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Tactical Conflict Detection with Altitude Restrictions in Terminal Airspace

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Automated conflict detection in terminal airspace is a challenging problem, in part because key information regarding flight intent is not available. Unlike en route controllers, terminal controllers currently do not enter altitude clearances when they issue them by voice, so the altitude at which a flight will level off is unavailable to the conflict detection automation. This uncertainty increases the likelihood of false alerts. Requiring terminal controllers to enter all altitude clearances may be met with resistance due to workload concerns. This Paper studies a new method in which a ground-based trajectory predictor predicts altitude leveloffs a priori, based on altitude restrictions on published runway descent profiles and at waypoints on nominal interior routes and area navigation departure procedures. The full benefit of the flight-intent information of all altitude clearances is shown to be achievable when controllers only make entry of altitude clearances not attributable to altitude restrictions, which leads to an insignificant workload increase; an unacceptable level of workload increase may result if all altitude clearances are entered during busy hours. In addition, the integration of altitude restriction improves on alert lead time by 16% on average based on operational error cases.

I. Introduction

TODAY, air traffic controllers are responsible for separating air traffic operating under Instrument Flight Rules (IFRs). One of the primary limitations of airspace capacity is controller workload. A reliable automation tool that assists controllers in their constant estimation of potential losses of separation may help reduce controller workload, providing safer operations.

The inherent complexities of terminal operations pose a number of challenges in the development of automated tools that alert air traffic controllers to potential conflicts. Routine large-angle turns without well-defined flight-intent information before final approaches require proper handling to prevent a proliferation of nuisance alerts, alerts that do not provide useful information beyond what the controllers know and are not necessary to maintain safety [1]. Spacing of aircraft near standard separation thresholds to maximize arrival and departure throughput increases the difficulty of predicting separation conflicts without causing false alerts, alerts on predicted losses of separation that do not materialize, with no indication of any controller or pilot intervention [2]. The difficulty also stems from the dynamic and complex nature of the standard separation criteria, which depend on relative course, aircraft weight classes, distance to the runway, and other factors [3].

The Common Automated Radar Terminal System (CARTS) [4], which has been operational since the 1980s, and the recent Standard Terminal Automation Replacement System (STARS) [5] have a conflict alert (CA) functionality that generates safety alerts when CA determines that two aircraft are in dangerous proximity to one another or are on a course that will put them in dangerous proximity to one another. The Federal Aviation Administration (FAA) analyzed CA performance and classified 80% of CA alerts in terminal airspace as nuisance [1]. The analysis suggested flight-intent information to be incorporated in conflict detection algorithms so the nuisance alerts may be reduced.

A ground-based initial prototype system that incorporates flight-intent information was studied in [2]. The system called Terminal Tactical Separation-Assured Flight Environment (T-TSAFE) took into account available flight-intent information to predict trajectories and employed a single-trajectory algorithm for conflict detection. It intended to alert controllers in the Terminal Radar Approach Control (TRACON) facilities to predicted losses of separation based on the separation standards with a look-ahead time of approximately 2 min. It was shown that the average alert lead time, the time to first loss of separation (LOS), was 38 s, based on T-TSAFE analysis of operational error cases, and the false-alert rate, the percentage of false alerts among the total number of alerts, was approximately 10%, based on an analysis of alerts generated from the playback of real-world traffic data. In human-in-the-loop experiments, controller participants using T-TSAFE provided positive feedback [6,7].

However, the operational concept for this initial prototype system required controllers to make a keyboard entry of every altitude clearance, which is not the current practice in TRACON operations. This operational concept for incorporating level-altitude flight-intent information was simulated in [2] with an inferred altitude clearance (IAC) method, in which level altitudes of flights were first inferred from recorded air traffic data and then inserted back as altitude amendments. While these altitude entries provide other benefits, such as helping TRACON controllers to keep track of the altitude clearances without the need for a flight data strip [7], subject matter experts (SMEs) suggest that the controllers would be reluctant or unable to make that number of entries due to the workload involved. This Paper presents a new method to supplement the T-TSAFE algorithm with altitude-intent information to improve conflict prediction without significantly increasing controller workload. Published altitude restrictions on waypoints and in runway altitude descent profiles are incorporated so that the controllers would only need to make entry for altitude clearances that are not attributable to altitude restrictions.

The rest of this Paper is organized as follows. Section II summarizes the heuristic rules of the trajectory model and describes altitude-restriction method. Section III explains the conflict prediction and declaration logic. Section IV describes the experiments. Section V presents the results and discussion. Section VI summarizes and concludes the work.

II. Trajectory Model

T-TSAFE trajectory prediction relies on aircraft current state and flight-intent information, as known to the air traffic control system, without reliance on numerical integration of the equations of motion. The result is the determination of an analytic kinematic trajectory, consisting of a horizontal track, a speed profile, and an altitude profile. The following subsections summarize the trajectory prediction algorithm from [2] and describe how altitude restrictions are applied.

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A. Flight-Intent Information

Flight-intent information currently used by T-TSAFE includes nominal interior routes (NIRs), area navigation (RNAV) departure procedures (DPs), flight-plan information, and altitude clearances [2]. T-TSAFE is designed to detect conflicts involving aircraft in all phases of flight. The filed flight plans generally do not contain departure procedures, so the RNAV DPs are needed to project fine-detailed departure trajectories. Similarly, the NIRs are needed to project fine-detailed arrival trajectories. Altitude clearances are needed for accurate prediction of trajectory changes.

Past air traffic automation efforts have attempted to predict aircraft movement in the TRACON by modeling typical flight paths that aircraft follow through terminal airspace. These are called nominal interior routes from the arrival meter fixes to the runways [8,9]. They are parts of the adaptation in the Time-Based Flow Management system [8]. Aircraft typically follow the NIR as a "backbone" with minor and transient tactical maneuvering (vectoring) expected. The NIR for a flight is typically unique for given airport configuration and depends on the aircraft engine type, arrival meter fix, runway, and airport. See [2] for more details on NIRs.

