

Tactical Conflict Detection in Terminal Airspace

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Air traffic systems have long relied on automated short-term conflict prediction algorithms to warn controllers of impending conflicts (losses of separation). The complexity of terminal airspace has proven difficult for such systems, as it often leads to excessive false alerts. Thus, the legacy system, called Conflict Alert, which currently provides short-term alerts in both en route and terminal airspace, is often inhibited or desensitized in areas where frequent false alerts occur, even though the alerts are provided only when an aircraft is in dangerous proximity of other aircraft. This research investigates how a minimal level of flight-intent information may be used to improve short-term conflict detection in terminal airspace such that it can be used by the controller to maintain legal aircraft separation. The flight-intent information includes a site-specific nominal arrival route and inferred altitude clearances in addition to the flight plan that includes the area-navigation departure route. A new tactical conflict detection algorithm is proposed, which uses a single analytic trajectory, determined from the flight intent and the current state information of the aircraft, and includes a complex set of current, dynamic separation standards for terminal airspace. The new algorithm is compared with an algorithm that models a known en route algorithm and another algorithm that models Conflict Alert. This is done by analysis of false-alert rate and alert lead time with the use of recent real-world data of arrival and departure operations and a large set of operational error cases from the Dallas/Fort Worth terminal radar approach control. The new algorithm yielded a false-alert rate of two per hour and an average alert lead time of 38 s.

I. Introduction

THE current U.S. air transportation system is expected to be unable to support the projected demand for air travel. One of the primary limitations of airspace capacity is controller workload. A combination of air- and ground-based automation is a potential solution to this limitation. One area of research central to this goal is the automation of conflict detection and resolution functions [1].

Recently, there has been considerable research directed toward a new concept for automated separation assurance, referred to as the Advanced Airspace Concept (AAC) [2–4]. The AAC provides two independent layers of separation assurance: a strategic layer and a tactical layer. The strategic layer focuses on midterm conflicts (losses of separation) predicted to be from 2 to 20 min into the future. The tactical layer addresses short-term or imminent conflicts predicted to occur within approximately 2 min. A third layer of safety is provided by an independent airborne collision avoidance system, such as Traffic Alert and Collision Avoidance System (TCAS) [5]. TCAS deals with potential collisions less than approximately 45 s away. The tactical layer, 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. TSAFE simplifies the problem of automated separation assurance and provides a safety net for the strategic layer. Most of the research to date has focused on en route airspace. En route prototypes of TSAFE have been developed and studied with the use of en route operational error cases [6–9], and some attention on TSAFE conflict resolution

has appeared [10–12]. TSAFE as an independent system to aid the controller for the near term has also been proposed [8–11]. A high-level specification for short-term conflict alert systems similar to TSAFE has also recently been released by Eurocontrol [13].

The complexity of terminal airspace has proven difficult for tactical conflict detection systems. The contributing factors include the dense air traffic, frequent large turns, an imprecise flight plan, a complex set of separation standards, and the frequent necessity to operate aircraft purposely near the required separation standards. Conflict Alert [14], the legacy system that relies mainly on dead reckoning (DR) to predict aircraft trajectories, currently provides tactical alerts in terminal airspace. It is designed to determine if two aircraft are in dangerous proximity of each other rather than if they are going to lose legal separation by the separation standards. It is often inhibited or desensitized in areas where frequent false alerts occur [15]. Thus, Conflict Alert was not designed for the controller to maintain legal aircraft separation and, as such, the separation standards for terminal airspace have not been adapted closely enough. On the other hand, the conflict detection algorithms in en route TSAFE have not been designed to address the unique problems of terminal airspace. To the best of our knowledge, no report on direct application of the en route algorithms to terminal airspace can be found in the literature, and there is no literature on tactical conflict detection algorithm that covers the whole terminal airspace and follows the separation standards.

In this paper, a new conflict detection algorithm is proposed that uses a single analytic trajectory that takes into account available flight-intent (FI) information and the current state of the aircraft. The trajectory consists of segments of straight lines and circular arcs that can be represented analytically. Apart from the flight plan, which can include an area-navigation (RNAV) departure route, the FI information includes segments of nominal Terminal Radar Approach Control (TRACON) routes, speed restrictions, and altitude clearances inferred from the recorded track data. A complex set of current, dynamic separation standards for terminal airspace, as documented in the Federal Aviation Administration (FAA) order 7110.65S [16], is adapted to define losses of separation. The new algorithm is compared with an algorithm that models the dual-trajectory algorithm of en route TSAFE [9] and another that models

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Conflict Alert. The comparison is done from analysis of false-alert rates and alert lead times through a replay of recent recorded real-world data of arrival and departure operations and 70 operational error cases from Dallas/Fort Worth (DFW) TRACON. The results show that the new FI algorithm yields a significantly reduced false-alert rate without much compromise in the alert lead time.

The rest of this paper is organized as follows. Section II discusses an FI trajectory prediction algorithm. Section III presents tactical conflict detection algorithms. A broad set of the standard FAA separation criteria used to define conflicts in this research is also described. Section IV provides results and discussions from analysis of the alert lead time. Section V discusses a classification of false alerts and results of false-alert analysis of real-world traffic data. Section VI presents conclusions.

II. Trajectory Predictions

Conflict detection starts with predictions of the trajectories of the flights involved. Short-term trajectory predictions become more reliable with knowledge of the intended routes, in addition to the current state information of the aircraft. FI routes and their usage in a trajectory prediction algorithm are discussed in this section.

A. Flight-Intent Routes and Horizontal Conformance

An FI route refers to the merged route of the FAA flight-plan route and the nominal TRACON route segments of an aircraft. The FAA flight plan today does not generally have complete details from the meter fix to the runways. On the departure side, the RNAV departure route of the flight plan provides accurate enough waypoints from the departure runway to the meter fix. However, published RNAV routes are not available at all airports.

Aircraft generally follow the same nominal paths that have some common flexibility in the TRACON. Past air traffic automation efforts have used these prescribed nominal TRACON paths from the meter fixes down to the runways [17]. They are sometimes referred to as nominal interior routes (NIRs). An NIR for an aircraft is unique, given the airspace configuration and the engine type, meter fix, airport, and assigned runway. A typical NIR is shown in Fig. 1, where the squares on the centerline indicate waypoints. The last two waypoints in the final leg are the final approach fix (FAF) and runway threshold fix (RWY). Most arrival aircraft in DFW TRACON are observed to follow the NIRs, except that a base extension or trombone is common. Thus, an NIR approximately describes the horizontal FI of an arrival aircraft in today's system. The FI route of an aircraft merges its flight-plan route with its NIR.

Horizontal conformance is defined and used in this research to construct the horizontal track of an aircraft. An aircraft is said to be in conformance or ontrack if its cross-track distance to the center of the NIR is within a conformance threshold; otherwise, the aircraft is said to be out of conformance or offtrack. Thus, as shown in Fig. 1, if an aircraft is within the shaded area defined by the conformance threshold, the aircraft is ontrack. The value for the conformance threshold is taken to be 0.5 n mile throughout. The conformance threshold is

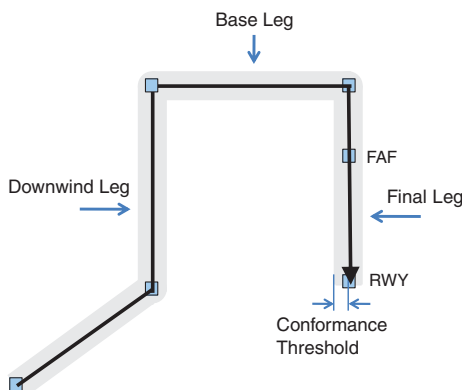


Fig. 1 A static NIR with a conformance region as indicated.

based on qualitative comparison of a large number of predicted and actual horizontal tracks. For simplicity, aircraft heading is not considered in defining the conformance. For the purpose of constructing horizontal tracks, heading becomes less important in the conformance definition in terminal airspace because of the shorter radar update cycle of 4.8 s, as compared with 12 s in the en route. The conformance threshold for final approach courses should be adjusted to optimize the detection of blunders in the final approach.

B. Flight-Intent Trajectory

This section describes an algorithm, referred to as the FI trajectory algorithm, for predicting a kinematic trajectory of an aircraft. This FI trajectory algorithm first predicts a flyable horizontal track of an aircraft with straight-line and circular-arc segments based on current aircraft state, the FI route, and the conformance status. The algorithm then creates a groundspeed profile for the aircraft to fly along the track. Finally, the algorithm generates an altitude profile to superimpose on the horizontal trajectory. The trajectory can be represented analytically with some standard parameters for straight lines, circular arcs, and kinematic states. Straight-line and circular-arc segments have been used to build aircraft horizontal tracks for some time [18].

