

# Tactical Separation Algorithms and Their Interaction with Collision Avoidance Systems

Huabin Tang<sup>1</sup>

*NASA Ames Research Center, Moffett Field, CA 94035*

Dallas Denery<sup>2</sup> and Heinz Erzberger<sup>3</sup>

*University of California, Santa Cruz*

*and*

Russell Paielli<sup>4</sup>

*NASA Ames Research Center, Moffett Field, CA 94035*

The nation's air transportation system is currently unable to support the forecasted demand for air travel. New airborne and ground-based capabilities are being investigated to address the myriad of challenges that pilots, operators, and air navigation service providers will face. One approach being studied considers a layered architecture involving a strategic and a tactical system to provide automated separation assurance. Because the tactical system will operate in a time horizon that may overlap with on-board collision-avoidance systems, it must be designed not to interfere with these systems. This paper presents a new set of vertical conflict resolutions for a conflict aircraft pair. Heuristics are presented which govern the use of the new vertical and recently-developed horizontal conflict resolution algorithms to minimize interference with an on-board collision-avoidance system. To address the expected increase in traffic density, an algorithm for globally resolving conflicts involving multiple aircraft is also presented. Evaluation using real-world encounters in both en route and terminal airspace demonstrates the effectiveness of both the vertical algorithm and the heuristics used to reduce the interference.

## Nomenclature

$\tau$	=	simple tau
$\tau_m$	=	modified tau
$\tau_{CPA}$	=	actual time to closest point of approach
$\tau_{TH}$	=	range threat threshold

---

<sup>1</sup> Aerospace Engineer, AFA 210-6, Moffett Field, CA 94035, [huabin.tang-1@nasa.gov](mailto:huabin.tang-1@nasa.gov), Member AIAA

<sup>2</sup> Senior Scientist, University of California, Santa Cruz, [ddenery@ucsc.edu](mailto:ddenery@ucsc.edu), Fellow AIAA

<sup>3</sup> Adjunct Professor, University of California, Santa Cruz, [heinze@ucsc.edu](mailto:heinze@ucsc.edu), Fellow AIAA

<sup>4</sup> Aerospace Engineer, AFC 210-10, Moffett Field, CA 94035, [russ.paielli@nasa.gov](mailto:russ.paielli@nasa.gov), Associate Fellow AIAA

$\tau_v$	=	vertical tau
$\tau_{TV}$	=	vertical threat threshold
$r$	=	slant range
$h$	=	altitude
$h_{TH}$	=	altitude threat threshold
$\Delta h$	=	altitude difference
$DMOD$	=	modified distance
$HMD$	=	horizontal miss distance
$VMD1$	=	vertical miss distance at simple tau
$VMD2$	=	vertical miss distance at modified tau
$ VMD $	=	altitude separation at closest point of approach

## I. Introduction

THE nation's air transportation is currently unable to support the forecasted demand for air travel. To meet the demand a combination of air and ground based automation is necessary. One area of research central to this goal is the automation of conflict detection and resolution functions. It is widely acknowledged that airspace capacity is limited by controller workload. An automated conflict detection and resolution capability that makes use of the ground and flight deck systems is a potential solution to this limitation.

There have been many studies on aircraft conflict detection and resolution in the literature.<sup>1-8</sup> These studies have mostly involved computationally intensive optimization of predefined cost functions and do not address requirements to assure fail-safe operations. Additionally, they do not directly address the acceptability of the resulting maneuvers to pilots and controllers.

Recently there has been considerable research directed towards a new concept for a separation assurance capability, referred to as the Advanced Airspace Concept (AAC).<sup>9-11</sup> The AAC provides two independent layers of separation assurance, a strategic separation layer and a tactical separation layer. At each layer, conflicts are resolved through a series of maneuvers that are compatible with current operational procedures. A third layer of safety is assumed to be provided by an independent airborne collision avoidance system such as TCAS (Traffic Alert and Collision Avoidance System). TCAS, or a modified version of it, is expected to continue to be required as an airborne independent backup collision avoidance system in the next generation air transportation system. The strategic layer of the AAC addresses conflicts from 2 to 20 minutes into the future. The tactical layer addresses conflicts in a time horizon of less than about 2 to 3 minutes into the future. The independent airborne collision avoidance system addresses possible collisions in a time horizon of less than about 45 seconds. The strategic layer is expected to perform the equivalent functions of controllers in today's environment but under much higher levels of traffic demand. It provides adjustments to the flight plan aimed at providing separation assurance while maintaining an efficient traffic flow. As such, resolutions take into account the intended flight plan and any downstream metering constraints. Because the strategic layer is so complicated it cannot be made sufficiently reliable to be used alone as an autonomous agent in a safety-critical application. The tactical layer of protection, known as Tactical Separation Assured Flight Environment (TSAFE), is proposed as a backup system that duplicates a limited set of safety-critical functions of the strategic layer. Thus, TSAFE both simplifies the problem of automated separation assurance and provides a safety net for the strategic layer. In a way, TSAFE replicates a controller's response to a "conflict alert" in today's environment. Because the tactical system will operate in a time horizon that may overlap with the on-board collision avoidance system (TCAS), the ground-based TSAFE automation must be designed not to interfere with a TCAS resolution.

Significant research has already been completed on various aspects of the AAC concept. In a recent paper,<sup>12</sup> Erzberger developed an automated conflict detection and resolution capability for use in the strategic layer. Most

TSAFE studies to date have focused on the detection of loss of separation (LOS) in en route airspace. Tests on documented operational error cases show that TSAFE can provide timely warnings of imminent conflicts more consistently than the current conflict alert used in today's system.<sup>13,14</sup> Recently, Erzberger defined a set of horizontal resolution maneuvers for use with TSAFE.<sup>15</sup> Paielli is addressing possible vertical resolutions.<sup>16</sup> These studies have not addressed possible interactions with TCAS.

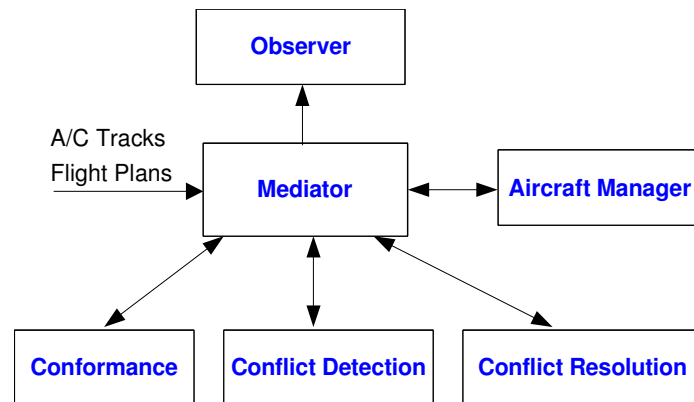
In this paper, a tactical resolution algorithm to resolve conflicts involving two or more aircraft is presented, which generalizes vertical and horizontal resolution algorithms for a single aircraft pair by introducing constraints that limit possible maneuvers on an aircraft. The resolutions are selected to minimize the interference with TCAS. The set of vertical maneuvers for resolving a pair conflict are developed in the paper. The horizontal maneuvers are based on the algorithms developed by Erzberger and Heere.<sup>15</sup> The vertical maneuvers and the approach for minimizing the interference with TCAS are evaluated using track data from real-world encounters in both terminal and en route airspace.

The paper is organized to first present a testbed system designed to evaluate algorithms for the tactical system in Sec. II. This is followed by a discussion of the method used to minimize the interference of the tactical system with TCAS in Sec. III. The vertical and horizontal resolution maneuvers are discussed in Sec. IV, where the proposed conflict resolution algorithm that makes use of both the vertical and horizontal maneuvers to resolve conflicts involving two or more aircraft is also covered. The evaluation results are presented in Sec. V. Some concluding remarks are given in Sec. VI.

## II. Testbed System

A stand-alone testbed software system has been designed and implemented to evaluate tactical algorithms for conformance, conflict detection, and conflict resolution. The general TSAFE architecture as discussed in Ref. 9-11 was used to design the system. The major components of the system are shown in Fig. 1. The arrows indicate data flow. The role of each component is briefly discussed to understand the method used to evaluate the algorithms.

The conformance component determines whether or not an aircraft is deviating from its flight plan. It is used with TSAFE en route conflict detection for trajectory prediction and false alert minimization. It is less useful in today's terminal area because of the lack of intent information and more reliance on dynamically adjusted procedures to optimize traffic flow. It is expected, however, that in the future there will be greater use of time-based scheduling along predefined routes that will allow conformance monitoring to be used in the terminal area as a major way of reducing false alerts.