Departure flights from most major airports typically follow closely the published RNAV DPs, which T-TSAFE selects dynamically based on the aircraft engine type, departure meter fix, runway, and airport. Overflights are modeled to follow the filed flight-plan route or, lacking a flight-plan route, to progress along a dead-reckoning trajectory. The full filed flight plan for an overflight is not currently available in STARS, but a dead-reckoning trajectory would be accurate enough as there are fewer turns involved. STARS does have the information for selecting NIRs and RNAV DPs. Departure runways were assumed to be given previously [2]; they are now detected automatically. As will be discussed in Sec. V.C, many altitude clearances are attributable to altitude restrictions; the nonattributable ones may be entered into the system by controllers.

The Next Generation Air Transportation System will adopt efficient performance-based navigation (PBN) arrival procedures using RNAV and required navigational performance (RNP) as in the recent Terminal Spacing and Sequencing (TSAS) capability [10]. This will result in more precise flight routes with less vectoring for spacing, and thus better flight-intent information will become available. This would make T-TSAFE trajectory prediction more accurate and reliable.

B. Horizontal Track and Speed Profile

Flight trajectories in the TRACON based on NIRs were constructed in the Final Approach Spacing Tool [9]. More recently, flight trajectories based on efficient PBN arrival procedures using RNAV and RNP were constructed in TSAS [10]. Both were for the purpose of aircraft scheduling with the aircraft expected to fly the routes, and when deviating from them, heuristics were used to model its trajectory to the runway so an estimated time of arrival could be calculated. For conflict prediction on a short time horizon in the TRACON, given the current state of the aircraft, which can be arbitrary relative to its route, one needs to choose the most probable trajectory from many possibilities including dead reckoning with conflict probing rather than scheduling in mind. Thus, different heuristic rules for constructing the flight trajectories may be needed.

The horizontal track of a flight is constructed analytically with segments of straight lines and circular arcs following heuristic rules [2], which depend on whether the aircraft is in conformance (on track) with its intent route, a route defined as the merge of the NIR, RNAV DP, and flight plan. Two basic heuristic rules are as follows:

1) If an aircraft is on track, it captures the next waypoint in its intent route.

2) If it is off track, it starts with a straight line along its current course and then joins its intent route, upon interception, with circular-arc segments; otherwise, it continues along a straight line. Additional special rules apply to aircraft near different segments of the NIR [2].

An aircraft is assumed to fly along the constructed horizontal track with a kinematic speed profile based on ground speed and acceleration. To avoid reaching unrealistic speeds due to the acceleration, upper bounds for departure flights and lower bounds near the final approach and runway threshold fixes are imposed. Speed restrictions on waypoints are not currently imposed as flight-intent information. Once a speed bound is reached, the aircraft is projected to fly at constant speed. The along-track acceleration of the aircraft is assumed to be the larger of its current acceleration or the acceleration as determined from the speed bound (assuming uniform acceleration). The constructed analytic horizontal track allows the along-track distance between any two points on the track to be determined. Thus, the speeds at the beginning and the time duration of each track segment can be calculated. The aircraft along-track position as a function of time is then determined.

C. Altitude Profile

After the horizontal track and the speed profile, the determination of an along-track altitude profile is next to complete the aircraft trajectory. The altitude profile can be modeled as one or more subprofiles pieced together, each piece consisting of zero to two level segments and zero to one climb or descent segment. Thus, a subprofile can be described as a climb or descent from a start altitude to a target altitude and can be modeled in three phases: an initial acceleration phase, a constant-rate phase, and a final deceleration phase [2]. If an aircraft is in the initial acceleration phase, its vertical speed at the constant-rate phase is obtained from a lookup of the nominal climb or descent rate from the Base of Aircraft Data from Eurocontrol [11].

The level altitudes in the vertical profile are expected to come from available flight-intent information. It was assumed in [2] that the controllers would make keyboard entry of all clearance altitudes. However, SMEs suggest such a requirement would encounter considerable resistance from controllers due to additional workload incurred. A new method is proposed here for obtaining the level-altitude flight-intent information with only minor changes to current operations. There are typically well-known altitude restrictions at certain waypoints on a TRACON route (NIR or RNAV DP) or in the descent profile for a particular arrival runway. It is unnecessary to repeatedly enter the same clearance altitude for all aircraft near a particular waypoint when the altitude is attributable to the waypoint altitude restriction.

In most cases, the waypoint restrictions do not depend on the route nor the arrival and departure procedures. Thus, in this Paper, a simple approach in which the waypoint restrictions depend on some particular waypoints only is adopted. Furthermore, only altitude restrictions of "at or above" for arrival flights and "at or below" for departure flights are considered for now. Sometimes, an aircraft may fly a route that does not follow precisely the nominal interior route or the route it flies may not have waypoint restrictions, so the runway descent profiles are also used, as published in the Instrument Approach Procedures (IAPs) [12]. The altitude restrictions are looked up in real time through tables of waypoints and runway descent profiles. Waypoint altitude restrictions often match the level altitudes in the runway descent profile; when a mismatch is found, the higher altitude restriction prevails.

Figure 1 illustrates notionally a descent profile for an arrival runway, as depicted in an IAP chart (i.e., an approach plate). The altitude restrictions include one at or above 2300 ft at the final approach fix, 5.1 n miles from the runway threshold, and others at or above 3000 ft at 7.4 n miles from the runway, at or above 3000 ft at 13.7 n miles from the runway, and at or above 4000 ft at 16.9 n miles from the runway. After a horizontal track is initially determined and before the speed profile is built, the trajectory is split into subtrajectory segments based on the distance to the runway threshold, and the altitude restrictions are imposed on the waypoints of the segments. A controller-assigned clearance altitude will override altitude restrictions on waypoints or runway descent profiles.

