CONFLICT DETECTION AND ALERTING FOR SEPARATION ASSURANCE SYSTEMS

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Introduction

Many of the nation's airspace users desire an increase in efficiency in the air traffic control system. Some feel that an increase in efficiency can be achieved by moving away from a centralized control paradigm towards a distributed control paradigm. In a distributed control paradigm, the cockpit crew would have more freedom in selecting and modifying their routes. This new paradigm is part of the Free Flight concept.

Increased autonomy of operations will require increases in cockpit information, pilot responsibility, and avionics capability. One of the key enabling capabilities will be the detection and resolution of airspace conflicts. Conflict detection and resolution (CD&R) systems will serve in a separation assurance role for the flight deck. Conflict detection is the first step. This paper contains the following:

- background information on airborne conflict detection and alerting;
- a baseline conflict detection algorithm based on instantaneous state vectors; and
- an analysis of the algorithm's performance for flight data from the ADS–B Operational Evaluation (OpEval) held at Wilmington, Ohio, in July 1999.

Airborne Separation Assurance

RTCA Task Force 3

In October 1995, RTCA Task Force 3 released its final report on Free Flight Implementation [1]. The report offered recommendations of actions to implement the concept of Free Flight. The recommended structural improvements were organized into four technology areas – digital data link, automatic dependent surveillance, global positioning system, and decision support systems. One of the key decision support systems discussed in the report is "conflict probe" for both pilot and controller.

Conflict probe was described in the Task Force 3 report as a system that monitors an "alert zone in which all possible maneuvers are contained." The report continued, "As long as an aircraft's alert zone does not touch another aircraft's alert zone, it should be permitted to maneuver freely."

In one of the report's scenarios, Task Force 3 envisioned the nature of procedures surrounding the use of conflict probe. They suggested that "…the system will propose a resolution that will alter one of the aircraft's path to assure safe separation. Through a clear handshaking protocol, the responsibility for separation based on proposed resolution will be transferred from the ground ATC infrastructure to the affected aircraft." Airborne Collision Avoidance System (ACAS) is always included in the concept as a final safety net.

CD&R Research

The aviation research community has studied the technologies that support conflict probe for the last decade [2]. Both ground-based controller decision support tools and pilot decision support tools have been considered. Much of the research has focused on algorithms for both predicting and resolving airspace conflicts. In addition to the algorithm research, NASA [3] and NLR [4] have performed extensive human factors analyses.

In the above mentioned research, the terms "conflict detection" and "conflict resolution" have been adopted to differentiate the alerting and guidance portions of conflict probe. The abbreviation “CD&R” has become common, especially for discussion surrounding cockpit decision support tools. The term “conflict alerting” is also convenient for further differentiating the problem of appropriately displaying the results of the conflict detection logic to the pilot and controller.

CD&R has started to make the transition from research into standards development. In December 1998, an RTCA working group on CD&R held its first meeting in Orlando, Florida. Representatives from cargo airlines, passenger airlines, U.S. and European research agencies, manufacturers, and system providers have met regularly to develop a CD&R operational concept and begin identifying requirements for an airborne CD&R system. Rockwell Collins has been actively involved in this subgroup.

ADS–B Data Link

CD&R will likely evolve into the embodiment of the airborne separation assurance aspect of Free Flight. Conflict detection and resolution could be performed on aircraft computers with information provided through an inter-aircraft Automatic Dependent Surveillance-Broadcast (ADS–B) data link.

In July 1999, the Cargo Airlines Association and the FAA Safe Flight 21 program sponsored an Operational Evaluation (OpEval) of ADS–B in Wilmington, Ohio [5]. These demonstrations, which involved over twenty ADS–B equipped aircraft, was an unique opportunity to collect ADS–B data for evaluation of CD&R algorithms. The content of this paper is derived from the author’s involvement in the CD&R working group and OpEval.

One of the purposes of the CAA/FAA OpEval flight tests was to evaluate ADS–B enabled procedures like “Enhanced See-and-Avoid.” The tests revealed the challenge of clutter that is posed by displaying a dozen aircraft on a CDTI. Conflict detection and alerting will help identify the traffic that most requires the attention of the pilot.

