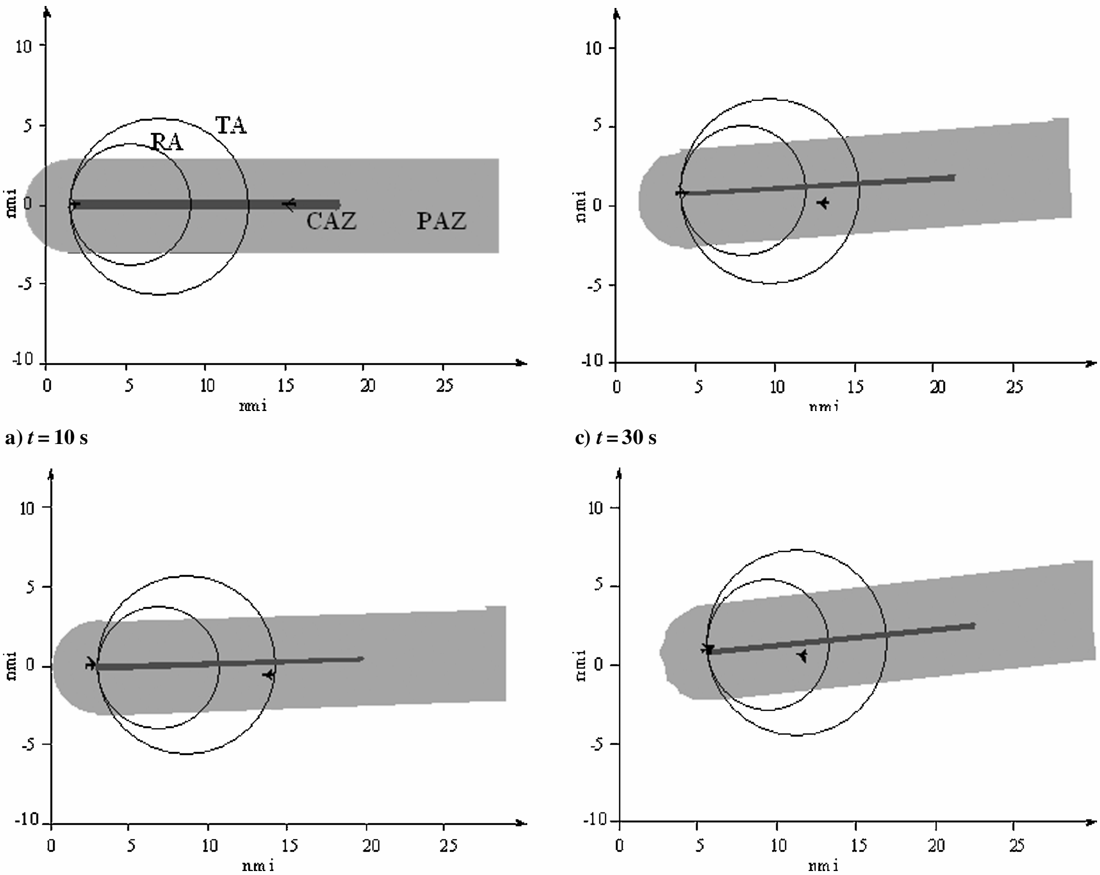
Fig. 5 Closeup of the effect of sensor error on TCAS TA boundary, 260 kn opposite direction.

Dissonance Due to Dynamic Effects

In addition to examining the alerting regions to expose areas where alert stage dissonance could exist, it is also necessary to examine the process dynamics to see how dissonance may evolve over time. One of the major issues with the integration of ACM and TCAS is how to manage ACM alerts that are later upgraded to TCAS alerts. If prompt, appropriate action is taken in response to an ACM alert, it is preferable that no TCAS alerts occur.[4] Accordingly, one issue to examine is what types of ACM resolution maneuvers are required to prevent TCAS alerts from occurring.

As an extreme example, consider a situation in which a CAZ alert is issued against one aircraft directly in front of another and heading in the opposite direction, with both aircraft at 500 kn. In response to the CAZ alert, assume that one aircraft begins a turning maneuver with a certain response delay, a roll-in to a certain bank angle and a roll-out at a certain new heading angle. To address this issue, a point-mass simulation was executed to examine the interaction between aircraft trajectories and the alert stages of ACM and TCAS.