1. Horizontal Track

The horizontal track for an FI trajectory assumes that, whenever possible, an aircraft attempts to conform to its FI route and other available intent information. Thus, when in conformance, it will stay in conformance; otherwise, it will move along a straight line along its current course. However, the aircraft is assumed to be aware of its FI in the sense that, when possible, it joins smoothly back with the next segment in its FI route. So the aircraft flies along a horizontal track constructed using straight-line and circular-arc segments based on the following general rules:

- 1) If the aircraft is ontrack, capture the next waypoint in the FI route.
- 2) If the aircraft is offtrack, start with a straight line along its current course; then, if possible, join the FI route upon interception. Otherwise, continue along the straight line.

The radius of the circular-arc segments, assuming a coordinated turn, is estimated from the aircraft's current groundspeed V and a bank angle ϕ_B by $r_c = V^2 / g \tan \phi_B$, where g is the acceleration of gravity and $\phi_B = 30^\circ$. While a straight-line segment is completely specified by its two endpoints, a circular-arc segment requires specification of the center and the turn direction (left or right) in addition to the two endpoints. All these parameters for the segments can be determined analytically given the initial position of the aircraft and the estimated radius. Thus, the trajectory can be calculated and represented analytically. As an example, Fig. 2 schematically shows the FI route of an offtrack aircraft and its FI trajectory predicted from the preceding rules. Given the initial position and heading, the radii of turns, and the waypoints in the FI route, it is mathematically straightforward to find the analytic expressions for the straight-line and circular-arc segments between any two dots on the trajectory shown.

Since base extensions are common and turns onto the final are restricted, special rules apply to downwind-to-base and base-to-final turns. The rules are summarized as follows, with the numerical values being based on engineering experience.

For the downwind-to-base rule, first, before a turn is detected, the aircraft is predicted to continue along its velocity vector. That is, a downwind-to-base turn will not commence until an actual turn of the aircraft has been detected. This rule is based on the observation that the base leg of the NIR is extended in most cases. The detection of a turn is defined as three consecutive course changes in the same direction (left or right). After a turn toward the base is detected, the actual turn radius is calculated based on the current rate of course change ω and the current groundspeed by $r_a = V / \omega$. If the current heading of the aircraft is more than 150° from the final approach course, the aircraft is predicted to continue turning for 10 s, or about two radar update cycles with the current actual turn radius r_a , and

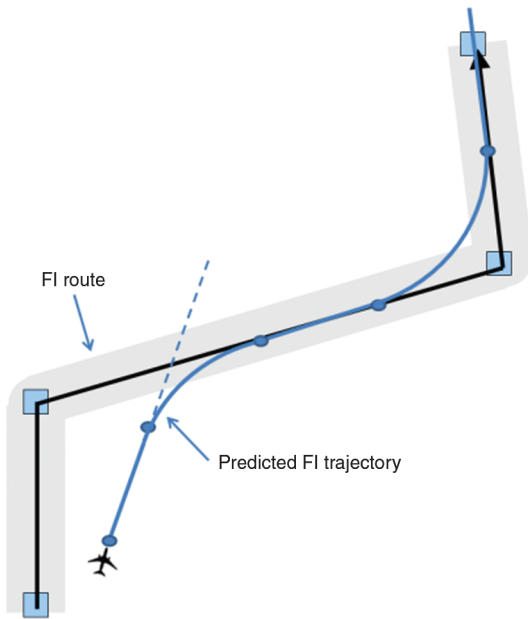


Fig. 2 Analytically expressible FI trajectory prediction for an offtrack aircraft.

then continue along a straight-line projection at the end of the turn. If the current course of the aircraft is within 150° of the final approach course, the aircraft is assumed to continue turning with radius r_a to a course perpendicular to the final approach course. If the turn is not possible because r_a is too large, the coordinated turn radius r_c is tried. If the turn is still not possible, a straight line is used.

For the base-to-final rule, an aircraft approaching the final approach course with some angle is generally assumed to turn and start to intercept the final approach course at some minimum perpendicular distance d (see Fig. 3 for a typical turn scenario). Based on visual inspection of many actual trajectories, we take $d = 2$ n mile. Circular-arc and straight-line segments are used to construct the trajectories of interception. An interception angle θ of approximately 30° before the FAF is assumed. If an aircraft is already closer than 2 n mile to the final approach course, it is assumed to turn and intercept right away. If it is not possible to turn, it is assumed to fly along a straight line.

As an illustration, Fig. 4 shows the FI trajectories predicted at each radar track position for an aircraft following an NIR. The dashed line is the static NIR, which connects the waypoints represented by the squares. The FAF and runway threshold (RWY) are also indicated. The base was extended about 9.5 n mile. The circles and diamonds are the actual radar track positions, with the circles indicating ontrack and the diamonds offtrack while the plus sign marks the start of the

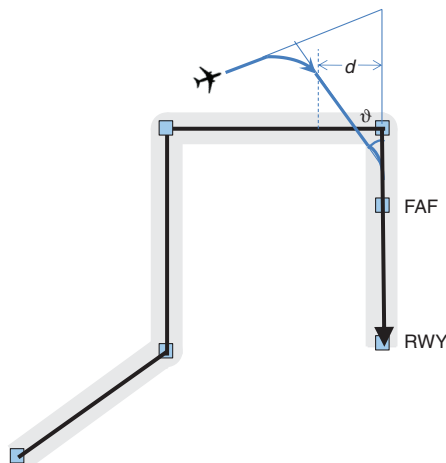


Fig. 3 A typical interception of the final approach course.

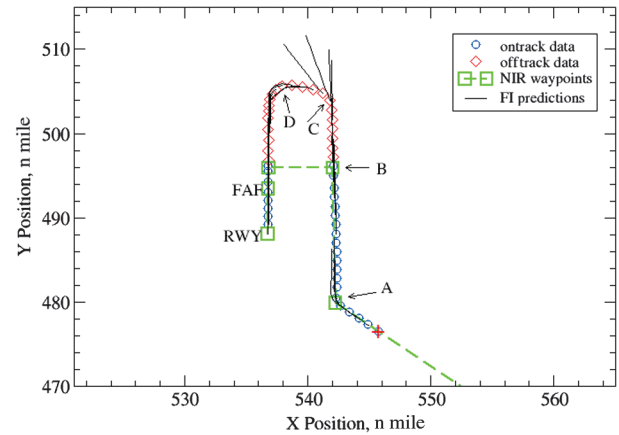


Fig. 4 Sample ground track with predicted FI trajectories for an aircraft following an NIR.

radar track. The solid lines are the FI predictions. The turn into the downwind leg, indicated by label A, is an example of an ordinary turn. The intersection between the downwind and the expected base legs is indicated by label B. The actual base and final turns, which the special rules apply, are indicated by labels C and D, respectively. Notice that the FI trajectories turn only after proper turns have been detected at C instead of following the base turn of the NIR at B. Before the base turn at C is detected, the aircraft follows the downwind leg and continues along its course in a straight line, since it is offtrack. Then, when the turn at C is detected while the course of the aircraft is still more than 150° from its final approach course, the aircraft turns 10 more seconds (approximately two radar update cycles) before continuing along a straight line. Once its course is less than 150° from the final approach course, the aircraft turns into the base, approaches, and properly intercepts the final approach course. For comparison, Fig. 5 shows the corresponding DR predictions (straight lines along the aircraft current course headings) for the same aircraft. As can be seen, the FI trajectories generally provide more accurate predictions than the DR trajectories.