**Figure 1. The architectural components of a testbed TSAFE software system.**

The conflict detection component detects conflicts by searching along, if available, two trajectories for each aircraft: the Dead-Reckoning (DR) trajectory and the Flight-Plan (FP) intent trajectory. These trajectories are generated by the Aircraft Manager component. Conflicts are determined based on evaluating the resulting four pairs of trajectories: DR versus DR, DR versus FP, FP versus DR, and FP versus FP. TSAFE attempts to predict conflicts up to three minutes into the future. Based on today's separation standard, the en route criterion is 5 nmi horizontally or 1000 ft vertically (2000 ft if one aircraft is at or above FL410) the terminal airspace criterion is 3 nmi horizontally or 1000 ft vertically. For simplicity, we leave the influence of wake turbulence and other factors, which may become

important during the approach and landing phases of flight, for future consideration.

Upon detecting one or more conflicts, the conflict resolution component identifies a set of maneuvers that will resolve the conflicts over a 2-3 minute time horizon. TSAFE does not provide maneuvers for returning the aircraft to its original flight-plan path. The philosophy within the AAC is that this function will be provided by the strategic layer of separation assurance.

The aircraft manager component manages all active aircraft. It generates the DR and FP trajectories of an aircraft that are used in other components. The DR trajectory is based on simple kinematics using the current position and velocity of the aircraft. The FP trajectory takes into account the intent of the aircraft to maintain or get back on its flight plan route. In the horizontal plane, an FP trajectory is generated using the current speed of the aircraft and a smoothed flight-plan route, which is obtained by connecting straight lines and circular arcs among the flight-plan waypoints. Vertically, the aircraft are leveled off at their assigned or temporary altitudes. The climb or descend rates of the aircraft are based on the Base of Aircraft Data (BADA) model.<sup>17</sup>

The mediator component receives aircraft track and flight-plan data and provides communications among other components. It sets up and initializes other components.

The observer component receives and stores data on aircraft non-conformance, loss of separation, and conflict resolution maneuvers. These data are used to analyze and understand TSAFE algorithms and performance.

### III. Interaction of TSAFE with TCAS

Since the ground-based TSAFE operates in a time horizon that overlaps with the on-board TCAS, it is necessary to consider a design that minimizes the interference between the two systems. The FAA has mandated that TCAS override a controller advisory in today's environment and the same philosophy is applied to TSAFE. However, this alone may not be sufficient since, if not designed properly, a TSAFE resolution could contradict an immediately following TCAS resolution advisory (RA).

TCAS is the last line of protection against collision and is designed to be independent of ground-based air traffic management systems. TCAS detects and defines a maneuver to resolve a threat. A threat is identified if *the expected time to* and *the altitude separation at* the closest point of approach (CPA) fall below a range threat threshold and an altitude threat threshold respectively. These two tests are referred to as the range test and altitude test.

The expected time to CPA is estimated using range data calculated from transponder interrogations and range rate derived directly from the range data. Altitude data obtained from the transponder replies, together with an approximated time to CPA, are used to determine the projected altitude separation at CPA. Although an estimate of bearing is available from a directional antenna, it is not directly used in detecting a threat because of its lack of accuracy. Because bearing is not used in determining the location of a threat, a TCAS RA is restricted to climbs and descents.

The climb or descent advisory is based on determining if adequate separation can be obtained by passing above or below the threat aircraft. TCAS is designed to avoid an RA reversal or an altitude crossing unless absolutely necessary to preserve safety of flight. An RA reversal occurs when an initial advisory to descend or climb is reversed during the encounter. An altitude crossing occurs if the RA is to climb (descend) "own-ship" while it is more than 100 ft below (above) the threat aircraft. The TCAS logic has evolved based on extensive testing and operational experience to improve the resolutions and to minimize the number of nuisance resolutions. A complete description of the logic can be found in Ref. 18.

Since there is a desire to keep the TSAFE logic simple for reliability, a simplified and conservative modeling of TCAS RA issuance conditions is needed. By conservative, it is meant that the conditions are necessary but may not be sufficient. Given these conservative range and altitude tests, the following rules are applied to minimize interference of TSAFE with TCAS:

- 1) Restrict maneuvers to the horizontal plane when a TCAS RA is imminent. This assures that TSAFE and TCAS will not issue opposing vertical maneuvers.

- 2) Allow both horizontal and vertical maneuvers when a TCAS RA is not imminent.
- 3) Prioritize horizontal maneuvers so as to reduce the likelihood of a TSAFE maneuver inducing a TCAS RA.
- 4) Do not allow an altitude crossing so as to improve the compatibility between the two systems.

As mentioned above, the range and altitude tests within TCAS are based on an approximated time to CPA. However, the actual time to CPA, denoted by  $\tau_{CPA}$ , is not available due to the limited measurements. To approximate  $\tau_{CPA}$ , two other parameters are computed:

$$\tau = -r/\dot{r} \quad \text{for } \dot{r} < 0 \quad (1)$$

$$\tau_m = -(r/\dot{r})[1 - (DMOD/r)^2] \quad \text{for } \dot{r} < 0 \text{ and } r > DMOD \quad (2)$$

where  $\tau$  is called simple tau,  $\tau_m$  is called modified tau,  $r$  is the slant range between the aircraft, the dot over a symbol means a time derivative, and  $DMOD$  represents a minimum desirable range between the two aircraft and is primarily included to protect against slow closure rates.  $\tau$  provides time to collision for two aircraft on a collision course with constant  $\dot{r}$ , which is the time to CPA in this special case. However, as the horizontal separation between the two aircraft at CPA, referred to as horizontal miss distance and denoted by  $HMD$ , increases,  $\tau$  becomes increasingly greater than  $\tau_{CPA}$  thereby overstating the actual time to CPA.  $\tau_m$  was introduced to help correct this problem. When both aircraft are on constant velocity vectors, it can be shown that replacing  $DMOD$  by  $HMD$  in Eq. (2) yields  $\tau_{CPA}$ . Thus, as is easily seen, if  $HMD < DMOD$ ,  $\tau_m$  is less than  $\tau_{CPA}$ . A range test based on  $\tau_m$  would thereby declare a threat earlier than would be declared if  $\tau_{CPA}$  were used. This is not the case when  $HMD > DMOD$ . However, since  $\tau_m < \tau$  is always true, a range test based on  $\tau_m$  would be more conservative than that on  $\tau$ .

A simplified and conservative range test for use in TSAFE is therefore given by

$$\tau_m < \tau_{TH} \quad (3)$$

where  $\tau_{TH}$  is the range threat threshold that depends on the altitude of the aircraft. When  $\dot{r} \geq 0$  and  $r > DMOD$ ,  $\tau_m$  is set to infinity. When  $r \leq DMOD$ ,  $\tau_m$  is set to zero.

An equivalent altitude test for use in TSAFE is not as evident. The reason can be seen by recognizing that within TCAS the Vertical Miss Distances between the “own-ship” and the “threat” at  $\tau$  and  $\tau_m$  are calculated respectively by

$$VMD1 = \Delta h + \tau \Delta \dot{h} \quad (4)$$

$$VMD2 = \Delta h + \tau_m \Delta \dot{h} \quad (5)$$

where  $\Delta h$  is the current difference in altitude between the two aircraft. If the Vertical Miss Distance at  $\tau_{CPA}$  were bracketed by  $VMD1$  and  $VMD2$ , a conservative estimate of the altitude separation at  $\tau_{CPA}$  would be provided by

$$|VMD| \equiv \begin{cases} 0 & \text{if } VMD1 \cdot VMD2 \leq 0 \\ \min(|VMD1|, |VMD2|) & \text{otherwise} \end{cases} \quad (6)$$

However, since  $\tau \geq \tau_{CPA} \geq \tau_m$  when  $HMD \leq DMOD$  and  $\tau > \tau_m > \tau_{CPA}$  when  $HMD > DMOD$ , two cases need to be considered to provide a representation of TCAS altitude test.

In the case where  $\tau \geq \tau_{CPA} \geq \tau_m$ , the Vertical Miss Distance at CPA is bracketed by  $VMD1$  and  $VMD2$  and a

conservative estimate of the altitude separation is provided by Eq. (6). This leads to the simple altitude test  $|VMD| < h_{TH}$ , where  $h_{TH}$  is the altitude threat threshold specified as a function of altitude. It can be shown that, when the aircraft are initially separated in altitude, there are encounter conditions that would lead to nuisance TCAS RAs. TCAS protects against these nuisance RAs by also requiring the time to co-altitude

$$\tau_v = -\Delta h / \Delta \dot{h} \quad (7)$$

to be less than a vertical threat threshold,  $\tau_{TV}$ , where  $\tau_{TV}$  is also specified as a function of the altitude.