The trajectory segments with altitude restrictions on some endpoints together with the speed profile allow specification of the altitude restrictions at specific times. The overall altitude profile as a function of time can then be determined as superposition of

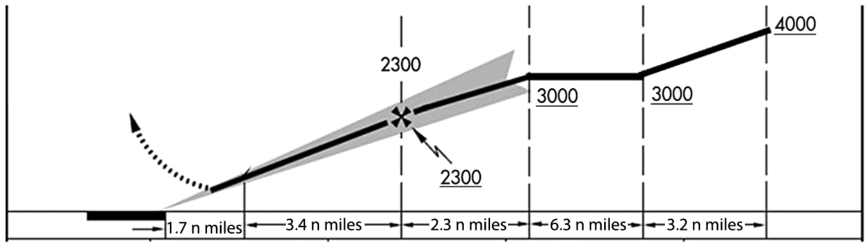

Fig. 1 Illustration of a runway descent profile.

subprofiles with their start and target altitudes as well as durations calculated. Thus, the complete aircraft trajectory as a function of time needed to predict conflicts with other aircraft is determined. With a look-ahead time of 2 min, the constructed trajectory should significantly outperform dead reckoning.

III. Conflict Prediction and Declaration

A conflict is defined as a violation of the separation or safety requirements based on the standard in FAA Order JO 7110.65X [3]. The older version of 7110.65 V [13] was applied for the traffic data in our experiments and is thus the base for the alert thresholds in this Paper as described in [2]. Given aircraft state information at each radar update and trajectory intent for each aircraft, computed trajectories are compared for each aircraft pair to detect instances in which the applicable separation requirements are violated. Potential conflicts are detected by comparing predicted states with the required separation standards, at four-second intervals along the trajectories for the prescribed look-ahead time (2 min). The track history of the preceding aircraft may be needed to determine if the trailing aircraft is operating directly behind the leading aircraft for wake–turbulence conflicts. One principle behind the conflict detection algorithm for terminal airspace here is to minimize false alerts without missing detection of actual conflicts while maintaining average alert lead time at an acceptable level. Here, alert lead time is the time to first violation of alert thresholds.

A single definitive trajectory is used for conflict probing with the trajectory model summarized in Sec. II. Uncertainty is only reflected in the fact that a new trajectory is predicted every update cycle. For example, the position of an aircraft at some future time may be different for different trajectories predicted at different radar updates. This flight-intent-based single-trajectory approach to conflict prediction [2] introduces minimal aircraft state prediction uncertainty and thus minimizes false predictions, at the expense of slightly shorter lead time to a potential conflict, as compared to the dual-trajectory approach [14–16].

In real-world operations, uncertainties from many sources, such as controller vectoring, intent inference error, trajectory modeling error, and radar tracking noise, may result in false alerts. Further reduction of false alerts can be achieved by declaring conflicts only when certain alert conditions are satisfied by the predicted violations of the separation or safety requirements. The conventional rule of m of n cycles for specifying alert conditions has been commonly used and is being used in Conflict Alert. Thus, we refine and enhance the rules used in [2] within the context of the rule of m of n cycles in this Paper. Here, the cycle is the 4.8 s TRACON radar track update cycle, so m of n cycles means that there are m predictions of violation of the alert thresholds out of n radar update cycles.

Table 1 shows the values of m and n chosen following the principle of minimizing false alerts. Different values are chosen for different ranges of the time t to the first predicted violation of the alert thresholds. The 1-of-2 rule is a physical requirement to ensure that no actual conflicts are missed so any detection of the violation of the alert thresholds within 15 s is declared or alerted as a conflict. The time of 15 s is chosen in consideration of an overall response time of $10 \sim 15$ s; a value of 30 s was used in [2]. Here, a 2-of-3 rule is used instead when the time is between 15 and 35 s. The refined 2-of-3 rule helps remove some false alerts as expected from the averaging over three update cycles, which is confirmed from examination of the alerts with real-world data. Between 35 and 60 s, the 3-of-5 rule is used rather than the rule of two consecutive predictions used in [2]. This again helps reduce false alerts at the expense of slightly smaller alert lead time as one may need to wait up to five cycles before alerting. For the same reason, time averaging over more cycles than in [2] is adopted for larger time ranges. While suppression of many false alerts was observed from detailed examination of the flight trajectories involved, a quantitative study was not done, partly because the examination process was not automated. There can be some adjustments in these rules in practice to further reduce nuisance alerts depending on the accuracy of future track data, but the current values should be a good starting point.

Table 1 m of n criteria for conflict declaration

Time t, s	m of n criterion
$t \leq 15$	1 of 2
$15 < t \leq 35$	2 of 3
$35 < t \leq 60$	3 of 5
$60 < t \leq 90$	4 of 6
$t > 90$	5 of 7

To further reduce false or nuisance alerts, we also allow the alert thresholds of nonwake encounters to fall slightly short of the standard separation minima: 1% for horizontal separation and 5% for vertical separation when at least one aircraft is not flying level and 10% when both are flying level. These values are observed to reduce alerts that last only one or two radar cycles. They are also checked against cases of operational errors to ensure the known losses of separation in operational errors are not missed.

In this Paper, we distinguish between a separation alert that results from a potential violation of the required separation minima and a safety alert [3,13] that results from a potential violation of safety alert thresholds. The separation alert involves a pair of IFR flights, and the safety alert involves an IFR flight and either a Visual Flight Rules (VFR) flight or a visual-approach flight or a flight unassociated with a flight plan. A safety alert involving an IFR flight and an unassociated flight is called a Mode C Intruder (MCI) alert. When not specified, a LOS in this work may refer to either a separation or a safety violation.