2. Groundspeed Profile

A groundspeed profile based on current groundspeed and acceleration is generated for the aircraft to fly along the constructed horizontal track. Our experience from comparing the trajectory predictions with the actual TRACON tracks suggests that the groundspeed changes significantly enough that it is necessary to model the acceleration. However, since the actual duration of deceleration of an aircraft is not known, the rate of the deceleration may be so large that the aircraft may be predicted to reduce its speed unrealistically to zero within the 2-min look-ahead period. Thus, a lower limit for the groundspeed is necessary, especially during base

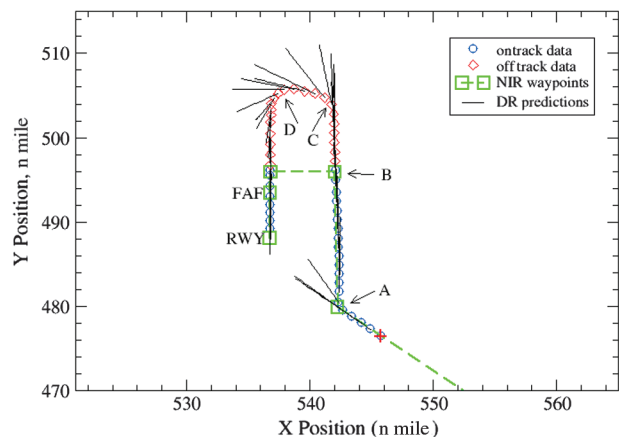


Fig. 5 Sample ground track with predicted DR trajectories for an aircraft following an NIR.

leg and final approach periods. Similarly, the acceleration of a departing flight may be so large that an upper bound on the groundspeed may need to be imposed. In this paper, groundspeed lower bounds near the FAF and RWY are imposed, and an upper bound is imposed on certain departure flights. Other bounds may be added in the future. When a groundspeed bound is imposed, the aircraft is projected to fly at that speed bound once it is reached.

The lower bound on the groundspeed near the FAF is set at 160 kt. The bound at the runway threshold is 130, 115, or 95 kt, depending on whether the engine type of the aircraft is jet, turboprop, or piston, respectively. The groundspeed upper bound for departure flights is 260 kt for flights below 6500 ft. These numbers are based on observations of a large set of flight data. The results are not sensitive to the precise values. Given the current groundspeed, the length of the constructed trajectory, and the speed bound, one can calculate a required acceleration. In the case of a deceleration, if the magnitude of the required deceleration is larger than the current measured value, the required value will be used. Otherwise, current ground deceleration is used. Note that while wind effects are not explicitly considered, they are implicitly taken into account through ground-acceleration modeling.

3. Altitude Profile

The climb or descent of an aircraft is simply modeled in a three-phase altitude profile: an initial acceleration phase, a constant-rate phase, and a final deceleration phase. A vertical constant acceleration of 0.1 g is assumed for the initial and final phases. With this acceleration, it takes about 10 s for an aircraft to increase its climb rate by 2000 fpm. Figure 6 illustrates the model of a three-phase climb. The following rules are used to determine the phase of a flight:

- 1) When the vertical distance to the cleared altitudes of an aircraft is more than 200 ft and its climb or decent rate is more than 500 fpm, it is in the constant-rate phase.
- 2) When the distance is more than 200 ft and the climb or decent rate is less than 500 fpm, it is in the acceleration phase. (It is not in a deceleration phase, since the speed would have to be larger for a stopping distance of 200 ft.)
- 3) Otherwise, the aircraft is in the deceleration phase.

Note that the preceding numbers are adjustable, and they appear reasonable when the predicted trajectory profiles are compared with many actual traffic trajectories. The conflict prediction results are not sensitive to the precise values. If an aircraft is in the constant-rate phase, its constant vertical rate is given by its current vertical rate. If an aircraft is in the initial acceleration phase, its vertical speed at the constant-rate phase is obtained by looking up the nominal climb or descent rate in the Base of Aircraft Data from Eurocontrol [19].

While most altitude clearances are entered into the host computer at each air route traffic control center (ARTCC), these clearances are usually only transmitted by voice in the TRACON without being entered into the TRACON's Automated Radar Terminal System or Standard Terminal Automation Replacement System computer. In the future, such cleared altitudes may be entered into the system; in which case, the clearances would become available intent data for use in predicting the trajectory. To study the effects of temporary altitude clearances, we extract the location and duration of level segments from a recorded file of aircraft tracks and use them to generate

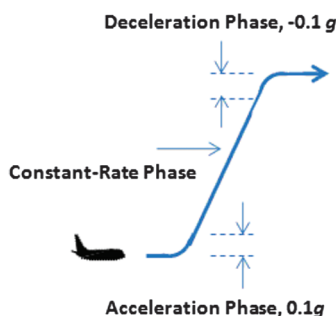


Fig. 6 A three-phase climb of an aircraft.

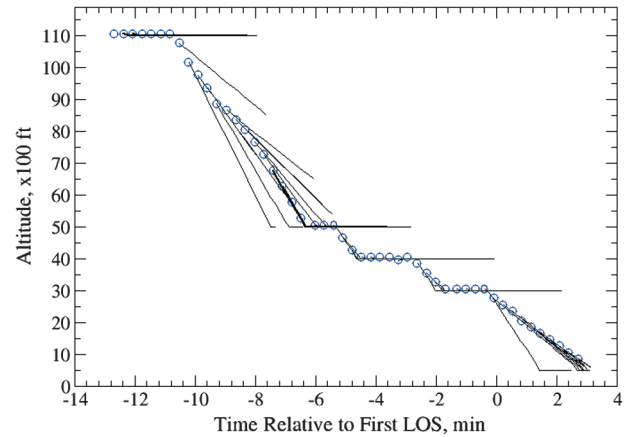


Fig. 7 Sample altitude profiles with IACs.

simulated altitude clearances. The resulting cleared altitudes are referred to as inferred altitude clearances (IACs). By comparing the false-alert rates with and without the use of IACs, the importance of making them available can be addressed.

A sample altitude profile that uses IACs is shown in Fig. 7, where the circles represent the actual altitude above mean sea level (MSL) and the solid lines are predictions from the altitude profile algorithm. As seen in the figure, the predicted trajectories level off at the inferred altitudes. Without the IACs, the predicted trajectories would have continued descending below the cleared altitudes. Inevitably, this could cause false alerts.

C. Trajectory Comparison

The FI trajectory builds upon available intent information and thus provides more accurate trajectory predictions than the DR trajectory, which simply extrapolates the current aircraft state along a straight line in the direction of the aircraft's current velocity. As can be seen from the algorithm described previously, the FI trajectory generally follows the FI route of the aircraft. However, it simply becomes a straight-line trajectory in the direction of the velocity when no intent information is available. Therefore, it will perform just as well as the DR trajectory when FI information lacks.

In the dual-trajectory conflict probing of en route TSAFE [9], both DR and flight-plan trajectories are used, and each of these trajectories also has a vertical uncertainty envelope. The dual trajectories can be considered as a single trajectory with uncertainties. In comparison, our FI trajectory essentially reduces the uncertainties to zero while still allowing the aircraft to dynamically select flying along a straight line or following the available FI route based on its conformance status. As a result, false alerts will be minimized, and some compromise in the alert lead time will be unavoidable.

The FI trajectory may be more suitable for use in short-term conflict detection in the TRACON, where the radar update cycle is only 4.8 s. This is because the start of the FI trajectory may change abruptly from the straight-line prediction in one radar update (when the aircraft is offtrack) to the FI prediction in the next (when the aircraft becomes ontrack). Thus, it is more susceptible to outlying data and requires more filtering in today's radar environment. Of course, this will only improve with the introduction of automatic dependent surveillance-broadcast.

III. Conflict Detection

An operational error usually refers to the failure of an air traffic controller to detect a conflict with sufficient lead time to resolve it before LOS occurs. A key technical means of reducing operational errors in the near term would be to provide timely alerts of impending conflicts to controllers. This paper will not address the graphical user interface to alert controllers but instead focuses on the detection problem.

Conflict detection starts with trajectory predictions, as described in the previous section. With the predicted trajectories, the vertical and

horizontal separations between a pair of aircraft are calculated by stepping along the predicted trajectories, starting from the current positions. An LOS is found when the predicted separations are less than the standard separation criteria within a look-ahead period. No separation buffers are used in this research, since any such buffer is unnecessarily subjective. The standard separation criteria in terminal airspace are dynamic, as they depend on the specific encounter geometry and the types of aircraft involved.

A. Separation Criteria

FAA order 7110.65S [16] documents the required separation between aircraft. In the following subsections, the precise separation criteria used in this research are listed along with the assumptions made.

1. General Separation Minima

Aircraft in terminal airspace are generally required to maintain a separation of at least 3 n mile horizontally or 1000 ft vertically. When a pair of aircraft is in transition from terminal to en route airspace, en route separation minima of 5 n mile and 1000 ft apply. An example as to when this criterion would be applied is when one of the aircraft is above the TRACON ceiling, which is at 17,000 ft for DFW TRACON.