Conflict Detection Overview

Before conflict resolution makes its way into cockpits, conflict detection alone will likely have to prove itself as a valuable asset in future Cockpit Display of Traffic Information (CDTI).

Definitions

There is a subtle inconsistency in the research literature surrounding the definition of a “conflict.” It can be defined as a “violation of a separation standard.” Under this definition, a conflict does not exist until two aircraft are within a certain distance of each other.

Alternatively, a conflict can be defined as a “predicted violation of a separation assurance standard.” Under this definition, a conflict exists when two aircraft will come within a certain distance of each other at some time in the future. Obviously, this second definition makes the existence of a conflict dependent on the type and parameters of the chosen prediction algorithm.

Modeling Uncertainty

The conflict detection algorithms in the research literature vary in at least two ways – uncertainty models and protected airspace zones. The simplest approach to conflict detection is the use of the instantaneous state vectors to calculate the closest point of approach (CPA) and time remaining until separation standards are violated (t_{sv}). If the CPA is less than some minimum and the t_{sv} is within a look-ahead window, then a conflict is declared. In this case, conflict detection becomes a binary decision function.

Of course, there are uncertainties that can be modeled in the conflict detection problem – uncertainty in the state vectors [6] and intent of the aircraft [7]. The most common way to model these uncertainties is with probabilistic models. This approach has the advantage of generating a probability of conflict, which can be used to prioritize conflict alerting.

Protected Zones

Another variation in the design of conflict detection algorithms is the shape and size of the "protected zone." The protected zone is actually defined by the thresholds that are used in the conflict detection logic. That is, mathematical models of three-dimensional volumes are generally not maintained in real-time implementations. Rather, the airspace volumes serve as conceptually useful concepts for understanding the conflict detection logic.

The "oblate spheroid" is a mathematically convenient shape for a protected zone. This volume is usually derived by considering some vertical separation to be equivalent to some horizontal separation [8]. For example, in cruise flight, 1000 feet vertical separation could be considered equivalent to five miles of horizontal separation. The vertical units are simply scaled to match the corresponding equivalent horizontal separation. It is mathematically convenient because a single value can be calculated to characterize the separation between two aircraft. Figure 1 illustrates the "oblate spheroid."

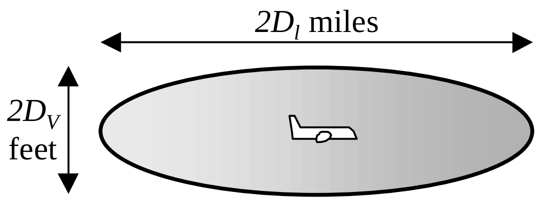

Figure 1. Oblate Spheroid Protected Zone

The "cylindrical" protected zone is the other common shape used in conflict detection algorithms. For this protected zone, the separation criteria in both axes are tested separately. Figure 2 illustrates the conceptual volume that results from this scheme. Five miles horizontal separation and 1000 feet vertical separation are still appropriate examples of the separation parameters. While the oblate spheroid is mathematically simpler, the cylindrical protected zone has the advantage of being consistent with the existing separation criteria in use today. Also, it is likely more consistent with pilots' perception of airspace separation.

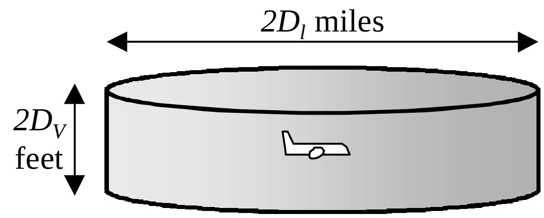

Figure 2. Cylindrical Protected Zone

The RTCA CD&R Working Group is moving towards the simultaneous use of two protected zones for each aircraft – a Protected Airspace Zone (PAZ) and a Near Mid-air Collision (NMAC) zone. The PAZ would define the desired separation standards for the airspace. A five-mile, 1000-foot criterion, for example, would define the PAZ. The NMAC zone would be intended to more closely enclose the aircraft. The smaller protected zone could be used to generate high-level alerts.