In the case where  $\tau > \tau_m > \tau_{CPA}$ , the vertical miss distance at  $\tau_{CPA}$  is not bracketed by  $VMD1$  and  $VMD2$ . In this case, when the aircraft are initially separated vertically, it can be shown that there are situations where the actual altitude separation at CPA can be less than the altitude threat threshold, even though the estimate from Eq. (6) yields  $|VMD| > h_{TH}$ . As a result, a TCAS RA may fail to be issued. TCAS protects against this possibility by also using a test on the time to co-altitude:

$$\tau_v \leq \min(\tau, \tau_{TV}) \quad (8)$$

The altitude test for use in TSAFE covers these cases with the following three conditions:

- 1)  $|\Delta h| < h_{TH}$  and  $|VMD| < h_{TH}$
- 2)  $|\Delta h| > h_{TH}$  and  $\Delta \dot{h} \cdot \text{sign}(\Delta h) < 0$  and  $\tau_v < \tau_{TH}$  and  $|VMD| < h_{TH}$
- 3)  $|\Delta h| > h_{TH}$  and  $\Delta \dot{h} \cdot \text{sign}(\Delta h) < 0$  and  $\tau_v < \tau_{TH}$  and  $\tau_v < \tau$

Here the range threat threshold,  $\tau_{TH}$ , has been used in place of the vertical threat threshold,  $\tau_{TV}$ . This provides a conservative representation of the TCAS altitude test because the vertical threat threshold used in TCAS is always less than or equal to the range threat threshold. The altitude test passes if any one of the above three conditions is true.

Table 1 shows the values of the threat thresholds,  $\tau_{TH}$  and  $h_{TH}$ , and  $DMOD$  as a function of altitude that are used in TCAS. Currently, the same parameters are used in TSAFE. The altitude of the higher aircraft in the conflict is used to determine the thresholds and  $DMOD$  that are used by TSAFE.

**Table 1. TCAS Sensitivity Parameters as a Function of Altitude**

Own Altitude (feet)	$\tau_{TH}$ (seconds)	$DMOD$ (nmi)	$h_{TH}$ (feet)
1000-2350	15	0.20	300
2350-5000	20	0.35	300
5000-10000	25	0.55	350
10,000-20,000	30	0.80	400
>20,000	35	1.10	600

#### IV. Conflict Resolution Algorithms

Conflict detection produces a set of aircraft pairs that are potentially at loss of separation (LOS) in the next 3 minutes. Conflict resolution is to provide a set of maneuvers for some or all of the aircraft such that it is conflict-free for the next 3 minutes once the maneuvers are executed.

A few points on conflict resolution maneuvers are necessary. First, the maneuvers are required not to generate any secondary conflicts. A secondary conflict may cause a chain effect that produces additional new conflicts since the aircraft is already near or at LOS. This requirement is not too restrictive since there are usually many candidate maneuvers, both vertical and horizontal, that can be tried. Next, as noted earlier, TSAFE does not provide maneuvers for returning an aircraft to its original flight-plan path. Finally, for this paper, a vertical maneuver will be in the form of a clearance to some altitude and a horizontal maneuver will be a left or right turn to some heading. These are the maneuvers routinely used by pilots and controllers today.

In a general situation, more than one pair of aircraft could be in conflict and these pairs could be in conflict with one another. Thus two conflict pairs may involve the same aircraft. Conflicts involving three or more aircraft are less likely than those involving a single aircraft pair, nevertheless the likelihood increases with traffic density.

The approach to resolve conflicts of a single conflict pair is, first, to develop a prioritized list of resolution maneuvers and then, to use the same conflict detection logic that generates the initial conflicts to try the maneuvers, starting from the highest priority resolution, until a resolution is found. The same approach applies to conflicts involving multiple aircraft pairs where a prioritized list of maneuvers are built upon those of the individual pairs, with possible influences of other conflict pairs taken into account as constraints. Adopting the simple altitude and vector clearances help simplify the specification of constraints.

The general prioritization rules, applicable to both vertical and horizontal maneuvers, for an arbitrary conflict pair prior to LOS are as follows:

- 1) Favor single-aircraft maneuvers over cooperative ones that involve both aircraft.
- 2) Favor vertical maneuvers over horizontal ones.
- 3) Restrict to horizontal maneuvers when the TSAFE range and altitude tests pass.

It should also be noted that a response delay is allowed for the pilots to execute a maneuver. This is typically about 10 seconds for TSAFE. If a TCAS RA is expected during the delay period based on the TSAFE range and altitude tests, a TSAFE vertical resolution is also prohibited. If the aircraft are already at LOS and a TCAS RA is not expected yet based on the TSAFE tests, the relative priorities of vertical and horizontal maneuvers may depend on current horizontal and vertical separations. This situation needs further study.

In the rest of this section, a prioritized list of vertical maneuvers for an arbitrary conflict pair is first discussed. This is followed by a discussion on a similar list of horizontal maneuvers. These maneuver lists are then used to develop a prioritized list of vertical and horizontal maneuvers for an arbitrary conflict pair with possible influences of other conflict pairs taken into account as constraints. The algorithm for resolving multiple conflict pairs then becomes straightforward.

### **A. Vertical Maneuver**

A prioritized list of vertical maneuvers is developed for a single conflict pair with arbitrary encounter geometry. The list does not include all possibilities but identifies a subset which, when used with the horizontal maneuvers, should be adequate for any encounter.

The algorithm to generate the list is based on the first of the general rules above and the following simple rules:

- 1) Do not allow altitude-crossing maneuvers.
- 2) Favor maneuvering a climb aircraft over a descent or level-flight aircraft.
- 3) Favor maneuvering a descent aircraft over a level-flight aircraft.
- 4) Favor maneuvering the lower aircraft if both are climbing.
- 5) Favor maneuver the higher aircraft if both are descending.
- 6) Favor climb maneuvers over descent ones.

It is significant that these rules can be applied to all encounter scenarios in the tactical time horizon, yielding familiar maneuvers that seem to match what controllers would typically select today in similar situations.

For an aircraft pair that is not yet at loss of separation, the encounter geometry in the vertical plane can be conveniently described in terms of their altitudes at current and projected LOS positions. The projected altitudes at LOS are already known from the trajectories used to predict the conflicts. As a result, the resolution algorithm is independent of the details of the trajectory algorithm, so the classification of encounters and the relevant computations involved are greatly simplified.

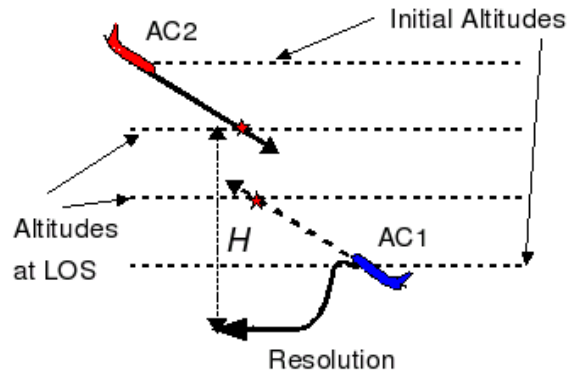
Figure 2 illustrates a sample encounter where aircraft AC1 is climbing and AC2 descending. The dark dashed line shows the trajectory of AC1 without a resolution. The two stars indicate predicted points of LOS. The dark solid curve shows the resolution with aircraft AC2 not maneuvered. The resolution is a clearance to a flight level (FL) that

assures at least the vertical separation standard,  $H$ , from the LOS altitude of AC2. Flight levels are given in multiples of 500 feet when the aircraft is below FL100, 1000 feet between FL100 and FL410, and 2000 feet above FL410. Here 500 feet is used below FL100 because actual examples of such clearances by controllers today can be found.