2. Wake Separation Minima

When a trailing aircraft operates horizontally within 2500 ft of the flight path of the leading aircraft over the surface of the Earth, the trailing aircraft is said to be directly behind the leading aircraft. The wake turbulence separation minima in Table 1 are required when an aircraft: 1) operates directly behind and is either at the same altitude as or within 1000 ft below another aircraft and 2) follows another aircraft conducting an instrument landing system (ILS) approach.

Since it is impossible to tell, based on the track data, whether the aircraft are conducting ILS approaches, all approaches are treated as ILS approaches in this research.

In addition, the aircraft must be ensured to be able to maintain the separation minima in Table 2 when the leading aircraft is over the runway threshold.

When certain required conditions are satisfied, a reduced separation of 2.5 n mile is authorized. These required conditions are as follows:

- 1) The leading aircraft's weight class is the same as or less than the trailing aircraft.
- 2) Both aircraft are established on the final approach course within 10 n mile of the runway threshold.
- 3) An average runway occupancy time of 50 s or less was documented.
- 4) Certified tower radar displays were operational and used for quick glance references by controllers. In this research, we assume that conditions 3 and 4 are satisfied whenever conditions 1 and 2 are satisfied. Heavy and B757 (Boeing 757) aircraft are permitted to

participate in this separation reduction only as trailing aircraft. An aircraft is considered to be established on the final approach course (localizer) if it is within a given angular course width, measured from the localizer transmitter, which is typically 1000 ft away from the far end of the runway. The course width of a final approach course is tailored to provide 700 ft full scale at the threshold [20]. A typical runway length of 9000 ft is assumed in this research, which corresponds to a course width of about 4°. In a real system, the localizer dimensions for a given runway are available and can be input to the system.

3. Other Separation Minima

1) When two aircraft are on parallel dependent ILS approaches to runways with a centerline separation of at least 2500 ft but no more than 4300 ft, a minimum of 1.5 n mile is required.

2) In the case of an arrival trailing a departure, a minimum of 2 n mile and 1000 ft must be maintained between the aircraft if the separation will increase to a minimum of 3 n mile within 1 min after the takeoff.

3) Between a visual-flight-rules (VFRs) flight and an instrument-flight-rules flight, the separation minima are only 1.5 n mile and 500 ft.

4. Exceptions

There are exceptions to the preceding minimum separation requirements when diverging courses are involved. Two aircraft are said to be on same, crossing, or opposite courses if the angular difference between their courses is contained in the mathematical intervals $[0, 45^\circ]$, $[45, 135^\circ]$, or $[135, 180^\circ]$, respectively [16]. There is no LOS if two aircraft are: 1) on same or crossing courses, with their courses diverging by more than 15° , and one aircraft has crossed the projected course of the other; 2) on opposite courses, and they have passed each other; and 3) successively departing, separated by more than 1 n mile.

For successive departing aircraft, the standard criterion requires the courses to diverge by 15° or more. However, many successive departures appear not to follow this divergence requirement, and further investigation is needed to clarify this. Thus, the diverging requirement is relaxed in this paper.

Another exception case is when both aircraft are established on their independent final approach courses. In this case, there is no separation requirement. It is generally impossible to tell whether the runways are dependent or independent based on current track data. However, when their centerlines are separated by more than 4300 ft, they are used more often as independent runways. Thus, unless usage of dependent runways is stated explicitly, as in the operational error report, we assume that the runways are independent when their centerlines are separated by more than 4300 ft. In a real system, this can be input information. When the centerlines are separated by a distance within 2500 and 4300 ft, dependent runways are expected and the 1.5 n mile criterion, as described previously, is used.

Table 1 Wake separation (n mile) for different weight classes of aircraft in terminal airspace

| Leading aircraft | Trailing aircraft | | | |
|------------------|-------------------|------|-------|-------|
| | Heavy | B757 | Large | Small |
| Heavy | 4 | 5 | 5 | 5 |
| B757 | 4 | 4 | 4 | 5 |

Table 2 Wake separation (n mile) for different weight classes at runway threshold

| Leading aircraft | Trailing aircraft | |
|------------------|-------------------|-------|
| | Heavy | Small |
| Heavy | 4 | 6 |
| B757 | — | 5 |

B. Flight-Intent Conflict Prediction Algorithm

In this section, a conflict prediction algorithm is described, which is based on the single FI trajectory discussed in Sec. II.B, as contrast to the dual-trajectory algorithm of en route TSAFE [9].

Given a set of aircraft and their updated states, the FI conflict prediction algorithm first predicts the FI trajectories for each aircraft. Each trajectory is predicted two or more minutes into the future, except when the last segment is a (DR) straight-line segment due to lack of FI information; in which case, the last straight-line segment is kept for only 1.5 min. This is the case, for example, when an aircraft is at a position before the downwind-to-base turn of the NIR, and the prediction extends beyond the base leg. Next, for each pair of aircraft, the algorithm steps through a look-ahead period of 2 min. It determines the separation minima dynamically based on the criteria described in Sec. III.A. When the minima are violated, an LOS is predicted unless it is filtered by the alert filtering methods described next.

Similar to en route TSAFE and Conflict Alert, some heuristic alert filtering methods are used to reduce false alerts. A three-out-of-three rule is applied if the predicted time to LOS is larger than 60 s. That is, an LOS must be predicted for three consecutive radar updates. Similarly, a two-out-of-two rule is applied if the predicted time to LOS is between 30 and 60 s. A one-out-of-one rule (no repeat required) is applied if the predicted time to LOS is less than 30 s or if there exists an LOS prediction (not filtered by this rule) within the previous 25 s. The numbers used here are to suppress nuisance alerts due to outlying track positions, groundspeeds, or vertical rates. When the prediction time is below 30 s, it appears that the risk of delaying a critical alert due to filtering outweighs the benefit. The values should be made adjustable and further tuned in a real system.

Since the FI trajectories level off at assigned or clearance altitudes, an altitude-rounding technique is necessary, as many aircraft do not always level exactly at those altitudes. The standard altitude-rounding rule that is used in the host computer at each ARTCC is adopted here. The rule is that any aircraft flying nominally level within 200 ft of its cleared altitude is considered to be exactly at its cleared altitude for the purposes of separation requirements. Also, for the first or second radar updates, the course is usually not accurate, so those data points are excluded from conflict detection.

While the future states of a pair of aircraft generally determine whether an LOS shall be predicted, the situation is more complicated when wake turbulence is involved, as the track history is required to determine if the trailing aircraft is operating directly behind (within 2500 ft of the flight path of) the leading aircraft. Thus, a 3-min track history of each aircraft is kept. To check if wake separation applies to a pair of in-trail aircraft, the cross-track position of the trailing aircraft with respect to the track history of the leading aircraft must first be located. Then, if the altitude of the trailing aircraft is within 1000 ft below that of the leading aircraft at the perpendicular cross-track position, wake separation applies.

C. Other Conflict Prediction Algorithms

Two other, DR and dual-trajectory, conflict prediction algorithms have been designed to compare their performances with that of the FI algorithm. The DR algorithm attempts to model the algorithm of Conflict Alert, while the dual-trajectory algorithm models the algorithm of en route TSAFE. The alert filtering methods and altitude-rounding technique for the FI algorithm apply to both the DR and dual-trajectory conflict detection algorithms.

The DR algorithm uses DR trajectories obtained from straight-line tracks along the aircraft courses together with their current ground velocities and accelerations. The altitude profiles of the DR trajectories are obtained in the same way as described in Sec. II.B.3 for the FI trajectories. Aircraft positions are predicted with a look-ahead period of 1.5 min. This reduced look-ahead period is chosen to reduce false alerts. When an aircraft is on its final approach course, determination of the separation criteria, as described in Sec. III.A, requires knowledge of the NIR. Therefore, the NIR is assumed to be known to the DR algorithm for this purpose. Otherwise, the DR algorithm would yield significantly more false alerts.

The dual-trajectory algorithm uses both DR and FI trajectories with 1.5- and 2-min look-ahead periods, respectively. The algorithm imposes vertical climb or descent uncertainty envelopes on both the DR and FI trajectories by using two vertical rates in the constant-rate phase of each altitude profile. These two rates are simply obtained by variation of the vertical rate in the constant-rate phase, as determined by the method in Sec. II.B.3, by $\pm 10\%$. As in the en route TSAFE algorithm, no additional horizontal uncertainty is introduced, other than the fact that both DR and FI trajectories are used to probe for conflicts. Thus, the algorithm checks all four combinations of trajectory types (DR/DR, DR/FI, FI/DR, and FI/FI) for each aircraft pair. If one or more of the combinations are insufficiently separated within the look-ahead periods, a conflict is predicted.