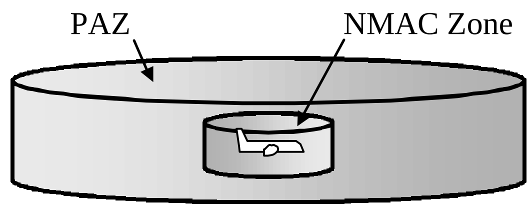

Figure 3. PAZ and NMAC Protected Zones

Conflict Alerting

When designing conflict alerting logic, the question to be asked is, "What will be most useful for the pilot?" Consequently, conflict alerting must be tested and refined with human-in-the-loop experiments. In light of this, the following merely suggests the basic structures that have been used for performing conflict alerting. It is a starting point that will require refinement. The section, Flight Test Results, describes results that suggest the next step in that refinement.

All conflict detection algorithms should estimate the time until separation is lost, t_{sv}. The simplest alerting logic is one based solely on t_{sv}. Thresholds can be set on t_{sv} to determine the conflict alert levels, as shown in Figure 4. For probabilistic conflict detection, the probability of a conflict can be used to specify alert levels. The probability can be used solely or in conjunction with t_{sv}, depending on the uncertainty that is modeled by the probabilities.

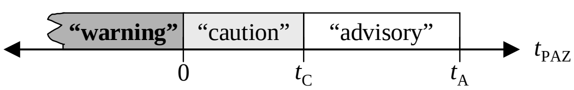

Figure 4. Alerting Based on Time to Separation Violation

If two protected zones are used, as described earlier, an additional alerting level can be used to indicate that the NMAC zone will be penetrated within a certain time window. The alerting logic can be designed with three parameters, as illustrated in Figure 5.

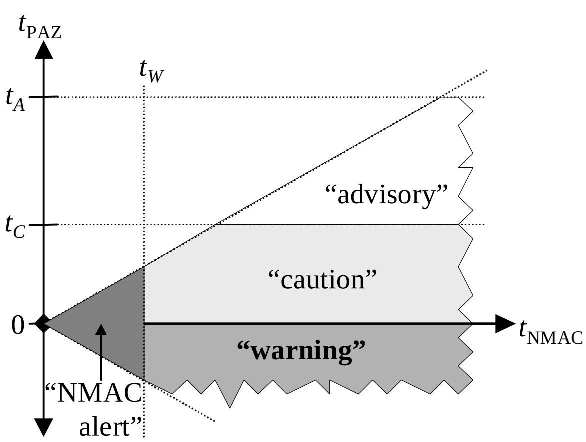

Figure 5. Alerting for Two Protected Zones

Other variables can be considered for designing conflict alerting logic. It has been suggested that alerting be based on the “cost” to resolve a conflict. In [9], for example, alerting is based on the number of maneuvers available to the pilot that resolves the conflict. As the pilot’s options decrease, the alerting level increases.

A Conflict Detection Algorithm

The following is the development of conflict detection algorithm based on instantaneous state vectors, a cylindrical protected zone, and a look ahead window of T seconds. The protected zone has a horizontal radius, D_l, and a vertical height, $2D_v$.

The choice of a cylindrical protected zone motivates the division of the conflict detection problem into a horizontal component and a vertical component. The two components are considered separately, with the final conflict detection decision based on a composite of these two sub-problems.

The horizontal distance, $d_l(t)$, between two aircraft is given in equation (1), where x and y are the distances from “your” aircraft to the “other” aircraft in a Cartesian reference frame. The reference frame could be derived from GPS positions broadcast over an ADS–B data link.

$$d_l(t) = \sqrt{(x + \dot{x}t)^2 + (y + \dot{y}t)^2} \qquad (1)$$

Substituting the horizontal separation standard, D_l, and solving for t yields two times, t_l and t_l'.

$$t_l, t_l' = \frac{-B \pm \sqrt{B^2 - A \cdot C}}{A} \qquad (2)$$

$$A = \dot{x}^2 + \dot{y}^2$$

$$B = x\dot{x} + y\dot{y}$$

$$C = x^2 + y^2 - D_l^2$$

In general, t_l is the time that the other aircraft first enters your protected zone in the horizontal dimension. Similarly, t_l' is the time that the other aircraft exits your protected zone in the horizontal dimension. However, there is the possibility for negative or complex solutions. Table 1 summarizes the possible solution conditions and their implications.