Figure 6 shows four snapshots (spaced every 10 s) of the two aircraft and the alert thresholds assuming the leftmost aircraft follows a turning avoidance action with a 10-s time delay after the CAZ alert, rolls instantaneously into a 10-deg bank angle, and makes a 20-deg heading change. Figure 6a shows the situation immediately following the 10-s time delay. Approximately 10 s later (Fig. 6b), the CAZ region is exited, but the aircraft crosses the boundary of the TCAS TA region and a TA is issued. Here, dissonance might be perceived because ACM is downgrading the alert stage and TCAS is upgrading the alert stage. Finally (between Figs. 6c and 6d), an RA is issued from TCAS, commanding the pilot to climb or descend. Therefore in this extreme situation, there is a progression from taking action in response to an ACM alert that ultimately ends in a TCAS RA.



a) $t = 10$ s c) $t = 30$ s

b) $t = 20$ s d) $t = 40$ s

Fig. 6 TCAS and ACM thresholds during avoidance maneuver.

The RA command itself may also cause some confusion because the pilot must determine whether to continue the turn that has already been initiated, or to execute the climb or descent command. A more rapid or aggressive response could avoid this dissonance, as will be discussed.

The same thresholds in Fig. 6 could also be placed on the second aircraft, which might then also receive and react to alerts. In particular, it may be relatively common for ACM to be installed on one aircraft while TCAS is installed on the other. In that situation, the ACM aircraft would begin maneuvering in response to the PAZ or CAZ alert. Unless that aircraft performed a sufficiently aggressive maneuver, a TCAS TA or RA could still be issued on the second aircraft. If not designed properly, ACM might not be able to prevent the second aircraft from having to maneuver in response to TCAS, which would reduce the benefits of having ACM installed.

In situations where ACM alerts are triggered, we want to identify the required maneuvers that should be taken to avoid triggering a subsequent TCAS alert. To run this simulation, a point-mass intruder aircraft was placed in front of a host aircraft, traveling in the opposite direction, with each aircraft at 500 kn. When the PAZ alert threshold was crossed, a given time delay was implemented and then the host aircraft performed a roll-in to a certain bank angle and rolled out at a given heading angle. The transition between roll angles was assumed to be instantaneous; the addition of lags would enhance the realism of this analysis. Time delay, lateral offset, bank angle, and heading change parameters were then systematically varied. Depending on the combination of lateral offset, response latency, bank angle, and turn angle, either 1) no TCAS alert would be issued, 2) a TA would be issued during the maneuver, or 3) both a TA and RA would be issued, in sequence.

Figure 7 shows the interactions between delay, bank angle, turn heading, and TCAS alert status for a case with zero lateral offset. The curves in Fig. 7 represent boundaries between different TCAS alert behaviors. Two groups of curves are shown. When there is no

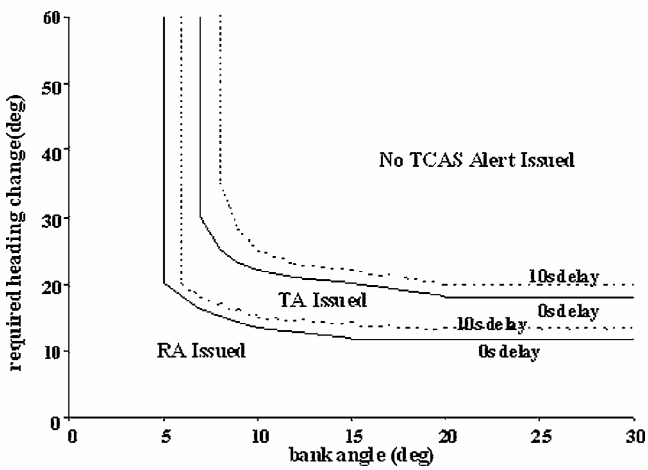


Fig. 7 Effect of PAZ avoidance maneuver on TCAS alert status, 500 kn opposite direction.

time delay, the boundary between an RA and a TA is shown by the lower solid line, and the boundary between a TA and no alert is shown by the upper solid line. The dashed lines show similar boundaries when there is a 10-s response delay after the PAZ alert. A combination of bank angle and turn angle toward the lower-left of the plot will result in an RA. Performing a maneuver between sets of curves will result in a TA. Making a large enough turn with a large enough bank angle (upper-right part of Fig. 7) will avoid any TCAS alert from occurring.