IV. Alert Lead Times

A prototype terminal TSAFE system, built upon the test bed system in [12], has been developed that sets up a framework to

incorporate different conflict detection and resolution algorithms while real-world or simulated aircraft traffic data are replayed. The input to the system is an archived data file containing radar tracking data, mode C barometric altitude data, flight-plan route data, and altitude amendments. These input data are used to generate trajectories that are passed through the conflict detection algorithms to detect potential conflicts. Aircraft trajectories and conflict information are then recorded.

The FI conflict detection algorithm was evaluated along with the DR and dual algorithms with the prototype terminal TSAFE system through comparison of their performance in alerting the controller of potential conflicts. As in en route TSAFE [9], two metrics are used to measure the performance of the algorithms. Alert lead times are discussed in this section, and false-alert rates are discussed in the next section. Alert lead time for predicting an LOS is defined as the difference between the actual LOS time and the time of the first prediction. Thus, the larger the alert lead time, the larger the predictive power of the system.

A. Variety of Operational Errors

Alert lead times are studied here based on a replay of track data of 70 operational error cases from DFW TRACON during the period between January 2007 and April 2009. For each operational error case, a set of conflict plots for each detection algorithm was generated and examined along with the corresponding operational error report from the FAA. The operational errors covered a wide variety of situations, as can be seen in Table 3. At least one aircraft was on final approach in 44 of the 70 cases. Fifteen cases involved aircraft coming from or going to different airports. Fifty-nine cases involved at least one arrival flight, and 17 cases involved at least one departure flight. Also, there were 15 cases that involved violations of wake separation, and 13 cases resulted in the execution of a missed approach. Note that these were losses of separation rather than near misses. At least two cases triggered a TCAS resolution advisory.

B. Sample Operational Error

Figures 8–10 show various plots for one of the 70 operational error cases. Figure 8 shows several minutes of ground-track data for two aircraft (AC1 and AC2) leading up to the LOS. AC1, represented by the solid line, was an MD82 on a downwind leg. AC2, represented by the dashed line, was an MD82 on a base leg. The circles are 3 n mile in diameter at the point of the first LOS. The asterisks are minute markers going back to 3 min before the first LOS. The squares and the gray lines of similar types connecting the squares represent the NIR for each aircraft. Both aircraft are on extended base legs. The sharp turn to the right of AC2 results from a controller intervention.

Figure 9 shows several minutes of the altitude profiles leading up to the LOS. The zero reference time is at the first LOS, which corresponds to the circles on the ground-track plot. The altitudes are measured relative to MSL. AC1 was descending to 7000 ft while AC2 was not descending as fast as the controller anticipated. The controller anticipated AC2 to reach 5000 ft before AC1 and AC2 lost horizontal separation. Since AC2 did not descend fast enough, an LOS resulted. The controller did not respond until a few seconds before the first LOS. The descent of AC1 and the climb of AC2 were a result of the controller intervention.

Figure 10 shows a plot of the horizontal and vertical separations as the two flights lose separation. The lower left quadrant represents the

Table 3 Characteristics of 70 operational errors

| No. of cases | Characteristics |
|--------------|---------------------------------------|
| 44 | One or both making final approaches |
| 15 | To or from different airports |
| 4 | Same airport arrival versus departure |
| 59 | One or both arrivals |
| 17 | One or both departures |
| 15 | Wake turbulence |
| 2 | TCAS resolution advisory executed |
| 13 | Missed approach resulted |

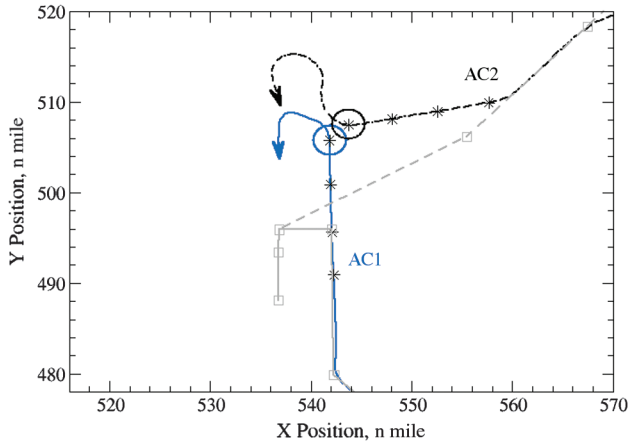


Fig. 8 Ground tracks for a sample operational error.

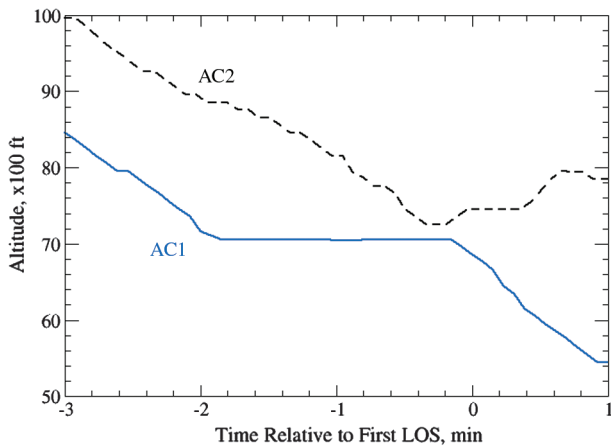


Fig. 9 Altitude profiles for a sample operational error.

region of insufficient separation. The discrete points represent the discrete radar samples at intervals of 4.8 s. The arrow indicates the evolving direction of the separation with time. The asterisk corresponds to the first LOS.

Figure 11 shows an example of the results of conflict detection when the dual-trajectory algorithm is used. The time origin is the first-LOS reference time. A detection of LOS at a radar update is marked with an \times . The alert types represent predictions using various combinations of FI and DR trajectories. Type 0 corresponds to the detection of the actual losses of separation. Type 1 (FI/FI) corresponds to the detection when FI trajectories are used for both aircraft. Types 2 (FI/DR) and 3 (DR/FI) correspond to the detections

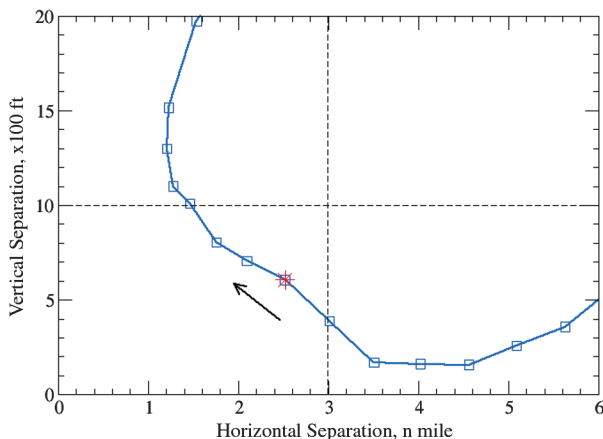


Fig. 10 Two-dimensional separation for a sample operational error.

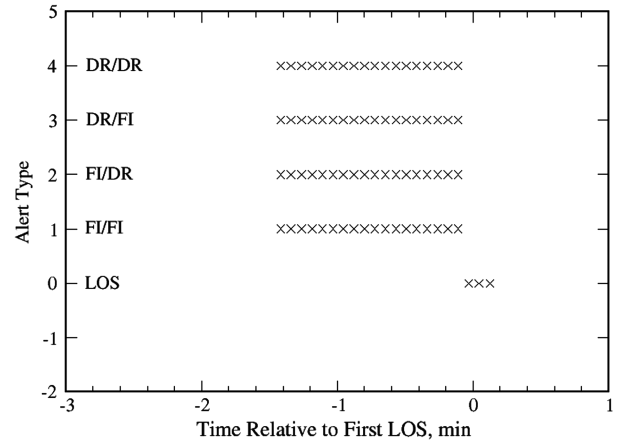


Fig. 11 Conflict detection results for a sample operational error.

when DR trajectory is used for one aircraft and FI trajectory is used for the other aircraft. Type 4 (DR/DR) corresponds to the detection when DR trajectories are used for both aircraft. Thus, there are only alert types of 0 and 1 in the case of the FI conflict detection algorithm where only one type of trajectory is used. Similarly, there are only alert types of 0 and 4 in the case of the DR conflict detection algorithm. In the case of dual-trajectory algorithm, the alert lead time is the time between the first LOS prediction of any type and the first actual LOS detection. In the example of Fig. 11, the alert lead time is approximately 95 s, and the first predictions of LOS for the four non-0 alert types happen to be at the same time.