Table 2 summarizes the prioritized lists of vertical maneuvers for all encounter conditions, which are divided into six types based on the aircraft's vertical flight status of level flight, climbing, or descending. The flight status can be determined from the current and projected LOS altitudes. Thus, aircraft  $i$  is in level flight if

$$|h_i - h_i^{\text{LOS}}| < 200 \text{ ft} \quad (9)$$

where  $h_i$  ( $h_i^{\text{LOS}}$ ) with  $i=1, 2$  is the current (LOS) altitude of the aircraft. It is climbing if  $h_i^{\text{LOS}} - h_i > 200 \text{ ft}$  and descending if  $h_i - h_i^{\text{LOS}} < 200 \text{ ft}$ . The third column provides maneuvers for the six encounter conditions for the case in which both aircraft are at nearly the same altitudes (within 100 ft of each other) and altitude crossing maneuvers are allowed. The fourth column provides maneuvers for the six encounter conditions for the case in which the aircraft are at different altitudes (more than 100 ft in altitude separation) and altitude crossing maneuvers are not



**Figure 2. A vertical resolution for a two-aircraft encounter in the vertical plane.**

**Table 2. Trial vertical maneuvers on two conflict aircraft, AC1 and AC2, for all encounters**

Encounter Type	Encounter Condition	Aircraft at nearly the same altitudes	Aircraft at different altitudes
1	Both AC1 and AC2 are cruising.	Climb AC1 to $h_2^{\text{HL}} + H$ Climb AC2 to $h_1^{\text{HL}} + H$ Descend AC1 to $h_2^{\text{LL}} - H$ Descend AC2 to $h_1^{\text{LL}} - H$	Climb AC1 to $h_2^{\text{HL}} + H$ if $h_1 > h_2$ Descend AC2 to $h_1^{\text{LL}} - H$ if $h_1 > h_2$ Climb AC2 to $h_1^{\text{HL}} + H$ if $h_1 < h_2$ Descend AC1 to $h_2^{\text{LL}} - H$ if $h_1 < h_2$
2	Both AC1 and AC2 are climbing.	Clear AC1 to $h_2^{\text{LL}} - H$ Clear AC2 to $h_1^{\text{LL}} - H$	Clear AC1 to $h_2^{\text{LL}} - H$ if $h_1 < h_2$ otherwise clear AC2 to $h_1^{\text{LL}} - H$
3	Both AC1 and AC2 are descending.	Clear AC1 to $h_2^{\text{HL}} + H$ Clear AC2 to $h_1^{\text{HL}} + H$	Clear AC1 to $h_2^{\text{HL}} + H$ if $h_1 > h_2$ otherwise clear AC2 to $h_1^{\text{HL}} + H$
4	One is climbing (AC1) and the other is descending (AC2).	Climb AC1 to $h_2^{\text{HL}} + H$ Descend AC2 to $h_1^{\text{LL}} - H$	Clear AC1 to $h_2^{\text{LL}} - H$
5	One is climbing (AC1) and the other is cruising (AC2).	Climb AC1 to $h_2^{\text{HL}} + H$ Descend AC2 to $h_1^{\text{LL}} - H$	Clear AC1 to $h_2^{\text{LL}} - H$
6	One is descending (AC1) and the other is cruising (AC2).	Descend AC1 to $h_2^{\text{LL}} - H$ Climb AC2 to $h_1^{\text{HL}} + H$	Clear AC1 to $h_2^{\text{HL}} + H$



allowed. Note that, apart from encounter type 1, there is only one vertical maneuver in the fourth column.

Note that TSAFE conflict detection allows multiple-trajectory probes. Specifically, the DR and FP trajectories are suggested. Thus, given one encounter, four possible conflicts can be predicted. The resolution must resolve all of these predicted conflicts simultaneously. Furthermore, a clearance altitude should coincide with a flight level. Therefore, the clearance altitudes in Table 2 must be rounded off to the next flight level that guarantees at least the standard separation,  $H$ , above the highest LOS altitude or below the lowest LOS altitude of the non-maneuvering aircraft. Here the highest (lowest) LOS altitude of an aircraft is the maximum (minimum) value of the LOS altitudes from the probe trajectories for the aircraft. Thus, the highest and lowest LOS altitudes of the  $i$ th aircraft for the case of dual trajectory probe are given by

$$h_i^{\text{HL}} = \max(h_i^{\text{FP}}, h_i^{\text{DR}}) \quad (10)$$

$$h_i^{\text{LL}} = \min(h_i^{\text{FP}}, h_i^{\text{DR}}) \quad (11)$$

where  $h_i^{\text{FP}}$  and  $h_i^{\text{DR}}$  are the LOS altitudes of the  $i$ th aircraft from the FP and DR trajectories.

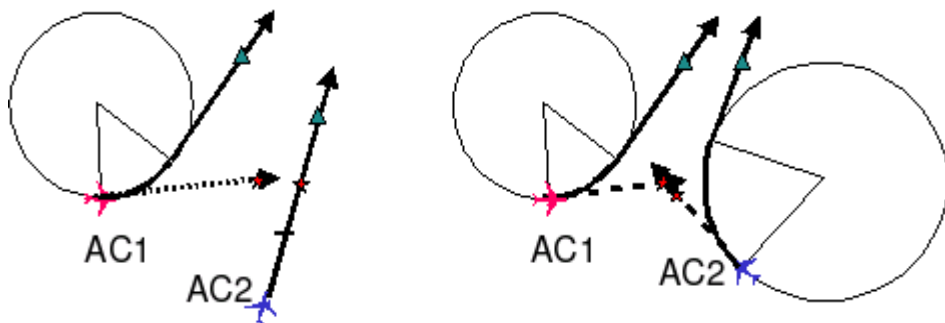
The priorities for some of the maneuvers in Table 2 are arbitrary. This is the case, for example, for the order for encounter type 1 in the third column where the aircraft are at nearly the same altitude. Further information may help resolve the arbitrariness.

## B. Horizontal Maneuver

The algorithm to develop a prioritized list of trial horizontal maneuvers is summarized for a single conflict pair of arbitrary encounter conditions, specified by the current positions and velocities of the aircraft. The details regarding the definition and generation of the horizontal maneuvers considered in this section can be found in Ref.15.

A horizontal maneuver is a vector clearance executed as a turn followed by a straight line segment. It is specified by a turn direction (left or right) and a heading change with either a normal or an expedited turn rate. The normal turn rate corresponds to a bank angle of 15 degrees and the expedited turn rate to a bank angle of 30 degrees.<sup>15</sup> The option to choose from two levels of turn rates allows the incorporation of severity and urgency of the conflict in the resolution maneuver. While both turn rates are used for a single-aircraft maneuver, only the expedited turn rate is used for a cooperative maneuver. This is because a cooperative maneuver is only expected to be required when the aircraft are very near or already at loss of separation. In a cooperative maneuver both aircraft are expected to spend equal amount of time in the turn segments.

Figures 3(a) and 3(b) illustrate the resolution of a conflict with a single-aircraft and a cooperative maneuver respectively. The dashed lines represent the initial conflict with the stars indicating LOS. The dark lines with circular arc segments illustrate the resolution with the points of minimum separation represented by the triangles.



**Figure 3. Horizontal resolutions for two aircraft encounters. (a) Only aircraft AC1 is maneuvered. (b) Both aircraft are maneuvered cooperatively.**

For a given set of encounter conditions, a maximum of twelve possible maneuvers can be generated out of three

types:

- 1) Single-aircraft maneuver with normal bank angle
- 2) Single-aircraft maneuver with expedited bank angle
- 3) Cooperative maneuvers with expedited bank angle.

This is the case because each type above yields up to four possible maneuvers. Indeed, in the case of a single aircraft maneuver, either aircraft can turn left or right. In a cooperative maneuver, both aircraft can turn either left or right.

A resolution maneuver is found when it yields a minimum separation that equals at least the required horizontal separation standard with a minimal heading change. To avoid a prolonged period in which the two aircraft are too close to each other, the time spent on the straight-line segment up to the point of minimum separation is required to be a small fraction of the time it takes to get to the point of minimum separation in the turn. If a resolution satisfying these conditions cannot be found, the aircraft may turn beyond the point of minimum separation in the turn before flying a straight-line segment. See Ref. 15 for details.

Given one of the three types listed above, a maneuver that achieves the required separation standard may not be possible. In this case, the maneuver is determined by calculating the heading change that maximizes the minimum separation. This kind of maneuvers is needed when a maneuver that avoids loss of separation cannot be found or cannot be used for some reasons, so they are given lower priority.

A prioritized list of horizontal maneuvers is obtained as follows. First, the higher-priority maneuvers that avoid LOS are listed by type in the order given above. Within each type, the four possible maneuvers are ordered to favor smaller turn period. Next, the lower-priority maneuvers that result in LOS are ordered to favor larger minimum separation. Finally, the maneuvers may be re-prioritized to reduce the likelihood of causing a TCAS RA in the turn segment. It was shown<sup>15</sup> that potential secondary conflicts can be avoided, which would occur if some higher-priority maneuvers were chosen, by selecting lower-priority maneuvers in the prioritized list.

## C. Multiple Aircraft Maneuvers

### 1. General Description

Conflicts involving a set of multiple aircraft pairs are resolved by first grouping the set into clusters of ordered aircraft pairs. A pair belongs to a cluster if one of the aircraft in the pair is in conflict with any other aircraft in the cluster. The pairs in a cluster are ordered by starting with the pair with the least time to loss of separation and, if possible, ordering the rest so that adjacent pairs share a common aircraft.