Table 1. Horizontal Separation Test Cases

Case	Condition(s)		Implication
L_1	$0 < t_l \leq T$		A horizontal separation violation is projected in the future, at time t_l.
L_2	$t_l > T$		A horizontal separation violation is projected to occur at a time beyond the look-ahead window.
L_3	$t_l \leq 0$	$t_l' \geq 0$	A horizontal separation violation currently exists.
L_4	$t_l' < 0$		A horizontal separation violation is projected to have occurred in the past.
L_5	$B^2 - AC < 0$		No horizontal separation violation is projected to occur.
L_6	$\dot{x} = 0$	$\dot{y} = 0$	The two aircraft are flying in parallel. The horizontal separation is constant.

The vertical distance, $d_v(t)$, between the two aircraft is given in equation (3). The difference in barometric altitude between the two aircraft is z.

$$d_v(t) = \left| z - \dot{z} \right| \tag{3}$$

Substituting a vertical separation standard, D_v, and solving for t, yields the t_v and t_v'.

$$t_v = \min\left(\frac{D_v - z}{\dot{z}}, \frac{-D_v - z}{\dot{z}} \right) \tag{4}$$

$$t_v' = \max\left(\frac{D_v - z}{\dot{z}}, \frac{-D_v - z}{\dot{z}} \right) \tag{5}$$

The min and max functions assure that $t_v < t_v'$. In general, t_v is the time that the other aircraft's altitude is first D_v above or below your aircraft. Similarly, t_v' is the time that the other aircraft's altitude is no longer within D_v of yours. Obviously, there is the possibility for a division by zero. This condition and others are listed in Table 2.

For a cylindrical protected zone, there are two ways a conflict can occur. Geometrically, the other aircraft enters your protected zone either through the side of the cylinder or through the top or bottom of the cylinder. Entering through the side of the cylinder occurs when the altitude difference between the two aircraft is less than D_v and the

Table 2. Vertical Separation Test Cases

Case	Condition(s)		Implication
V_1	$0 < t_v \leq T$		A vertical separation violation is projected in the future, at time t_v.
V_2	$t_v > T$		A vertical separation violation is projected in the future beyond the look-ahead window.
V_3	$t_v \leq 0$	$t_v' \geq 0$	A vertical separation violation currently exists.
V_4	$t_v' < 0$		A vertical separation violation is projected to have occurred in the past.
V_5	$\dot{z} = 0$		The two vertical speeds are identical. The vertical separation is constant.

Table 3. Conflict Detection Test Cases

Case	Conditions		Implication
C_l	Case L_1	$d_v(t_l) \leq D_v$	A conflict exists in the horizontal dimension. The time to horizontal separation violation is t_l.
C_v	Case V_1	$d_l(t_v) \leq D_l$	A conflict exists in the vertical dimension. The time to vertical separation violation is t_v.

lateral distance is D_l. Entering through the top or bottom of the cylinder occurs when the horizontal distance is less than D_l, and the difference in altitude between the two aircraft is D_v. Table 3 lists the conditions associated with determining that a conflict exists.

The less-than-or-equal-to condition in cases C_l and C_v account for the special case when $t_v = t_l$. When $t_v = t_l$, the other aircraft is entering your protected zone on the vertex of the cylinder.

A conflict is detected by checking for cases C_l and C_v. There are three point cases (L_5, L_6, and V_6) that must be checked to prevent mathematical errors. Since both C_l and C_v can not exist simultaneously, except when $t_v = t_l$, detecting a conflict in one of these cases is sufficient for determining t_{sv}.

Flight Test Results

The recent Operational Evaluation of ADS–B in Wilmington, Ohio, was a unique opportunity to collect flight data from a large number of ADS–B-equipped aircraft. This section contains results of analysis performed on nearly half an hour of the morning session's flights. Most of the aircraft were flying a pattern and go-arounds for one of the parallel runways. Figure 6 is a plot of the tracks for a one-minute segment of the data.

The number of conflict alerts during the 25-minute flight segment was calculated for various sizes of cylindrical protected zones. The conflict detection was based on the aircraft's instantaneous state vectors, as reported by ADS–B, without any type of filtering or prediction algorithms. The protected zone was varied in radius from 0.25 nautical miles to 5 nautical miles. The height was varied from 500 feet to 2000 feet. The look-ahead windows, or time to separation violation thresholds, included 30, 60, and 120 seconds. Portions of the results are summarized in Figure 7.