C. Alert Cumulative Distribution Function

The alert lead time for each of the 70 operational error cases was determined for each of the DR, FI, and dual conflict prediction algorithms. The resulting alert cumulative distribution function (CDF) is shown in Fig. 12. The alert CDF provides the cumulative probability of an alert as a function of time relative to the first LOS. The alert lead time is simply the negative of the time relative to the first LOS. Thus, for the FI algorithm, 67% of the losses of separation were predicted more than 30 s in advance. Note that all three algorithms predicted 100% of the losses of separation by the time of first LOS. This corresponds to zero missed alerts if alerts of negative alert lead time are defined as missed alerts. This result is expected from the algorithm design. The average alert lead times for the DR, FI, and dual-trajectory algorithms are, respectively, 38, 38, and 44 s before first LOS. These alert lead times should be compared with the fact that, among 66 out of the 70 cases, controllers either did not take any action or they acted after an LOS had already occurred. The fact that the controller had no time to respond in more than 90% of the

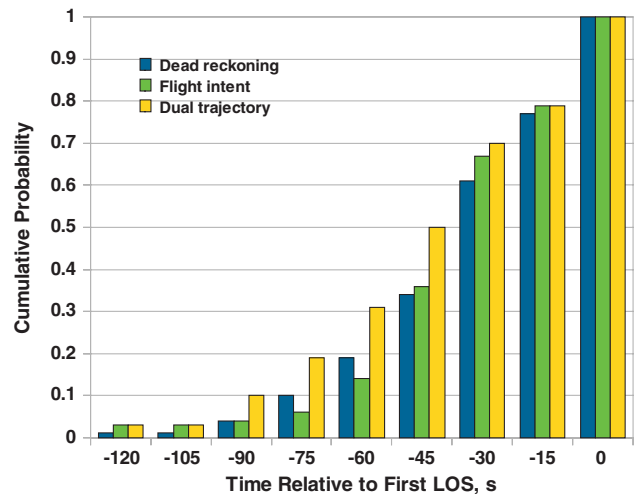


Fig. 12 CDF of alert time.

cases shows once again that the current system, the actual operating Conflict Alert, requires enhancement. The alert CDF, as well as the average alert lead times, shows that there is no significant improvement of the FI algorithm over the DR algorithm in terms of alert lead time. However, there is a higher probability of detecting an LOS sooner for the dual algorithm. This is because the dual-trajectory algorithm allows for larger uncertainties in both the vertical and horizontal dimensions, as discussed in Sec. II.C. In other words, when you use two trajectory bands instead of a single deterministic trajectory, you are expected to see the edges of the trajectory bands fall within the separation standard sooner. However, this conservative dual-trajectory approach yields a much larger false-alert rate, as shown in Sec. III.C later.

D. Operational Errors with Small Alert Lead Times

For many operational errors, the alert lead times were small or even zero. In 15 of the 70 cases, all of the three algorithms predicted an LOS less than 15 s before the first actual LOS. Examination of these late-detection cases revealed the characteristics of the encounters that prevented the algorithms from detecting the LOS sooner. Among 8 of the 15 cases, the aircraft made an abrupt descent or climb maneuver due to a controller error that was not expected by the algorithms and was too quick for them to respond. Figure 13 shows the ground tracks for an example of such late-detection encounters. Figure 14 shows the altitude profiles for the same encounter with the altitudes again measured above MSL. Aircraft AC1 was a departure that had leveled off at 4000 ft. Aircraft AC2 was an arrival that had leveled off at a cleared altitude of 5000 ft. Thus, while the two aircraft converged toward each other horizontally, they maintained the required standard separation of 1000 ft vertically. Following instructions from the controller, the pilot of AC2 started to descend it from 5000 ft

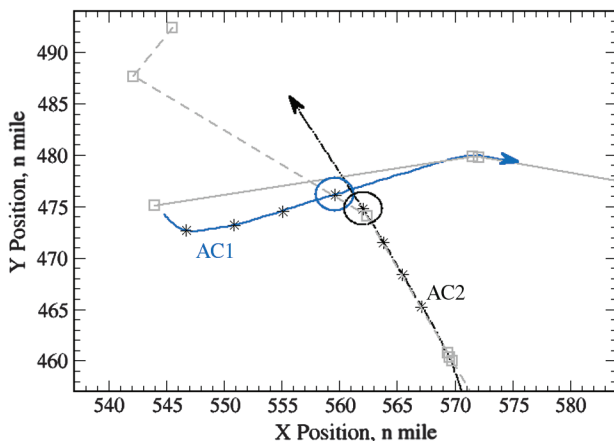


Fig. 13 Ground tracks for a sample late-detection operational error.

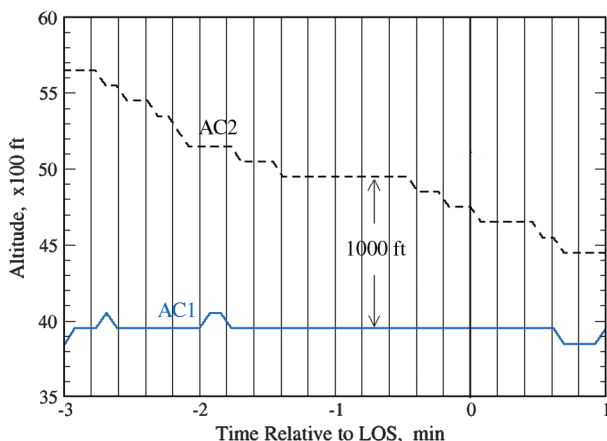


Fig. 14 Altitude profiles for a sample late-detection operational error.

while it was still converging with AC1 with their horizontal separation close to 3 n mile. An alert was generated by the FI algorithm about 14 s before the first LOS. Note that if a terminal TSAFE system was available that allowed the controller to enter the descent command into the system before informing the pilot to descend via voice, an alert could have prevented the controller from descending AC2 until it had passed AC1, and the LOS would have been avoided. This illustrates that it is not possible to provide adequate look-ahead time in all cases without additional intent information.

The other seven cases with alert lead times less than 15 s are classified as follows. There were two cases in which an LOS was detected soon after the aircraft appeared in the radar system. There were four cases that involved blunder behavior that ignores the FI route, such as abnormal sharp turns while the aircraft was on its base leg of the NIR or flying away from the RNAV departure route. Finally, there was one case that involved an unexpected level off. Thus, the alert lead times for most of the late detections may be improved with the FI algorithm if notice of a maneuver is provided as soon as possible. Again, this might be achieved through an interface for controllers to enter an intended descent or climb, a level off, or a turn.

V. False Alerts

The conflict detection algorithms were also evaluated with the prototype terminal TSAFE system in terms of false-alert rates. False alerts distract controllers and are potentially dangerous, since controllers must verify whether actual problems exist, diverting their attention from whatever genuine conflicts might be developing elsewhere in the airspace. In addition, when false alerts occur too often, they desensitize controllers to true alerts. The measures taken for reducing false alerts often decrease the alert lead time.

Three sets of 30-min track data from DFW TRACON have been analyzed to determine the false-alert rates of the algorithms. Each of the three sets contains one documented operational error. When real-world TRACON data are analyzed, the classification of alerts is not straightforward.

A. Classification of Alerts

Aircraft pairs for which both flights were military or VFR were excluded in the analysis for simplicity, since they may require different separation criteria. Also excluded were aircraft pairs for which either flight was a popup with unknown departure fix, destination fix, or both. Popup flights, examples of which include traffic helicopters and survey flights, require special treatment, since the separation rules may be different.

As in [9], although an aircraft pair can have an alert at each radar track update, successive alerts associated with the same aircraft pair will be counted as one alert. Thus, regardless of how many discrete alerts are actually generated for a pair of aircraft, they count as one alert.