Trial resolutions for a cluster are developed by starting from the first pair and working through the ordered list of pairs one by one. A prioritized list of vertical maneuvers, as discussed in Sec. IV.A, is constructed for the first pair. Additionally, constraints that limit other possible maneuvers on each aircraft in the pair are identified. These constraints are applied when a solution for a second pair in the cluster that shares a common aircraft with the first pair is obtained. If a solution to the second pair does not violate the constraints on the common aircraft in the first pair, the solution resolves both conflicts simultaneously. This process continues for other pairs in the cluster. The same is done to create a prioritized list of horizontal maneuvers for each pair. This yields a prioritized list of maneuvers for *each* aircraft pair with the vertical maneuvers being of higher priority than the horizontal ones.

To describe the multiple aircraft resolution algorithm more precisely, the concept of a maneuver is generalized to include various attributes that are used in the intermediate steps toward a final resolution. The additional attributes include a unique identifier, an identification for the aircraft to which the maneuver belongs, zero or more constraints, and a sequence of parent identifiers. A sequence of parent identifiers is assigned to a maneuver to record the fact that the constraints on the maneuver of each parent identifier have been taken into consideration while constructing the current maneuver.

Three additional concepts are required in implementing the algorithm: a composite maneuver, an empty maneuver, and a maneuver set. A *composite maneuver* includes both an altitude clearance and a vector clearance.

Composite maneuvers are needed when an aircraft common to two conflict pairs is constrained to perform only horizontal maneuvers in one pair but is allowed to perform vertical maneuvers in the other pair. An *empty maneuver* does not include an altitude or a vector clearance but may contain constraints. A *maneuver set* is composed of unique maneuvers, each of which belongs to a different aircraft. Two maneuvers created for two aircraft in an aircraft pair form a maneuver set. A resolution for multiple aircraft conflicts consists of a maneuver set that contains maneuvers (some of which could be the empty maneuver) for all aircraft involved.

More details on how to construct vertical and horizontal maneuver sets for a conflict pair are discussed next with constraints being allowed. This is followed by the details on constructing maneuver sets for multiple aircraft pairs.

## 2. Vertical Maneuver Sets for One Pair

For a given conflict pair, the TSAFE approximation of the TCAS RA issuance conditions, described in Sec. III, are first checked to determine if altitude clearances are allowed. An altitude clearance is not allowed when the TCAS range and altitude tests pass or are expected to pass in a predetermined delay period. If an altitude clearance is not allowed, an empty maneuver is assigned to each aircraft with the constraint of not allowing an altitude clearance when addressing a conflict with another aircraft.

If altitude clearances are allowed and a resolution for neither aircraft has yet been generated, the generic rules discussed in Sec. IV.A are used to generate one or more maneuver sets, one vertical maneuver for each aircraft in a set. Each maneuver will have constraints that specify the range of clearances the aircraft must avoid. For example, in the case where both aircraft are flying level at nearly the same altitude (encounter type 1 in Table 2) and “Climb AC1 to  $h_2^{\text{HL}} + H$ ” in the third column is selected, a constraint is added to the maneuver so aircraft AC1 will not go below  $h_2^{\text{HL}} + H$ . An empty maneuver is created for aircraft AC2 with the constraint that a climb clearance is not allowed. (A more restrictive constraint would be not to allow any altitude clearance.) Similar constraints are needed for descent clearances.

If one or both aircraft have already had vertical maneuvers generated, the existing trial vertical maneuvers are only modified so as not to violate their constraints. Because there may be different ways to modify the maneuver, it is cloned one or more times, each being assigned a unique identifier. Its identifier, as well as its parent identifiers, is placed into the parent identifier sequence of the cloned maneuver with its attributes and constraints modified as necessary. The parent identifier sequence is used to merge the pair maneuver sets into maneuver sets for the cluster.

## 3. Horizontal Maneuver Sets for One Pair

For a given aircraft pair, if neither aircraft have had a trial horizontal maneuver generated previously, up to twelve maneuver sets are generated following the algorithm in Sec. IV.B. Each maneuver has constraints that specify the range of heading changes the aircraft must avoid. In a single-aircraft turn situation, the non-turning aircraft is constrained not to allow any heading change. The turning aircraft is constrained so that it is only allowed to turn beyond the given heading change. Note that turning in a different direction is already considered by including all of the twelve maneuver sets for the pair.

If one or both aircraft have already had horizontal maneuvers generated, the horizontal maneuvers are modified without violating their constraints. This is done by cloning each maneuver, placing its identifier as well as its parent identifiers in the parent identifier sequence of the cloned maneuver, and adding or modifying the constraints as necessary.

Notice again that some of the horizontal maneuvers could potentially cause TCAS to issue an unnecessary RA during the turn. For example, there are cases where initially turning the aircraft toward each other would provide optimal minimum separation but would cause a TCAS RA. Maneuvers generating TCAS RAs are given lower priorities so that they are tried last.

## 4. Multiple Aircraft Maneuver Sets

Once a sequence of prioritized maneuver sets are created for each conflict pair in an aircraft cluster, a maneuver

set for the cluster is found by selecting one maneuver set from each conflict pair and merging them into a single maneuver set. The merging of two maneuver sets for two aircraft pairs that do not share a common aircraft is simply a union of the maneuvers. The merging for the case in which the two pairs share a common aircraft requires a further combining of the maneuvers for the common aircraft into a single maneuver. The maneuver obtained from the merging may be composite. It may also be invalid because the maneuvers to be merged are incompatible, in which case the resulting maneuver is referred to as null. Typically when two maneuvers of the same type are incompatible it means that the constraints in one were not considered while constructing the other. If the merging of two maneuver sets results in a null maneuver, the resulting maneuver set is discarded. Because of the way the maneuver sets are constructed, a valid merging of two maneuvers is assured if the identifier of one is in the sequence of parent identifiers of the other. With a given valid maneuver set for all the aircraft, a new trajectory can be synthesized for each aircraft with its maneuver taken into account. The new trajectories are then used to determine if the maneuvers clear all of the conflicts globally.

The actual process used to create a global resolution is now presented. First, the algorithm to merge two maneuvers, say M1 and M2, which belong to the same aircraft, to obtain a merged maneuver M is presented:

- 1) **M1 and M2 are not composite:** (a) If the identifier of M1 (M2) is in the parent identifier sequence of M2 (M1), M is the same as M2 (M1). (b) If they are of the same type but the identifier of one is not in the parent identifier sequence of the other, they cannot be merged by construction and M is null. This is because the maneuvers are not compatible since the constraints in one have not been considered while constructing the other. (c) If they are of different types, M is a new composite maneuver containing M1 and M2.
- 2) **At least one of M1 and M2 is composite:** (a) If M2 (M1) is composite, M is obtained from M2 (M1) by merging and replacing the maneuver in M2 (M1) that is of the same type as M1 (M2) with M1 (M2). The merging follows the rules in Step 1). If it yields null, M is null. (b) If both M1 and M2 are composite, the corresponding maneuvers of the same type in each composite maneuver are merged. M is null if any of the merging yields null, otherwise M contains the resulting merged maneuvers.

Next, the algorithm to merge two maneuver sets, X and Y, in which some of the aircraft involved are identical is as follows:

- 1) Create an empty set Z and add to it all the maneuvers in sets X and Y that belong to those aircraft which are not involved in both sets.
- 2) If two maneuvers, say, M1 in X and M2 in Y, belong to the same aircraft, merge M1 and M2 to form maneuver M. If M is null, Z is set to null. Otherwise, M is added in Z.
- 3) Repeat Step 2) for each aircraft that has maneuvers in both X and Y.