We use the classification of alerts in [2]. Under this definition, a LOS alert means a conflict declaration that is later confirmed to occur by the algorithm, while a non-LOS alert is not confirmed to occur later. Note that, due to differences in flight-intent information used by each algorithm, a LOS event might be declared when an actual loss of separation did not occur between the aircraft. A false alert is defined as an alert to a potential LOS that is not followed by an actual LOS and for which there is no evidence of any controller or pilot intervention. A valid non-LOS alert is one that is not followed by an actual LOS but in which evidence of controller or pilot intervention exists. The concept of missed alert may be ambiguous. We distinguish between missed prediction and missed detection of an actual LOS. A missed detection of a LOS refers to an instance in which a LOS actually occurred but the system cannot detect it even at the moment of LOS. In our approach, no missed detection is likely because when an actual LOS occurs T-TSAFE will report it, assuming the aircraft states are reported accurately. On the other hand, missed prediction of a LOS implies a failure to predict the LOS before some minimum lead-time threshold, e.g., 10 s, to allow the controller some response time. A nuisance alert is an alert that is not useful to the controller [1] and is thus somewhat subjective. A late (and thus nuisance) separation alert may not be useful to the controller to perform separation tasks, but it may still be useful for avoiding collisions, which is what safety alerts are for.

A rule adopted in T-TSAFE relevant for conflict detection and supported by SMEs is that any aircraft flying nominally level within 100 ft of its clearance altitude is considered exactly level at its clearance altitude. The standard rounding rule for en route in the host computer at each center uses a larger value of 200 ft.

IV. Experiments

The primary objective of this Paper is to use published altitude-intent information to effect better conflict prediction, minimizing the requirement for controllers' manual entry of altitude clearances. Two sets of experiments were conducted to validate this. One set uses mainly operational error data to show that incorporating the altitude restrictions in trajectory modeling can avoid some otherwise missed conflict predictions and may increase the alert lead time. The other set uses real-world full-day air traffic data to show that application of the altitude restrictions, together with entry of altitude clearances nonattributable to altitude restrictions, may work as well as if controllers make entry of every altitude clearance. This is done by comparing T-TSAFE alerts from two methods of making level-altitude flight-intent information available: altitude-restriction (ALR) and inferred-altitude-clearance methods. In the ALR method, T-TSAFE deduces level altitudes attributable to altitude restrictions on the waypoints or in the runway descent profiles, without information about level altitudes non-attributable to altitude restrictions. In the IAC method, T-TSAFE simulates controller entry of all level altitude clearances, so they become available flight-intent information, by inferring the level altitudes from analysis of the air traffic data and putting them back into the data as altitude amendments.

A. Experiment with Operational Error Data

To demonstrate that altitude restrictions may sometimes avoid otherwise missed conflict predictions and increase alert lead time, we designed a fast-time simulation that used real-world air traffic data with operational errors (failures of controllers to detect conflicts with sufficient lead time to resolve them). Average alert lead time is an indication of the effectiveness of the alerting system as it is the average time the controller has for resolving a potential LOS. While large alert lead time is preferable, one needs to strike a balance between the alert lead time and false-alert rate.

The simulation uses a large set of air traffic data of operational errors. Much information about the operation errors is available: a standardized description of the encounters, controller–pilot communications during the conflicts, and a summary of the causes and influential factors. This information helps envision the conflict events when evaluating T-TSAFE conflict predictions. The archived air traffic data were from 70 operational error cases in Dallas/Fort Worth TRACON (D10) during the period between January 2007 and April 2009. These operational errors covered a wide variety of encounters as described in [2], and they are still representative of conflicts occurring today. Because this set of data contains all the reported actual losses of separation over a period of more than two years, with a supported description of the development of events during the time periods, it provides a special variety set from which to measure the alert lead time. Other sets of losses of separation might contain unintended effects of unknown controller or pilot actions.

Actual recorded air traffic data files, with TRACON radar tracking data, Mode C barometric altitude data, and flight-intent information, containing the 70 operational errors were played back in a fast-time mode through T-TSAFE first with and then without altitude restrictions integrated. The look-ahead time was set to 120 s. The output XML files of all conflict pairs were examined; alert lead times relative to the actual losses of separation were computed; and the encounters were plotted and compared with the operational-error description.

B. Experiment with Full-Day Air Traffic Data

To show that altitude restrictions may significantly reduce the need for controller altitude entries while maintaining the benefits of making entry of all altitude clearances, we designed a second experiment to compare T-TSAFE alerts from the ALR and IAC methods of obtaining level-altitude-intent information. Use was made of recorded full-day real-world traffic data of 24 February 2012 from Southern California TRACON (SCT), where CARTS was operated, and full-day data of 26 July 2014 from D10, where STARS was operated. The SCT data resulted from mixed operations that involved a mix of aircraft conducting visual and instrument approaches. The D10 data involved mostly aircraft conducting visual approaches, based on the weather conditions and the observations of aircraft making approaches with short final segments, characteristic of visual-approach procedures.

In the IAC method, before the air traffic data were played back with T-TSAFE, level altitudes of IFR flights were deduced from a pattern-matching heuristic algorithm [17] and inserted back into the data as altitude amendments. The level altitudes must last typically 20 s or more to be identified so false identification is reduced. The effect of altitude entries on controller workload was assessed through the number and rate of occurrence of level altitudes within the TRACON for arrivals and departures of major and nonmajor airports. In the ALR method, inferred altitude clearances inserted in the air traffic data were ignored. Instead, T-TSAFE predicted the level altitudes attributable to altitude restrictions, although it was unable to identify the nonattributable ones.