After discarding the aircraft pairs mentioned previously, the remaining pairs for which alerts were generated can be classified into the usual true and false categories. In the absence of controller action, a true alert is followed by an actual LOS, while a false alert is not. However, when real-world data are used to analyze alerts, as is the case here, this becomes obscured, since a controller or a pilot may intervene before an LOS occurs. To properly classify alerts into the usual true and false-alert categories, we first classify the alerts objectively into LOS and non-LOS alerts. An LOS alert is one that is followed by an actual LOS, and a non-LOS alert is not. The non-LOS alerts are then classified subjectively as either valid or invalid alerts, as described later in this section. The invalid non-LOS alerts are further divided into level-off-related and non-level-off-related alerts. As seen later, the number of level-off-related invalid alerts are large and may be disturbing to the controller; thus, they are singled out. With this classification, true alerts then consist of LOS and valid non-LOS alerts, while false alerts consist of invalid non-LOS alerts, which include both the level-off-related and non-level-off-related alerts. Figure 15 summarizes the alert classification scheme.

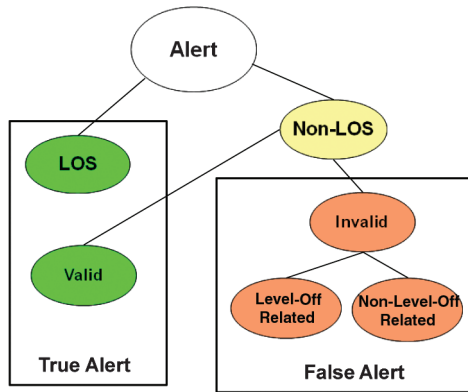


Fig. 15 Alert classification.

The classification of alerts based on real-world data is difficult due to the nature of terminal operations (vectoring for separation). While aircraft should not be close together in an en route operation, they are purposely placed near the required separation, more so near their final approaches. Thus, the distinction between valid and invalid alerts becomes difficult, since alerts beneficial to the controller can become nuisances when they occur too often. An example is a non-LOS alert generated before a level-off when an LOS is predicted because the trajectory used for the prediction does not stop at the cleared altitude. While in many cases the level-off might be anticipated by the controller, this could also be an unexpected maneuver to avoid a potential conflict. The alert may always be beneficial to the controller, whichever scenario it is. However, since the unexpected scenario is not frequent and those level-off-related alerts occur often, as is seen in the next section, they are put in the invalid category. Note that the classification has no effect on a real TSAFE system in the sense that, if the cleared altitude is a part of the available intent (e.g., when it is entered through an optional interface), the alert will not be present. Otherwise, it would be there to help the controller. More details on the non-LOS alerts are described next.

1. Valid Non-Loss-of-Separation Alerts

Valid non-LOS alerts are those that are not subsequently followed by actual losses of separation because controllers or pilots intervene with maneuvers. The maneuvers can be vertical maneuvers involving a climb or descent with significant change in the vertical rate, horizontal maneuvers involving a nonprocedural turn, or speed maneuvers involving a sharp change of speed. The nonprocedural turns are those that do not correspond to the standard operational procedures. Standard turns include the downwind-to-base, the base-to-final, or the RNAV departure turns.

An example of a valid non-LOS alert is shown by the altitude profiles in Fig. 16, where the altitudes of two departure aircraft AC1 and AC2 are plotted. The solid and dashed lines represent the actual altitude profiles of AC1 and AC2, respectively. The thick lines of similar types are the predicted altitudes of the two aircraft, and the small circles indicate the first predicted LOS. The arrow indicates that AC1 was assigned a cleared altitude at FL210 (flight level 21,000 pressure altitude) by a controller. The vertical thin lines indicate the times at which the conflicts were predicted. During these predictions, AC1 was leveled at 10,000 ft, AC2 was climbing, and horizontally, they were approaching 3 n mile separation (tracks are not shown). Their headings were at an angle of about 33°, and they followed their flight-plan routes closely. The time of the first prediction was about 1.6 min away from the horizontal closest point of approach (CPA), and the time to the predicted LOS was about 1.5 min, as indicated in Fig. 16. While the two aircraft got within 3 n mile horizontally, they maintained more than 1000 ft separation vertically. An actual LOS was avoided due to the change in climb rate from about 600 to 2700 fpm, as AC1 was issued the clearance to climb to FL210 after the prediction of the potential LOS. This is deemed a valid alert, since the controller intervened after the prediction of LOS.

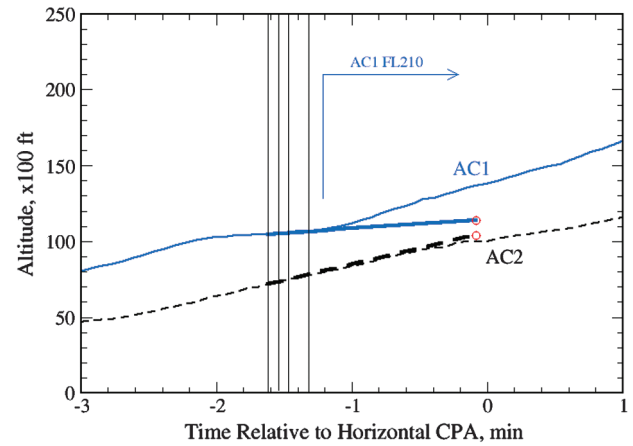


Fig. 16 Altitude profiles for a pair of aircraft with a valid non-LOS alert.

2. Level-Off-Related Alerts

Invalid level-off-related non-LOS alerts are those that are not subsequently followed by actual losses of separation, because the trajectories used to predict the conflicts are inaccurate for lack of FI data about the cleared altitudes. Three types of alerts in this category are possible: 1) alerts generated because the predicted trajectories do not level off at the cleared altitudes; 2) alerts generated while one of the aircraft is just leveling off, but its vertical rate is not zero yet as a result of the lagging due to data smoothing; and 3) alerts generated for aircraft that are supposedly in level flight, but outlying altitude points cannot be rounded to the cleared altitudes because altitude rounding cannot be applied without knowing the cleared altitudes as parts of the FI data.

As will be seen in Sec. V.B later, if these alerts are not properly isolated and avoided, their quantity can be large enough to become overwhelming to controllers.

Many altitude clearances in terminal airspace are anticipated from the approach procedures or standard controller techniques. For example, it is typical that an aircraft needs to level off at 4000 or 5000 ft before turning onto the final approach course. Thus, altitude clearances can be available to TSAFE ahead of time. However, this is not the case today, since altitude clearances are only communicated via voice in the TRACON. In this research, IACs, as discussed in Sec. II.B.3, are used to study the importance of including such FI information. In the next generation air transportation system, where altitude clearances will likely be explicitly entered by the controller, Terminal TSAFE may avoid many invalid level-off-related alerts. In the near term, a controller interface could be added to enter altitude clearances optionally when workload permits.

An example of invalid level-off-related non-LOS alerts is shown in Figs. 17, where the altitudes above MSL of aircraft AC1 and AC2 are plotted against the time relative to the horizontal closest point of approach. As in Fig. 16, the solid and dashed lines are for AC1 and AC2, respectively, and the thick lines of similar types are the predicted altitude profiles. The vertical thin lines indicate consecutive predictions of potential conflicts. AC1 was level at 11,000 ft while AC2 was climbing and intended to level at a cleared altitude of 10,000 ft (not entered into the system). Horizontally, both aircraft followed their flight-plan route closely, with their tracks being about to cross each other. Thus, a horizontal separation less than 3 n mile was unavoidable. However, for lack of the FI of the altitude clearance at 10,000 ft, AC2 was predicted to climb through that altitude, yielding a predicted conflict, as indicated by the small circles in Fig. 17.

3. Non-Level-Off-Related Alerts

Invalid non-level-off-related non-LOS alerts are technically invalid alerts that are not level-off related. They are not subsequently followed by actual losses of separation because the prediction

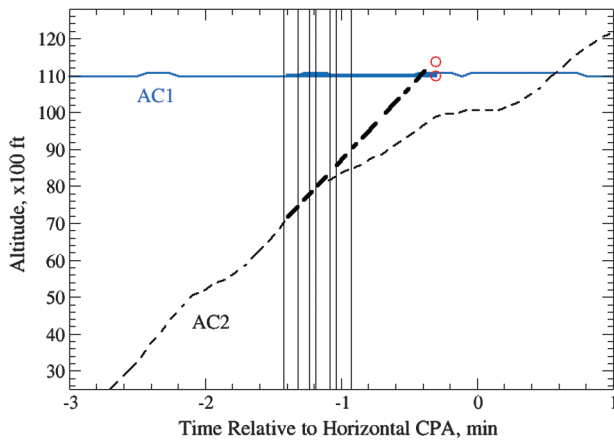


Fig. 17 Altitude profiles for a pair of aircraft with an invalid level-off-related alert.