For example, referring to Fig. 7, with no time delay and a 15-deg bank angle, the host aircraft must turn more than approximately 20 deg in heading to avoid triggering a TCAS TA. The host would

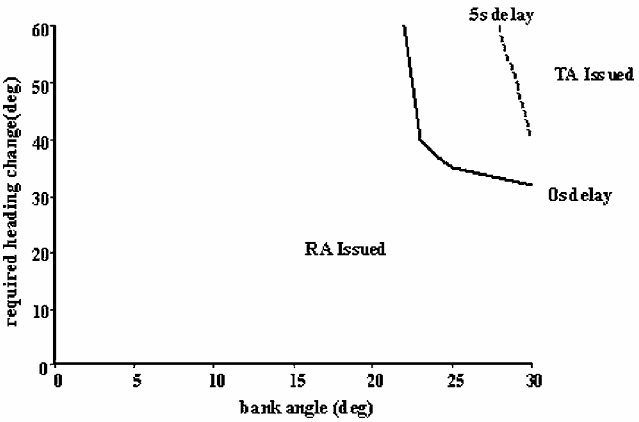


Fig. 8 Effect of CAZ avoidance maneuver on TCAS alert status, 500 kn opposite direction.

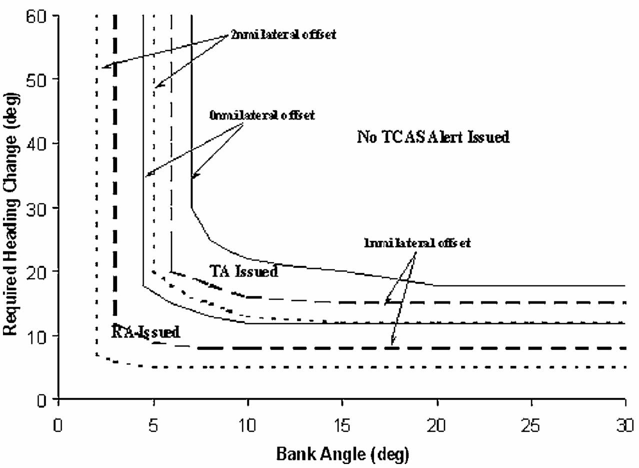


Fig. 9 Effect of lateral offset on PAZ avoidance maneuver for TCAS alert status, 500 kn opposite direction.

have to turn at least 12 deg to avoid triggering a TCAS RA. A 10-s response delay would add several degrees to these turn minima. Thus, relatively significant avoidance maneuvers must be performed following an ACM PAZ alert to prevent triggering TCAS TAs or RAs.

Initial published specifications for the magnitude of a PAZ alert resolution turn maneuver call for a 25-deg bank angle.[4] Compared with Fig. 7, a 25-deg bank angle corresponds to requiring a 12-deg heading change to avoid triggering a TCAS RA and an 18-deg heading change to avoid a TCAS TA.

It is even more difficult to prevent TAs and RAs following a CAZ alert. In fact, in this 500-kn opposite-direction example, a TCAS TA cannot be avoided without exceeding an extreme maneuver (at least a 30-deg bank angle and a 60-deg heading change). Figure 8 shows the TCAS alerting behavior following a response maneuver to a CAZ alert. Avoiding an RA after a CAZ alert also requires an extreme maneuver. With a 30-deg bank angle, a 32-deg heading change is required without time delay, and a 40-deg heading change is required if there is a 5-s delay.

The initial specification proposed in Ref. 4 for the CAZ conflict resolution turn maneuver is a 35-deg bank angle. As simulated in this 500-kn opposite-direction example, it is not possible to avoid triggering a TCAS TA with this CAZ turn maneuver. To avoid a TCAS RA with this 35-deg bank angle turn, at least 28-deg of heading change is required.

Finding two aircraft coaltitude flying in opposite directions with no lateral offset is certainly extremely unlikely, and the preceding example is a worst-case situation. The method shown here can be extended to examine all other types of encounters. In particular, we also studied the effect of lateral offset between two aircraft on the ACM turn avoidance maneuver. Figure 9 shows the required ACM PAZ avoidance maneuver for TCAS alerts given 0-, 1-, and 2-n mile lateral offsets between two aircraft. Three groups of curves are shown in Fig. 9, each group of lines (solid, dashed, or dotted) represents boundaries between different TCAS alert behaviors with 0-, 1-, and 2-n mile lateral offset, respectively, when there is no time delay following the PAZ alert. Compared to the case without lateral offset, the required PAZ avoidance maneuvers are less aggressive in as much as lateral offset increases because the host aircraft has a head start in increasing separation as it turns away from the intruder aircraft. For example, as shown in Fig. 9, with no lateral offset and a 15-deg bank angle, the host aircraft must turn beyond 20-deg in heading to avoid triggering a TCAS TA; with 1-n mile lateral offset and the same bank angle, a 15-deg heading change is required to avoid triggering a TCAS TA; only a 12-deg heading change is required with a 2-n mile lateral offset. Beyond 2 n mile, a TCAS TA cannot occur. (Refer back to Fig. 4.)