Finally, the algorithm for resolving conflicts that involve a set of conflict aircraft pairs is as follows:

- 1) Group the conflict pairs into equivalent class of aircraft clusters.
- 2) Sort the aircraft pairs in each aircraft cluster into an ordered list: start with the pair with the least time to LOS and, if possible, order the rest of the pairs in such a way that adjacent pairs share a common aircraft.
- 3) Generate a maneuver set of the highest priority for each aircraft cluster with the following algorithm:
  - a) Create a prioritized list of maneuver sets for each aircraft pair in the aircraft cluster in the order of the list of aircraft pairs based on the algorithms described in Sec IV.A and IV.B.
  - b) Re-prioritize each list of maneuver sets created in Step a) by taking into consideration whether the aircraft are conformed and whether terrain conditions allow the maneuver sets, etc. The relative priorities of a subset of the maneuver sets should not be changed if they are not affected by the additional considerations.
  - c) Select the maneuver set of the highest priority from each aircraft pair in the aircraft cluster and merge them to form a new maneuver set for the aircraft cluster. If the new maneuver set is null because of incompatible maneuvers for the common aircraft, the next maneuver set is selected from the prioritized

- list. This process is continued until a non-null set is obtained.
- 4) Create all aircraft trajectories using the trial maneuver set generated in Step 3).
  - 5) Check if the maneuver set chosen is conflict free using the trajectories created. If it is conflict free, a resolution that resolves the conflicts globally has been found. Otherwise, go back to c) of Step 3) above to generate the next maneuver set for the unresolved aircraft clusters. This iteration and recursion process continues until a conflict-free resolution is found. Otherwise, when all trial maneuvers are exhausted, the conflict is not resolved. In the rare condition that this should occur, the last line of defense against a collision would be TCAS.

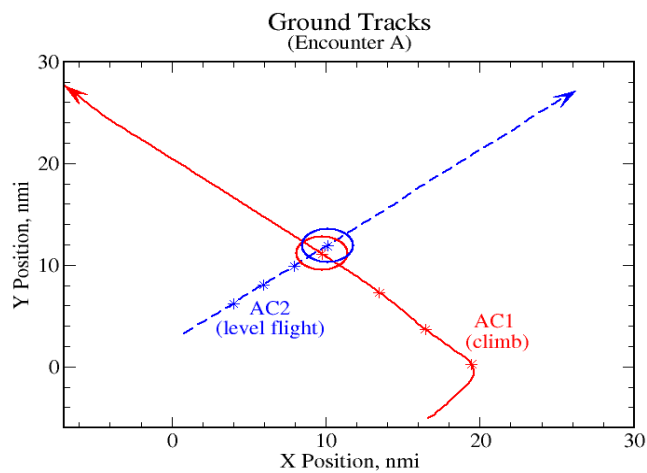
## V. Results

In this section, the algorithm for vertical conflict resolution is evaluated using trajectory data of real-world incidents. One incident involved a climbing departure and a level overflight in terminal airspace. The departure aircraft experienced a TCAS resolution advisory. Radar track data as well as TCAS RA information were available but flight plans were not. A second incident involved a pair of aircraft that were in conflict due to an operational error in en route airspace where radar track data as well as flight plans were available and a TCAS resolution was reported, which could be identified from the plot of the altitude profile. The third incident involved two arrival aircraft in a terminal airspace where radar tracks and flight plans were available and maneuvers by pilots and controllers were executed. No TCAS RA was reported. The track positions, the predicted conflicts from TSAFE, and the altitude profiles with the conflict resolution maneuvers generated from the vertical TSAFE algorithm described earlier are presented. The maneuvers are shown to resolve the conflicts as the aircraft approach their first LOS points.

### A. Encounter A (Incident with an Explicit TCAS Resolution in Terminal Airspace)

This incident involved two aircraft, designated here as AC1 and AC2. The data were obtained from MIT Lincoln Laboratory. Radar track data and TCAS RA information were available. Unfortunately, flight plan and other information were not available. Aircraft AC1 was departing from an airport and climbing through FL170 towards its assigned altitude of FL260. Aircraft AC2 was in level flight at FL170. A loss of separation occurred and a TCAS RA was issued on AC1 when the two aircraft came in proximity to each other near FL170. The first loss of separation occurred at a vertical separation of about 870 ft and a horizontal separation of about 0.9 nmi. The aircraft diverged from each other horizontally but they approach each other vertically and remained in conflict for about 25 seconds. It appears that the pilot continued climbing without taking any action. TSAFE was able to predict the conflict about 3 minutes prior to the first loss of separation while the TCAS RA was issued about 10 seconds before the first LOS.

Figure 4 shows the ground tracks of the two aircraft from their actual radar track data in the horizontal plane. The arrows indicate the flight directions. The stars indicate positions one minute apart with a circle of diameter 3 nmi around the point of first LOS.



**Figure 4. Aircraft ground tracks with first LOS positions indicated for Encounter A.**

The predicted conflicts from the TSAFE conflict detection component are shown in Fig. 5, where the prediction of LOS, from a specific trajectory combination of the two aircraft, is plotted against the time relative to that of the first LOS. Thus each point in Fig. 5 indicates a prediction of a conflict using a combination of predicted trajectories defined by FP/FP =1, FP/DR=2, DR/FP=3, and DR/DR=4. Since flight plan and other information on the aircraft were not available, the predictions were based solely on dead-reckoning trajectories. The occurrence of a loss of separation is indicated by LOS=0. TSAFE predicts a LOS starting from about 3 minutes to the point of first LOS. Note that, because of inaccuracy of predicted trajectories, the predicted time to LOS may be less than the time to first actual LOS.

The actual altitude profiles of the aircraft are shown in Fig. 6 along with the TSAFE resolutions generated for each predicted conflict that is two minutes or less to the predicted LOS. The profile depicts the altitudes of the aircraft as a function of the time relative to the first LOS. The downward arrow indicates that a TCAS downward-sense RA was issued. Once TSAFE predicts the conflict, if the time to predicted LOS is 2 minutes or less, it follows the

vertical maneuver algorithm, as defined in Table 2 for the encounter type 5 of climbing and cruising, to provide a vertical maneuver that clears the climbing aircraft AC1 to a temporary altitude 1000 ft below that of aircraft AC2 at a flight level of 16000 ft. This happens for each radar track position until either the aircraft are at LOS or they get within the region where it is expected that TCAS may issue a resolution, based on the TSAFE range and altitude tests as described in Sec. III. At this point TSAFE will no longer issue a vertical resolution to avoid potential interference with TCAS. The solid lines are the predicted trajectories of AC1 assuming the TSAFE resolutions were executed. A 10 second delay is included for the aircraft to execute a maneuver with climb rates as provided by the BADA model. As seen from the figure, the conservative thresholds used by TSAFE to model TCAS RA issuance prevent vertical TSAFE resolution maneuvers within the TCAS RA time horizon.

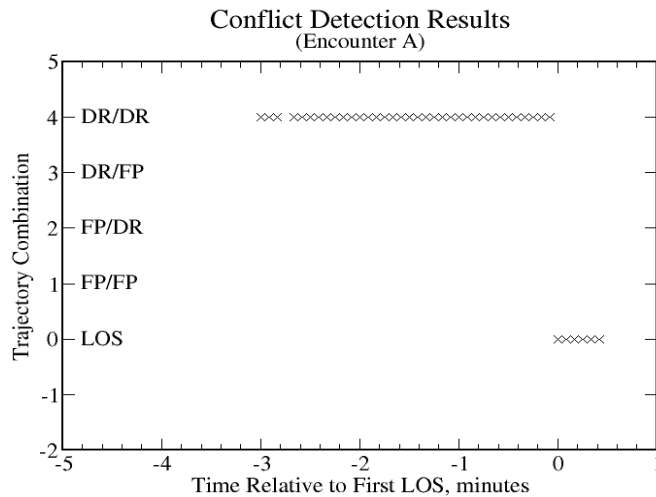


Figure 5. Predicted conflicts for Encounter A.

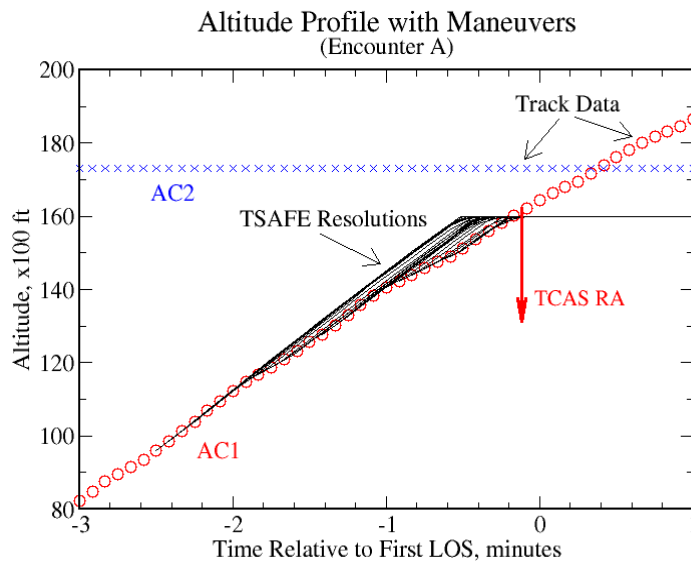


Figure 6. Predicted vertical maneuvers for Encounter A.