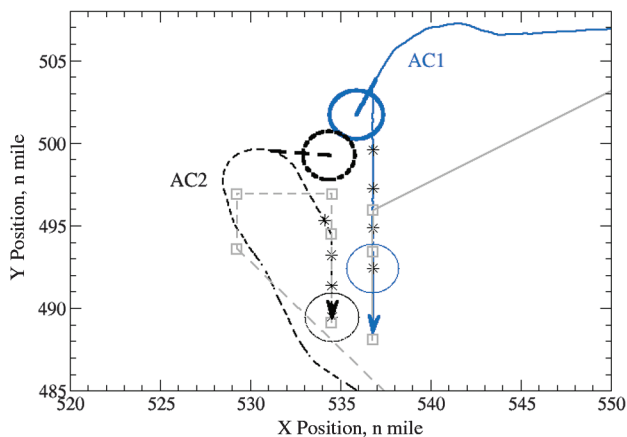


Fig. 18 Ground tracks for a pair of aircraft with an invalid non-level-off-related alert.

trajectories fail to model the standard operation procedures or there are still unfiltered outlying track data.

An example of an invalid non-level-off-related alert, when the DR conflict detection algorithm is used, is shown in Fig. 18, where the tracks of aircraft AC1 and AC2 are plotted. The solid and dashed lines correspond to the actual tracks of aircraft AC1 and AC2. The gray lines of similar types are the FI (nominal interior) routes. The dark solid and dashed lines are predicted trajectories using the DR algorithm. The dark circles of 3 n mile in diameter indicate the first prediction of a potential LOS, while the thin circles indicate the actual CPA. Because the aircraft followed the NIRs instead of the DR

trajectories, the predicted LOS never materialized. Note that alerts generated by the DR and dual-trajectory algorithms, designed for comparison with the FI algorithm, were classified by the same scheme.

B. False Alerts

Three 30-min data sets of recent arrival and departure operations at DFW TRACON are used for false-alert analysis. These data sets are summarized in Table 4, with each set containing one documented operational error. The average aircraft count in the data set is the average number of aircraft in the TRACON at a given time, which measures how busy the TRACON was. The number of LOS alerts for each data set generated based on the separation criteria described in Sec. III.A is also presented. This number is the same for all of the algorithms, in agreement with the earlier result that there are no missed alerts for each algorithm. It is also interesting to note that the higher the average traffic density in the TRACON, the higher the number of LOS alerts.

Excluding the alerts corresponding to the documented operational errors, a total of 21 LOS alerts for the three sets together were found. Table 5 shows the characteristics of these LOS alerts that were not reported as operational errors. Most of them involved small violations of the separation standards when one or both aircraft were turning on the final approach. Inspection of the weather conditions and radar tracks suggests that the associated aircraft were likely conducting visual approaches and, thus, these LOS alerts were likely not actual operational errors.

Table 6 shows the number of non-LOS alerts per hour of different types generated from the FI, DR, and dual-trajectory detection algorithms, with or without the use of IACs. The types of invalid alerts are LR for level-off related and NLR for non-level-off related. The results can be summarized as follows:

- 1) Apart from the FI algorithm with IAC, the number of valid alerts is small compared with the number of false (invalid) alerts.
- 2) Use of the IACs removes the level-off-related false alerts.
- 3) The number of false (invalid) alerts for the FI algorithm is significantly less.

The difference in false-alert rates for different algorithms can also be seen in the chart shown in Fig. 19. The effect of using IACs is also shown. Compared with the dual-trajectory algorithm, the false-alert rates for the DR and FI algorithms reduce by 40 and 61%, respectively, without the use of the IAC in the algorithms. The corresponding reductions become 34 and 93%, respectively, with the use of the IAC in the algorithms.

The total number of false alerts for the FI algorithm with IACs for the three data sets is three. One of them resulted from some outlying data points that were not filtered out and involved a VFR flight. The other two appeared to result from inadequate modeling of the standard operational procedures.

Table 4 Data sets for false-alert analysis

| Data | Date | Time, hrs | Avg. aircraft count | No. of LOS |
|---------|---------------|-----------|---------------------|------------|
| Set I | 5 June 2008 | 1507–1537 | 40 | 11 |
| Set II | 18 March 2009 | 2048–2118 | 51 | 12 |
| Set III | 12 April 2009 | 1431–1501 | 26 | 1 |

Table 6 Number of non-LOS alerts per hour of different types for different algorithms

| | FI | | | DR | | | Dual | | |
|----------|-------|-----|---------|-------|-----|---------|-------|-----|---------|
| | Valid | | Invalid | Valid | | Invalid | Valid | | Invalid |
| | LR | NLR | | LR | NLR | | LR | NLR | |
| With IAC | 7.3 | 0 | 2.0 | 5.3 | 0 | 19 | 8.7 | 0 | 29 |
| No IAC | 6.0 | 18 | 4.7 | 4.0 | 19 | 16 | 10 | 25 | 33 |

Table 5 Characteristics of LOS alerts not reported as operational errors

| No. of cases | Characteristics |
|--------------|---|
| 13 | LOS occurred when one or both of the aircraft on parallel final approaches were not established on the localizer. |
| 1 | LOS occurred because one of the aircraft on parallel final approaches stepped to a close-by departure runway (which is actually legal). |
| 3 | LOS occurred due to violation of wake turbulence separation on the same runway. |
| 4 | Other violations of the separation standards between two arrival flights. |

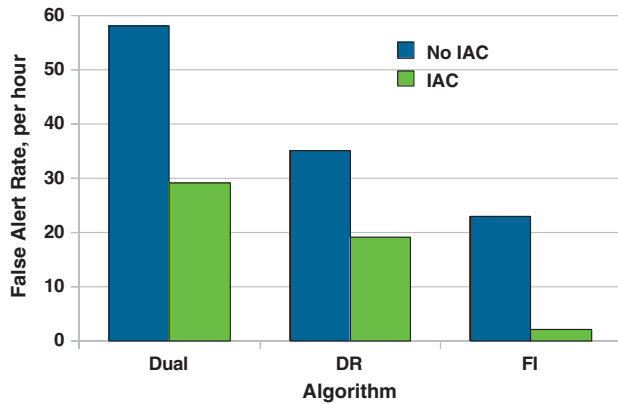


Fig. 19 False-alert rates for different detection algorithms.

The significant reduction of false alerts from the dual-trajectory to the FI algorithm and as a result of including IAC indicates that the use of NIRs, RNAV departure routes, and IACs removes a majority of the false alerts. The DR algorithm generates considerably more false alerts than the FI algorithm because it does not take into account the standard operational procedures. The dual algorithm generates significantly more false alerts as compared with the DR algorithm, because it includes false alerts generated by both DR and FI trajectory algorithms. The altitude envelopes used in the dual algorithm also contribute to the higher false-alert rate. The level-off-related false alerts are completely removed by introducing the IACs. The removal of the false alerts reduces the false-alert rate to a manageable level. These results show clearly the importance of including some additional intent information for short-term conflict prediction in the TRACON.

VI. Conclusions

A new FI tactical conflict detection algorithm for terminal airspace has been studied. The FI algorithm uses a single analytic trajectory that is based on available FI and current state information of the aircraft, with alerts determined by the standard separation criteria of the FAA in terminal airspace. The FI information includes the flight plan (which includes the area-navigation departure route), the NIR, the IACs, and some groundspeed bounds. The FI algorithm is compared with a dual-trajectory algorithm that models the algorithm used in en route TSAFE and a DR algorithm that models Conflict Alert. The comparison is done through analysis of the false-alert rates and alert lead times from a replay of track data of three sets of departure and arrival operations and 70 operational error cases from DFW TRACON during the period between January 2007 and April 2009. The FI algorithm shows significantly reduced false alerts without much degradation of the alert lead time. The false-alert rate for the FI algorithm was reduced to two alerts per hour, and the alert lead time average over 70 actual TRACON operational errors was 38 s. Smoother track data and better FI data available in the future would only improve the results.

While the false-alert rate may be at a manageable level, more extensive tests with broader data from other facilities, as well as human-in-the-loop simulation experiments, are still needed. It is also good to have a direct comparison between the results of terminal TSAFE and Conflict Alert. Unfortunately such comparison is not straightforward since, among other things, the separation criteria are quite different, and Conflict Alert is often inhibited in areas of frequent false alerts. Work in these areas is in progress. It appears that altitude clearances play a role as important as the additional FI

information for terminal TSAFE. Further research on how to obtain this information efficiently is needed.

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