Alerts generated under the same air traffic conditions for the ALR and IAC methods were compared. Alerts were distinguished in terms of the aircraft pairs involved so that jitters were ignored. Here, a jitter means there are time gaps (radar update cycles) of no conflict declaration between two consecutive declarations. If an alert in one method involves the same aircraft pair as another alert in the other method, the two alerts are said to be common alerts for both methods. Otherwise, the alerts are distinctive alerts. The focus will be on comparing the number of distinctive alerts and the number of false alerts in the distinctive alerts in the two methods. The results can differ between those involving major airports, for which the nominal interior routes and RNAV departure procedures are available as flight-intent information and are closely followed by flights, and nonmajor airports, for which either the NIRs and RNAV DPs are unavailable or they are not followed closely at all. Thus, the comparisons are made separately for major and nonmajor airports. Note that Dallas Love Field Airport (DAL) is included as a major airport because its NIRs and RNAV DPs are available and followed by flights, although not as closely as those of Dallas/Fort Worth International Airport DFW (Dallas/Fort Worth). The distinctive alerts in the ALR method may result from mismatches between the duration of the actual leveloff and that modeled from the altitude restriction. The distinctive alerts in the IAC method may result from the artifact that the end of level altitudes from IAC altitude amendments are not determined until a climb or descent from that level altitude is detected.

Since it is not possible to determine whether an aircraft is on visual approach at run time with the current data sets, all IFR arrivals are assumed to be on Instrument Landing System (ILS) approaches. This allows more alerts to be generated for both the ALR and IAC methods as visual-approach flights often get closer than the separation standards. Safety alerts involving visual-approach flights [18] are thus absent, but there may be MCI alerts and safety alerts involving general VFR flights. Tracks unassociated with flight plans are inserted in the recorded air traffic data. FAA's CARTS or STARS continuous data recording (CDR) data contain CA conflicts, associated and unassociated tracks, but no flight-plan information. Unassociated tracks in the CDR data were extracted and inserted into the NASA-recorded data.

The two full-day data files were played back with T-TSAFE in fast-time mode, once with the IAC method and once with the ALR method. The output eXtensible Markup Language (XML) files for conflict pairs were then analyzed. The look-ahead time was set to 90 s to reduce alerts from noisy radar tracks.

V. Results and Discussion

The results are presented in the following three subsections. Alert lead time measurements from a large number of operational error cases are analyzed in Sec. V.A with examples demonstrating the effects of altitude restrictions. The number of T-TSAFE alerts are analyzed and compared for the inferred-altitude-clearance and altitude-restriction methods of obtaining level-altitude flight-intent information in

Sec. V.B. Specific alerts from the two methods are illustrated. In Sec. V.C, effects of altitude entry on controller workload are studied for the ALR method augmented with the controller keyboard entry of altitude clearances not attributable to altitude restrictions.

A. Alert Lead Time

The alert lead times were measured from the actual first losses of separation for all conflicts in the set of 70 operational error cases. Comparison was made between the alert lead times determined for the ALR method, in which T-TSAFE dynamically extracted level-altitude-intent information from altitude restrictions, and for the baseline method, in which T-TSAFE did not have any level-altitude-intent information. When necessary, parameters of the trajectory model were adjusted to ensure all losses of separation were produced without missed detections.

Analysis of the XML output from fast-time playback of the traffic data files involving the operational-error cases allows us to determine the cumulative distribution function (CDF) $F_T(t) = P(T \leq t)$ of the alert lead time T, which is the cumulative probability of alerting within time t (>0) to the first actual loss of separation. Figure 2 shows a comparison of the alert CDF plots for the ALR and baseline methods. The cumulative probability for alert lead time t measures the percentage of the 71 LOS alerts (one of the operational errors involves three aircraft in two conflicts) having an alert lead time less than t, so $1 - F_T(t)$ gives the probability of having alert lead time greater than t. The zero cumulative probability at $t = 0$ indicates that all 71 losses of separation were detected at or before the LOS without missed detections. We assume that any large jitter with a nonalerting time gap of 30 s or more reinitiates the start time of the alert. There were 14 and 16 large jitters out of the 71 losses of separation for the ALR and baseline methods, respectively. Over a large range of alert lead times, the cumulative probability for the ALR method was consistently less than that for the baseline. Thus, it is more likely to have a larger alert lead time in the ALR method than the baseline. The percentage of alerts with lead time greater than 30 s for the ALR and baseline methods are 63 and 56%, respectively, which are slightly less than the corresponding value of 67% in [2]. This is due to the use of stronger m of n filtering criteria for conflict declaration here.

The average alert lead times over all of the alerts of loss of separation were calculated to be 43 and 37 s, respectively, for the ALR and baseline methods, showing a 16% improvement for the ALR method of incorporating level-altitude flight-intent information. The corresponding standard deviations are 33 and 32 s. A paired t-test indicated that the difference is statistically significant ($t = 2.31$ and $p = 0.012$). The reason for the relatively large standard deviation might be due to inaccuracy in the trajectory prediction. Large errors in trajectory predictions are common [19]. For comparison, similar calculations were also performed on the major-airport non-safety LOS alerts for the two real-world data sets from SCT and D10 TRACONs. The average alert lead times over 247 LOS alerts for the SCT data are 41 and 38 s, with standard deviations of 29 and 27 s and number of large jitters of 30 and 29, respectively, for the ALR and baseline methods. Paired t-test indicated that the difference is also statistically significant ($t = 2.44$ and $p = 0.0078$). The average alert lead times over 476 LOS alerts for the D10 data are 63 and 52 s, with standard deviations of 28 and 26 s and number of large jitters of 34 and 49, respectively, for the ALR and baseline methods. Paired t-test indicated again that the difference is statistically significant ($t = 11.0$ and $p < 0.0001$). Thus similar trend is observed although the operational error data may be more reliable since the LOS pairs in the daily data sets involved a large percentage of flights on visual approaches that were not constrained by the standard separation minima and the trajectories did not follow the NIRs closely. These results show that there is strong evidence that the altitude-restriction method improves on the alert lead time over the baseline.

If we define a miss prediction of LOS as one that has an alert lead time less than 10 s, the ALR method helps reduce miss predictions from a baseline value of 20 to 15%, a 25% reduction as seen in Fig. 2. As noted in [2], the relatively large number of miss predictions results mostly from unpredictable errors that might be avoidable by trial planning of maneuvers.

Study of the operational error reports shows that conflict alert provides a negative alert lead time (to loss of separation) since it either provided no alerts or only alerted after the losses of separation. This result is expected since the safety alert criteria for CA are much smaller than the standard separation minima.