## B. Encounter B (Operational Error Incident in En Route Airspace)

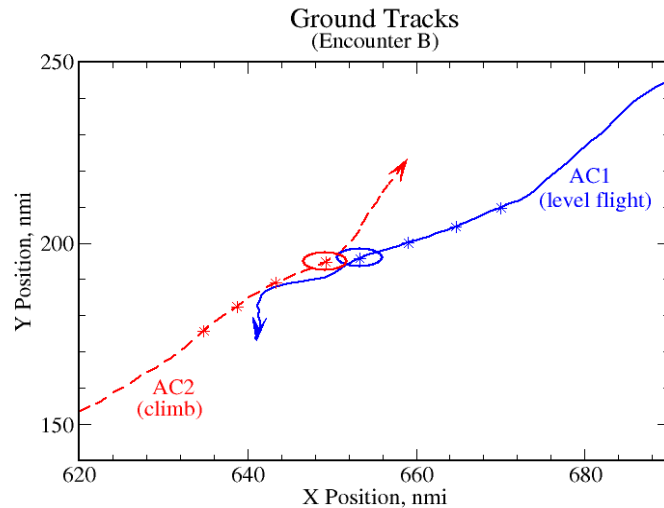
This operational error incident involves two aircraft designated again as AC1 and AC2, in which AC2 was a southwest-bound overflight at FL280 and AC1 was a northeast-bound overflight assigned at FL270. Aircraft AC1 was cleared to climb to FL290 and became conflicted with AC2. Aircraft AC1 was instructed to turn 30 degrees left and AC2 was instructed to turn 30 degrees left shortly afterwards as well. The turns were not executed until shortly after loss of separation. Both aircraft were TCAS equipped and it was reported that aircraft AC2 had a TCAS RA issued and the altitude profile indicates that the pilot appeared to follow the RA to descend the aircraft.

Figure 7 shows the ground tracks of the two aircraft in the horizontal plane. The first LOS positions are indicated with circles of 5 nmi in diameter. The arrows indicate the flight directions. The stars are positions one minute apart. The first radar-indicated loss of separation occurred at a vertical separation of about 600 ft and a horizontal separation of about 4.2 nmi. Thereafter, the aircraft remained in conflict for about 24 seconds while they were being maneuvered.

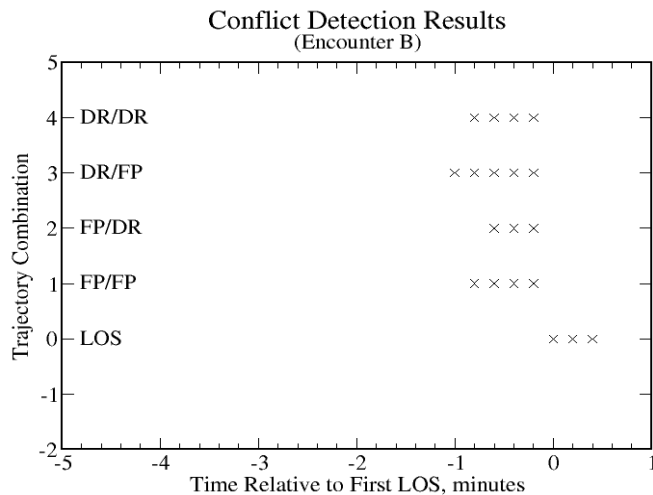
The predicted conflicts are shown in Fig. 8 as a function of time relative to the first LOS. The first prediction came from the DR trajectory of AC1 and the FP trajectory of AC2 (DR/FP). It occurred about one minute away from the first LOS. All trajectory combinations yield predictions on the conflict later.

Figure 9 shows the altitude profiles of the two aircraft as a function of time relative to the first LOS. As seen from Figure 9, aircraft AC2 was issued a temporary clearance to FL 290. TSAFE predicts a LOS before AC2 begins to climb. This is the case because TSAFE can make predictions as soon as the temporary clearance is entered into the system. The BADA model is used to determine the climb rates. The

algorithm selected the resolution in Table 2 for the encounter of climb vs cruise. The resolution assigned AC2 a clearance altitude of 27000 ft, which is 1000 ft below the altitude of AC1. This causes aircraft AC2 to descend as indicated by the solid lines, which are the predicted trajectories of AC2 assuming that the vertical maneuvers are executed by the pilot. The first maneuver was issued before AC2 started to climb so it would have prevented the

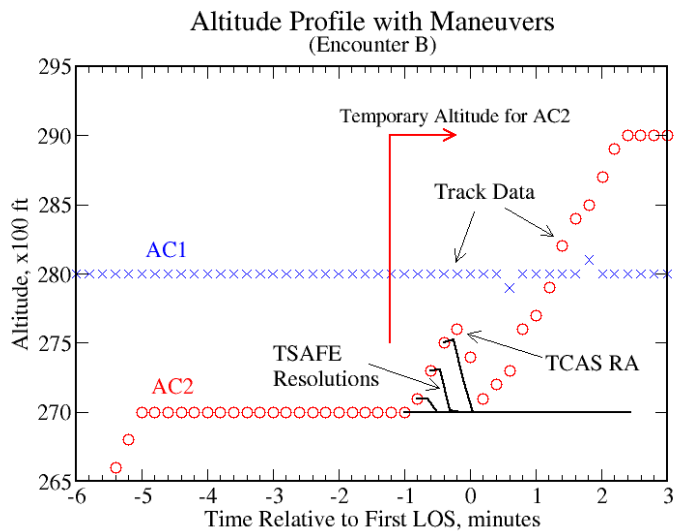


**Figure 7. Aircraft ground tracks with first LOS positions indicated for Encounter B.**



**Figure 8. Predicted conflicts for Encounter B.**

aircraft from climbing too soon and avoided the LOS as well as the TCAS resolutions. The initial short level flight or climbing in the maneuvers are due to the 10 second execution delay time previously discussed. Vertical maneuvers were inhibited when AC2 approached the region in which a TCAS resolution might occur based on the TSAFE range and altitude tests. The TSAFE resolutions could have been implemented about 50 seconds before the TCAS resolution appeared to be executed. Once again the conservative model of TCAS RA issuance conditions avoid interference with the TCAS RA, which AC2 appeared to execute shortly before the first LOS.

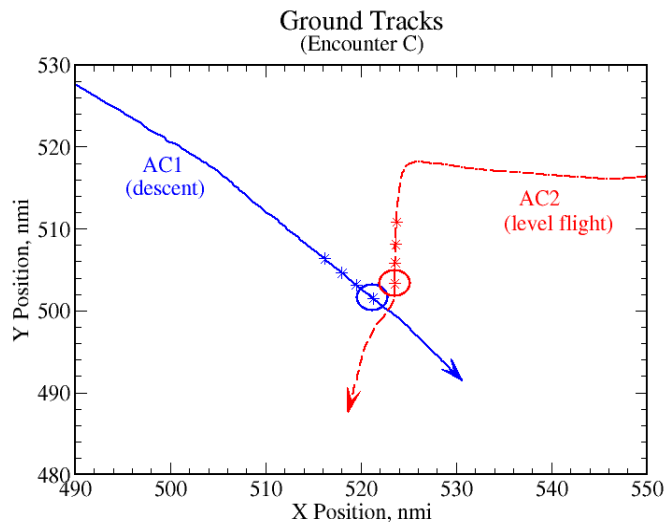


**Figure 9. Predicted vertical maneuvers for Encounter B.**

**C. Encounter C (Operational Error Incident in Terminal Airspace)**

This operational error incident involves two aircraft designated again as AC1 and AC2, in which AC2 was inbound to an airport from the north at 4000 ft and AC1 was inbound to another airport nearby on a localizer at 5000 ft. The two aircraft were on a converging course. Aircraft AC1 was instructed to descend to 4000 ft and separation was lost soon thereafter. Aircraft AC1 was then stopped at 4500 ft while AC2 was descended to 3000 ft to avoid the conflict. Aircraft AC1 was TCAS equipped. It is not known if AC2 was TCAS equipped. No TCAS RA appears to have been issued. The first radar-indicated LOS occurred when the vertical separation was about 700 ft and horizontal separation was 2.9 nmi. The aircraft remained at LOS for about 50 seconds while being maneuvered.

Figure 10 shows the ground tracks of the two aircraft in the horizontal plane. The first LOS positions are again indicated with circles of 3 nmi in diameter. The arrows indicate the flight directions. The stars are points one minute apart showing the approach to the first LOS. Figure 11 shows the predicted conflicts as a function of time relative to the first LOS. TSAFE predicted a LOS almost 4 minutes before the occurrence of the first LOS. The predicted conflicts came from various trajectory combinations. The time to the predicted point of LOS for the conflicts should be within three minutes. Thus the actual LOS occurs later than the TSAFE predictions, indicating some inaccuracy of the predicted trajectories.