One way to interpret Figure 7 is in light of Figure 4, the conflict alerting scheme mentioned earlier in the paper. Figure 4 shows that heightened levels of conflict alerts can be based on the predicted time remaining until the loss of separation.

Take for example, a protected airspace zone defined by a desired separation of 500 feet vertically and three miles horizontally. Figure 7 shows that for these thresholds, there were 21 conflict alerts for a two-minute look-ahead window, 7 conflict alerts for a one-minute look-ahead, and 8 conflict alerts for a thirty-second window. The "0 sec." plot shows actual loss of separation for these thresholds. There were four instances of another aircraft crossing the 500- foot, three-mile thresholds.

Keep in mind that there was no feedback of this conflict analysis to the pilots during the flight. There was no attempt to resolve the conflicts during the OpEval of July 1999. The data consist of ranges of values that might be expected in heavy traffic near an airport.

Take as another example, a protected airspace zone for 500 feet and two miles. Figure 7 shows that these thresholds would have resulted in twelve low-level alerts (i.e., two-minute look-ahead) and one high-level alert (i.e., one-minute look-ahead). There were no instances of these thresholds actually being crossed.

Conclusion

Before the Free Flight concept becomes a reality, airborne separation assurance systems must be researched, standardized, and purchased by the airspace users. Conflict detection algorithms are beginning to make the transition from research to standardization. The standardization process, however, is still in need of research using flight data with multiple aircraft. The ADS–B OpEval is enabling that research.

A baseline conflict detection algorithm was specified in this paper. The algorithm was used to analyze nearly half an hour of flight with multiple aircraft flying patterns around two runways. The number of conflict alerts was totaled for variations in protected airspace zone (PAZ).

For one 25-minute segment of OpEval, the number of conflict alerts increased significantly as the radius of the PAZ increased from 2 NM to 4 NM. Presumably, these alerts would be considered a nuisance to pilots performing operations in heavy traffic near an airport. Similarly, the increase from a 500-foot vertical threshold to a 1000-foot vertical threshold resulted in additional alerts. This is likely due to the 1000-foot separation that was maintained by ATC during the flights.

The increased alerts associated with a 1000-foot threshold would decrease with the use of a tracking filter. The use of estimation and tracking filters will be the focus of the continuing research in conflict detection and resolution. This study, which used only the reported, instantaneous state vectors, will serve as a baseline for incremental enhancements to the conflict detection algorithm.

The use of probabilistic models of intent uncertainty will also be the focus of future research. None of the aircraft at the July 1999 OpEval were broadcasting intent information (i.e. trajectory change points). The CD&R standard will require that intent information be utilized. However, future mixed-equipage airspace will likely include aircraft that are not broadcasting TCPs.