It is expected that altitude restrictions should help increase the alert lead time as they provide better flight-intent information. The result is seen in the CDF plots and the average alert lead time. How the altitude restrictions actually affect the alert lead time can be demonstrated with the following two examples.

Figure 3 shows the ground tracks and altitude profiles for an example encounter in which altitude restrictions help to increase the

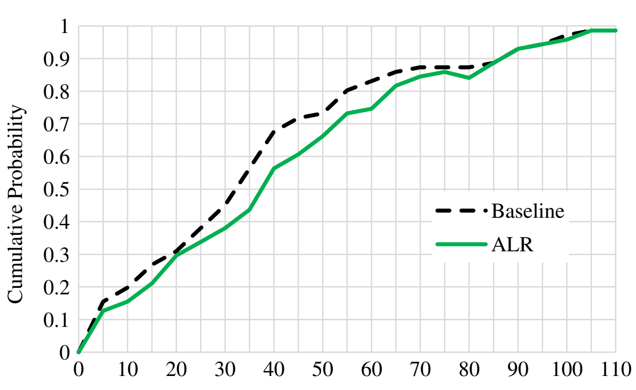

Fig. 2 CDF of alert lead time for the baseline and altitude-restriction methods.

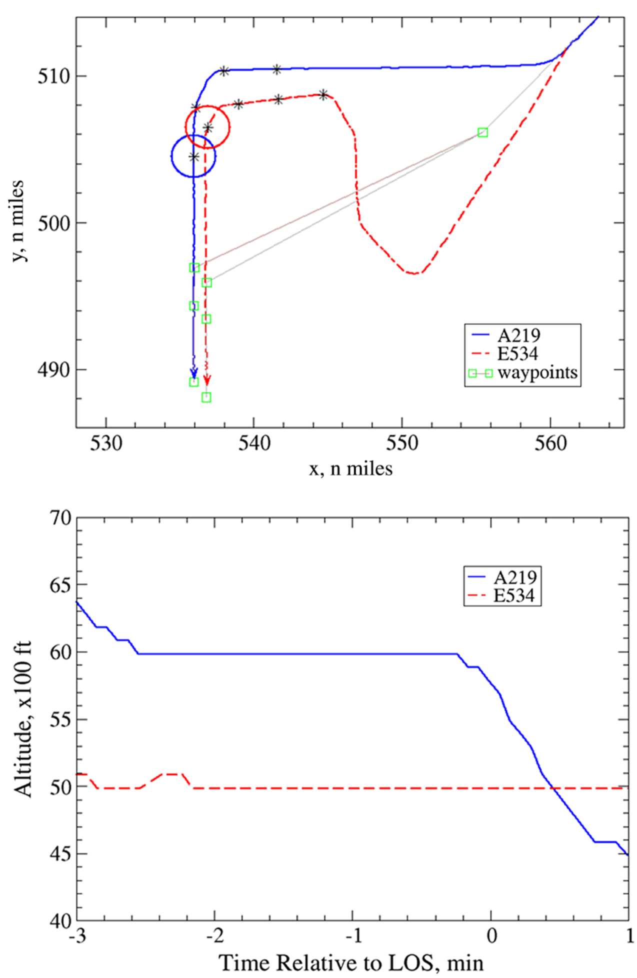

Fig. 3 Ground tracks and altitude profiles of a conflict for which altitude restriction increases alert lead time.

alert lead time. This was an operational error due to the controller's failure to project future status of the aircraft according to the description of the operational error. The two aircraft, A219 and E534, were conducting simultaneous ILS approaches to DFW runways 17C and 17L, respectively. The circles are 3 n miles in diameter and represent the location of first LOS based on the time of the first LOS determined by T-TSAFE. The stars represent time progression in 1 min intervals near the LOS. The squares represent the waypoints on the nominal interior routes. The solid line is for A219, and the dashed line is for E534, with the arrows indicating the directions of flight. Note that the nominal interior routes for both aircraft only indicate the shortest final segments, and the controller has the freedom to extend the base segments through vectoring. The altitude profiles of the two aircraft are for locations near the first LOS positions; the time origin has been set at the time of the first LOS. Aircraft A219 leveled at 6000 ft, while E534 leveled at 5000 ft. Aircraft A219 began a descent out of 6000 ft before aircraft E534 being established on the localizer of runway 17L, leading to the LOS. If altitude restrictions in the descent profiles were not available to T-TSAFE, T-TSAFE would not have detected the LOS before the descent of aircraft A219 was detected. However, when the altitude restrictions were made available to T-TSAFE, it anticipated the descent and alerted with a lead time of 46 s. In contrast, the controller was unaware that an operational error was developing and neither contemplated nor took any corrective action, as stated in the description of the operational error.

Note that an aircraft is considered to be established on its localizer if it is within the angular course defined by the starting point at the localizer transmitter at 1000 ft from the far end of the approach runway and expanding along the runway centerline with a full-scale course width of 700 ft at the runway threshold [12]; the actual length of the arrival runway is used to enforce this constraint. In addition, we require the course heading of the aircraft to be within 10 deg of the final approach course. This value was determined so that all losses of separation of the operational errors were produced.

The ground tracks and altitude profiles in Fig. 4 show another example that favors the ALR method with the alert lead time seemingly decreased when altitude restrictions were integrated in T-TSAFE. Aircraft W516 and K229 were cleared to make simultaneous ILS approaches to runways 17C and 18R at DFW, respectively. The circles, stars, squares, and arrows have the same meanings as before. According to the description of the operational error, the controller erroneously issued an altitude clearance to W516 to descend to 4000 ft but intended to provide a 5000 ft altitude clearance. Meanwhile, a tricky readback error occurred: the W516 flight crew read back the clearance as 5000 ft instead of 4000 ft, so the controller did not realize the error. Aircraft K229 was level at 4000 ft, so a loss of separation occurred when W516 continued to descend through 5000 ft. The controller instructed the pilot of W516 to climb back up to 5000 ft later on. The level of 5000 ft is an altitude restriction for runway 17C. When altitude restrictions were integrated, T-TSAFE did not alert until the altitude level was penetrated and thus alerted with zero alert lead time. Without the level-altitude flight-intent information, the conflict was predicted with a lead time of 18 s, but that would have been a nuisance alert had the controller issued the 5000 ft altitude clearance. Note that a dual-trajectory approach [14–16] could alert earlier though the alert would be a nuisance as well if the 5000 ft clearance were issued. The balance is in favor of a single-trajectory approach.