Table 1 Vertical climb rate requirements to avoid TCAS alerts[a]

	0-s Delay, ft/min		10-s Delay, ft/min	
ACM alert	TA	RA	TA	RA
PAZ	380	70	450	80
CAZ	——	600	——	900

[a]Pull-up load factor $1.2g$.

Simulations were also performed for vertical maneuvers following ACM PAZ and CAZ alerts. In response to an ACM alert, it was assumed that the aircraft performed a pull-up maneuver at a load factor of $1.2g$ to a given vertical rate. Table 1 shows the minimum climb rates that are required under these conditions to avoid receiving a TCAS TA or RA alert for initially coaltitude aircraft. Climbs or descents at approximately 380 ft/min are required to avoid a TA if action is started immediately after a PAZ alert is issued. RAs are more easily avoided, with rates of approximately 70 ft/min required. After a CAZ alert, TAs cannot be avoided without a significantly more extreme maneuver. (A load factor of approximately $2.4g$ is required.) RA after a CAZ alert could be avoided with final vertical rates between approximately 600 and 900 ft/min depending on the response delay of the pilot and aircraft.

A final issue worthy of discussion revolves around the core philosophy driving alerting decisions. There are two major kinds of conflict prediction methods: using physical metrics or using probabilistic metrics.[7] Both TCAS and ACM are physical-metric conflict probes. That is, they predict the expected aircraft positions in space and time and translate uncertainties into areas around these predicted aircraft positions (protection zones). Two aircraft are said to be in geometric conflict when the distance between the protection zones of those aircraft becomes smaller than the minimum allowed distance between them.[8] Meanwhile, several other conflict probes employ a probabilistic approach by predicting the probability that two aircraft come within the minimum allowed distance between them.[7] The conflict detecting functions of the center–terminal radar approach control automation system (CTAS) or the user request evaluation tool are examples of probabilistic conflict probes.[9,10] CTAS evaluates the conflict probability assuming that the trajectory prediction error for an aircraft is normally distributed. Given the direction of the relative velocity at time of minimum predicted separation and through a coordinate system transformation, an analytical expression is obtained to estimate the conflict probability.

Although the conflict detection principle of a probabilistic conflict probe is different from a physically based conflict probe, dissonance between these two kinds of conflict probes can also be analyzed with the generalized methodology described here. To analyze a probabilistic conflict probe, it is necessary to map a given conflict probability threshold into a physical-state region in state space. This mapping can be performed based on the algorithms used to compute probability thresholds. Indeed, several prior studies have described conflict probability levels as spatial probability contours.[11,12] The alert stages triggered by these contours can then be compared against physically based alerting systems to check for dissonance.

Conclusions

Alert system dissonance has not been a major concern in the past beyond the desire to minimize simultaneous alerts and prevent information overload. Conflicting alert information has now been seen in operation and is likely to become even more prevalent as alerting systems continue to be injected into complex system operations. Several areas in aerospace have already been identified where dissonance is likely to become a more critical issue in the near future, and certainly there are other regimes where similar problems are of concern.

An analysis of the initial specifications for the ACM system in connection with the current TCAS suggest that there may be operating conditions in which TCAS alerts could occur without having first received high-level ACM advisories. The simulations also show that it may be difficult to avoid receiving a TCAS alert even after taking action in response to an ACM alert in certain geometries. These may not be significant dissonance problems, but need to be investigated further to determine the scope of encounters that may lead to this type of behavior and to examine other human factors issues relating to this problem. Potential solutions include modifying the ACM threshold parameters or ACM resolution maneuvers (or both), or accepting that TCAS alerts may occur in certain geometries and training pilots to understand why that dissonance exists and how it can be resolved.

Sensor error may contribute additional dissonance to that originating from logic differences alone, especially for a target that suddenly begins transmitting information. In such a case, ACM may receive an accurate state estimate while TCAS does not have an accurate estimate because TCAS is reliant on filtered observations taken over a running time period. A preliminary analysis on steady-state errors suggests that, for targets that have been tracked for a sufficiently long time period (approximately 20 s), sensor error does not play a significant role in TCAS/ACM dissonance. More study into these transient dissonant possibilities is certainly warranted, including extensions to better model factors such as communication dropouts and filtering delays.

Acknowledgment

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