**Figure 10. Aircraft ground tracks with first LOS positions indicated for Encounter C.**



Figure 12 shows the altitude profiles of the aircraft as a function of time relative to the first LOS. It can be seen that the first LOS occurred before the controller leveled AC1 off at 4500 ft and descended AC2 to 3000 ft. TSAFE predicts LOS and provides vertical maneuvers long before the actual first LOS. The vertical algorithm selects the resolution in Table 2 for the encounter type 6 of descending and cruising, which assigned AC1 to a clearance altitude of 5000 ft, 1000 ft above the altitude of AC2. Again the initial 10 second decent of the maneuvers are due to the delay introduced. Vertical maneuvers were not inhibited until the aircraft were at the point of first LOS. No TCAS RA was reported in this incident. No such indication was found from the simplified range and altitude tests of TSAFE either. This once again indicates that the conservative TSAFE modeling of TCAS RA issuance conditions avoids interference with TCAS. Once the aircraft are at LOS, the horizontal maneuver algorithms are expected to come into play.

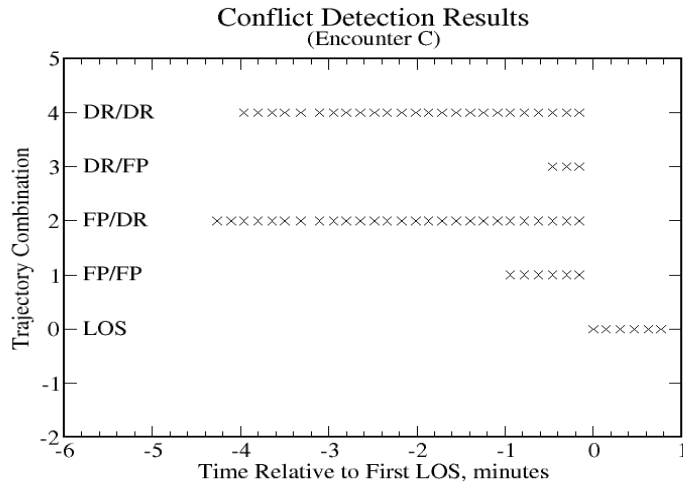


Figure 11. Predicted conflicts for Encounter C.

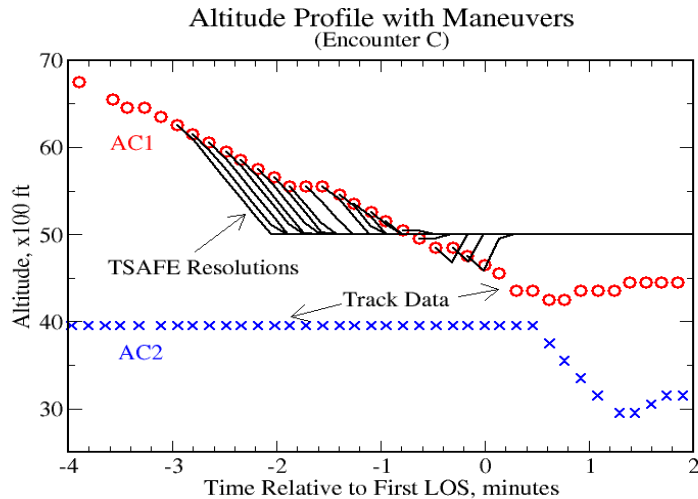


Figure 12. Predicted vertical maneuvers for Encounter C.

## VI. Concluding Remarks

This work proposes a new vertical resolution algorithm that provides tactical resolutions for all encounter conditions. The significance of the algorithm lies in the fact that it is based on simple rules yet it generates familiar altitude clearances that appear to match what controllers would select today in similar situations. An approach to minimize the interference of these maneuvers with TCAS resolutions is included. Evaluations using real-world encounters have successfully demonstrated the effectiveness of the vertical maneuvers for resolving conflicts well before loss of separation. The results also indicate that the approach used to minimize the interference with TCAS is successful. In the three cases considered, the vertical conflict resolutions are correctly provided prior to the TCAS resolutions and are inhibited shortly before the TCAS resolution occurred.

Additionally, an algorithm is proposed for resolving multiple aircraft conflicts. The algorithm uses simple altitude and vector clearances for a conflict pair as basic building blocks and introduces constraints that limit

possible clearances on an aircraft when resolving other conflict pairs that share a common aircraft. As a result, a prioritized list of vertical and horizontal maneuvers for each pair in a cluster of conflict pairs can be created and merged into maneuver sets that resolve the multiple aircraft conflicts simultaneously. Future studies are required to evaluate the effectiveness of the algorithm with the use of both the vertical and horizontal resolutions to resolve multiple aircraft conflicts in a high density environment.

## References

- <sup>1</sup>Kuchar, J. K. and Yang, L. C., "A Review of Conflict Detection and Resolution Modeling Methods", IEEE Transactions on Intelligent Transportation Systems, Vol. 1, No. 4, 2000, pp. 179-189.
- <sup>2</sup>Durand, N., Alliot, J.-M., and Chansou, O., "Optimal Resolution of En Route Conflicts", Air Traffic Control Quarterly, vol. 3, no. 3, 1995, pp. 139-161.
- <sup>3</sup>Bilimoria, K. D., "A Geometric Optimization Approach to Aircraft Conflict Resolution", AIAA Paper 2000-4265, Aug. 2000.
- <sup>4</sup>Bilimoria, K.D., Lee, H.Q., Mao, Z.-H., and Feron, E., "Comparison of Centralized and Decentralized Conflict Resolution Strategies for Multiple-Aircraft Problems", AIAA Paper 2000-4268, Aug. 2000.
- <sup>5</sup>Frazzoli, E., Mao, Z.-H., Oh, J.-H., and Feron, E., "Resolution of Conflicts Involving Many Aircraft via Semidefinite Programming", AIAA, *Journal of Guidance, Control, and Dynamics*, Vol.24, No.1, 2001, pp79-86.
- <sup>6</sup>Jardin, M.R., "Analytical Relationships between Conflict Counts and Air Traffic Density", AIAA, *Journal of Guidance, Control, and Dynamics*, Vol.28, No.6, 2005, pp1150-1156.
- <sup>7</sup>Paielli, R.A., "Modeling Maneuver Dynamics in Air Traffic Conflict Resolution", AIAA, *Journal of Guidance, Control, and Dynamics*, Vol.26, No.3, 2003, pp407-415.
- <sup>8</sup>Menon, P.K., Sweriduk, G.D., and Sridhar, B., "Optimal Strategies for Free-Flight Air Traffic Conflict Resolution", AIAA, *Journal of Guidance, Control, and Dynamics*, Vol.22, No.2, 1999, pp202-211.
- <sup>9</sup>Erzberger, H., "The Automated Airspace Concept", Proceedings of the fourth USA/Europe Air Traffic Management R&D Seminar, Santa Fe, New Mexico, USA, December 3-7, 2001.
- <sup>10</sup>Erzberger, H., and Paielli, R.A., "Concept for Next Generation Air Traffic Control System", Air Traffic Control Quarterly, vol. 10, no. 4, 2002, pp.355-378.
- <sup>11</sup>Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System", NASA/TP-2004-212828, October 2004.
- <sup>12</sup>Erzberger, H., "Automatic Conflict Resolution for Air Traffic Control", 25<sup>th</sup> International Congress of the Aeronautical Sciences, 2006.
- <sup>13</sup>Paielli, R.A. and Erzberger, H., "Tactical Conflict Detection Methods for Reducing Operational Errors", Air Traffic Control Quarterly, vol. 13(1), 2005.
- <sup>14</sup>Paielli, R.A. and Erzberger, H., "Design and Testing of a Tactical Conflict Alerting Aid for Air Traffic Controllers", 2007.
- <sup>15</sup>Erzberger, H. and Heere, K., "Algorithm and Operational Concept for Resolving Short Range Conflicts", University of California, Santa Cruz. Paper No. 383, International Congress of the Aeronautical Sciences (ICAS-08), Anchorage, Alaska, Sept. 14-19, 2008.
- <sup>16</sup>Paielli, R.A., "Tactical Conflict Resolution using Vertical Maneuvers in Enroute Airspace", AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Sept. 2008.
- <sup>17</sup>Eurocontrol, Base of Aircraft Data (BADA 3.6), The EUROCONTROL Experimental Centre, Brétigny, France, 2004.
- <sup>18</sup>"Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II)", RTCA, Airborne Equipment, DO-185A, 1997.