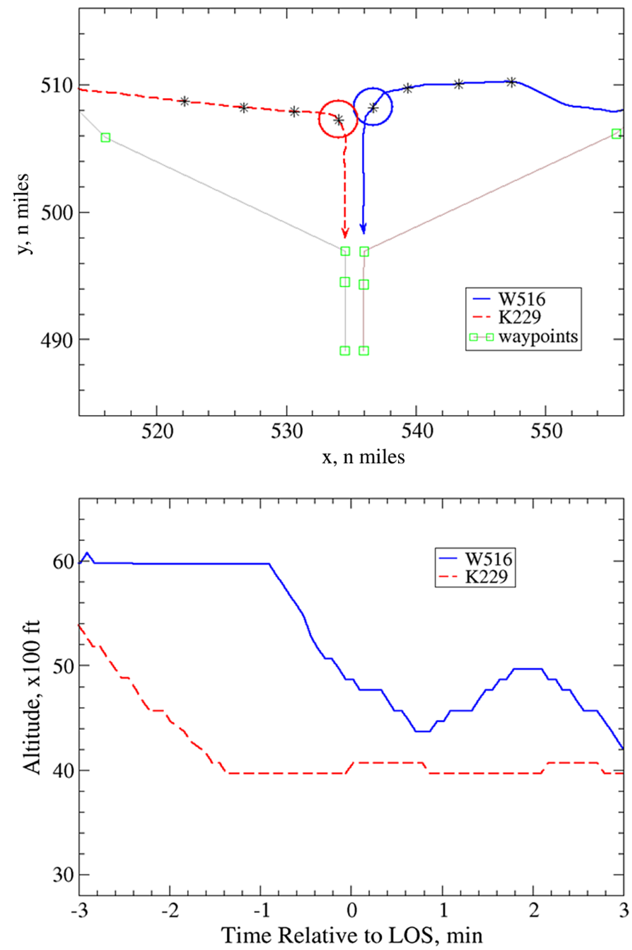

Fig. 4 Ground tracks and altitude profiles for a conflict for which the ALR method reduces alert lead time.

B. Alert Number and Analysis

The results for the altitude-restriction and inferred-altitude-clearance methods for incorporating level-altitude flight-intent information are compared in this section based on air traffic data from Southern California TRACON and Dallas/Fort Worth TRACON. As described earlier, the ALR method uses altitude restrictions to derive the corresponding level altitudes dynamically, while the IAC method emulates a concept of operation whereby controllers make a manual entry for every altitude clearance.

1. *Number of Different Types of Alerts at SCT*

To provide a baseline for comparison of the alerts from the ALR and IAC methods, we first compare alerts at SCT for the IAC method and the baseline method in which altitude restrictions and level altitudes are not known to the system. The comparison is grouped by major and nonmajor airports.

Table 2 shows the number of Los Angeles International Airport (LAX) and non-LAX, LOS and non-LOS alert pairs for the IAC and baseline methods with the full-day SCT traffic data. An alert for which one or both aircraft involved are LAX arrivals or departures is referred to as a LAX alert; otherwise, it is a non-LAX alert. As mentioned before, jitters were ignored when counting alert pairs irrespective of the size of time gaps between successive declarations. The first row shows the number of common alerts for which the same aircraft pairs appear in both the IAC and baseline methods. The second and third rows show the distinctive alerts in which the aircraft pairs appear in only one but not the other method. As explained in Sec. IV.B, the observed weather condition and traffic pattern for the specific day suggest that arrival traffic was a mix of visual and ILS approaches, but for this simulation, T-TSAFE was configured to treat all arrivals as conducting ILS approaches so the standard separation minima apply. Thus, visual-approach safety alerts were absent,

Table 2 Number of alerts of different types with the IAC and baseline methods for SCT

	LAX		Non-LAX	
Method	LOS	Non-LOS	LOS	Non-LOS
IAC and baseline	248	59	137	125
IAC only	0	4	0	31
Baseline only	4	45	9	80

but MCI alerts and VFR safety alerts might have been present. Nevertheless, only one of the 248 common LAX LOS alerts was a safety alert, but 74 of the 137 non-LAX LOS alerts were safety alerts.

As seen in Table 2, the main difference between the IAC and baseline methods lies in the distinctive alerts. The level-altitude flight-intent information in the IAC method helped remove 45% or 43% of all non-LOS LAX alerts in the baseline methods and introduced four different non-LOS LAX alerts. The removed baseline alerts are expected to be nuisance, given that level altitude information will be available through altitude restrictions or altitude entries. LOS alerts are typically common to both methods except for some rare special cases (nuisance alerts) in which the radar tracks fluctuate about an otherwise level altitude. When the fluctuations are within 100 ft, the IAC method rounds it off as if there is no fluctuation. The baseline method lacks level-altitude flight-intent information, so the fluctuations cause apparent losses of vertical separation. This is the reason for the four distinctive baseline-only LOS alerts that did not occur in the IAC method.

Table 2 also shows non-LAX alerts for which none of the aircraft involved is a LAX arrival or departure. They are instead overflights or aircraft arriving or departing from 29 nonmajor SCT airports, for which the NIRs or RNAV DPs and waypoint restrictions are either unavailable or not closely followed. As can be seen, more non-LOS alerts appeared, and while the IAC method eliminated 80 or 39% of all baseline non-LOS alerts, it added back 31 non-LOS alerts, which amounts to 15% baseline non-LOS alerts.