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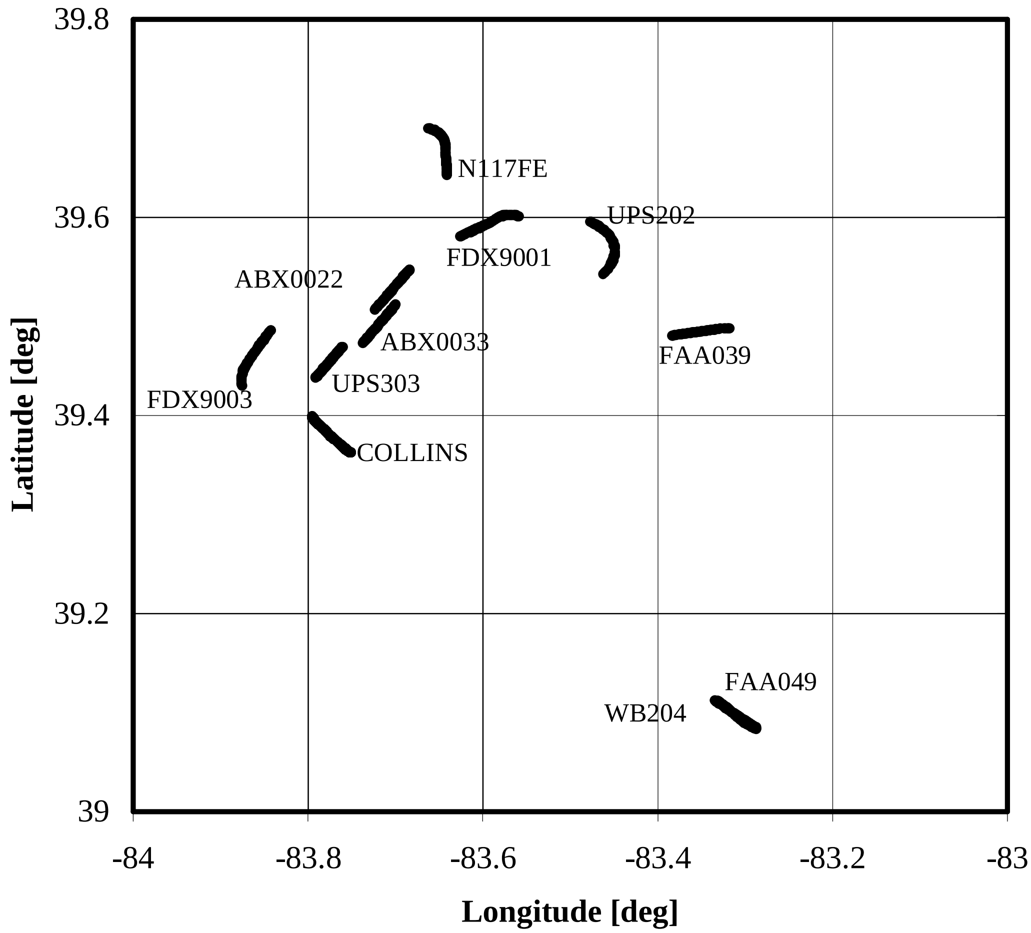

Figure 6. Sample Horizontal Tracks, One Minute.

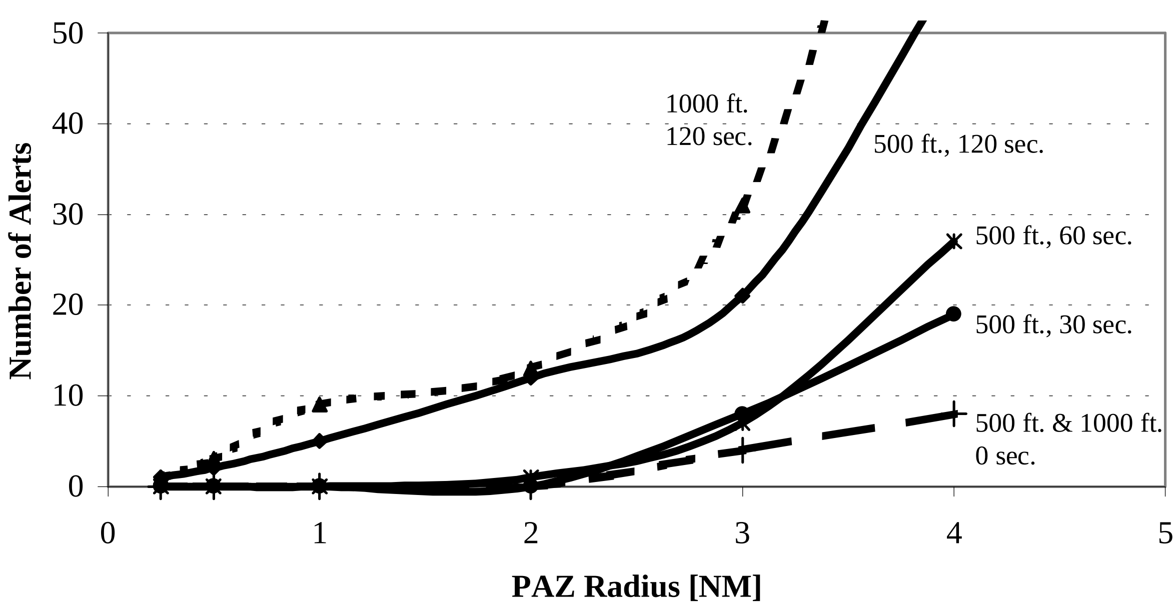

Figure 7. Number of Conflict Alerts During Test Segment