Table 3 shows a similar comparison between the ALR and IAC methods for the LAX and non-LAX alerts grouped in terms of common and distinctive alerts. The main difference in alerts between the two methods again lies in the number of distinctive alerts. There was a total of nine IAC-only and 12 ALR-only non-LOS alerts. As to be exemplified in the next subsection, eight of the IAC-only non-LOS alerts were false with just one being valid, which the ALR method did not predict because a level altitude was not an altitude restriction. Also, the 12 ALR-only non-LOS alerts were valid either because of the presence of level altitudes not attributable to altitude restrictions or the aircraft involved in some conflict-avoiding speed or vectoring maneuvers. The one ALR-only LAX LOS alert did not appear in the IAC method because an inferred altitude clearance not attributable to altitude restriction helped smooth out rounding errors. The alert would not show up for the ALR method if the level altitude were entered.

Table 3 shows the number of non-LAX alerts as well. These alerts involved aircraft arriving or departing from 29 nonmajor airports in SCT. As can be seen, a larger percentage of distinctive alerts than the case of LAX alerts appeared: 39% of ALR non-LOS alerts and 24% IAC non-LOS alerts. The nine ALR-only LOS non-LAX alerts appeared only in the ALR but not the IAC method because altitude fluctuations around level altitudes not attributable to altitude restrictions similarly made it inapplicable to round off around the level altitudes.

2. *Comparison of Distinctive LAX Alerts*

To better understand the difference between alerts from the IAC and ALR methods, three examples of LAX alerts distinctive for the two methods are examined in this subsection. The first example is a false alert out of the eight similar false alerts among the nine IAC-only non-LOS alerts. The second and third examples are ALR-only valid non-LOS alerts with the third one involving a vectoring maneuver.

Table 3 Number of alerts of different types with the IAC and ALR methods for SCT

	LAX		Non-LAX	
Method	LOS	Non-LOS	LOS	Non-LOS
IAC and ALR	248	54	137	119
IAC only	0	9	0	37
ALR only	1	12	9	75

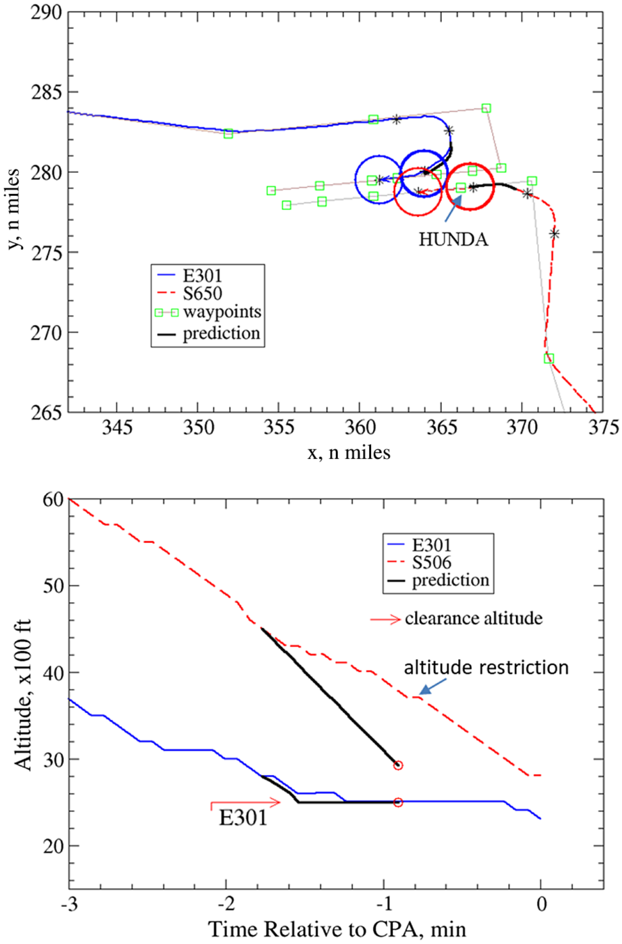

Fig. 5 Ground tracks and altitude profiles of aircraft involved in a false IAC-only alert.

Figure 5 shows the ground tracks and altitude profiles of two aircraft involved in a false alert that appeared only in the IAC but not in the ALR method. Both aircraft were LAX arrivals with E301 approaching runway 24R and S650 approaching runway 25L. The symbols have the same meaning as before with the circles being 3 n miles in diameter. The light solid and dashed lines are the actual trajectories, and the centers of the light circles represent horizontal closest point of approach (CPA). Each dark solid circle indicates the first predicted loss of separation centered at the end of the dark solid line, the predicted trajectory starting from the aircraft's current position.

The aircraft lost horizontal separation as seen from the overlap of the dark circles in Fig. 5. The corresponding altitude profiles indicate aircraft E301 leveled off at 2500 ft while aircraft S506 was descending. The dark solid straight lines represent the altitude profiles predicted by T-TSAFE with the end small circles indicating the predicted altitudes at the first LOS. The time is measured from the CPA. The IAC method uses the current descent rate to project the descent of aircraft S506, but S506 reduced its descent rate likely in anticipation of the (short-duration) altitude restriction at or above 3600 ft at waypoint HUNDA. The same altitude restriction is expected from the runway descent profile. As a result, the IAC method falsely predicted a potential LOS to occur in about 50 s before reaching HUNDA, which never materialized as the prediction stopped in a few radar update cycles when the descent rate of S506 was reduced. On the other hand, the ALR method anticipated the altitude restriction and predicted a leveloff at 3600 ft near HUNDA, so no alert was ever generated. While there appeared to be a short leveloff in the actual altitude profile, it was too short to be recognizable as such by T-TSAFE with the IAC method.

The second example involves a valid non-LOS alert that only appeared in the ALR method with the altitude profile of one aircraft

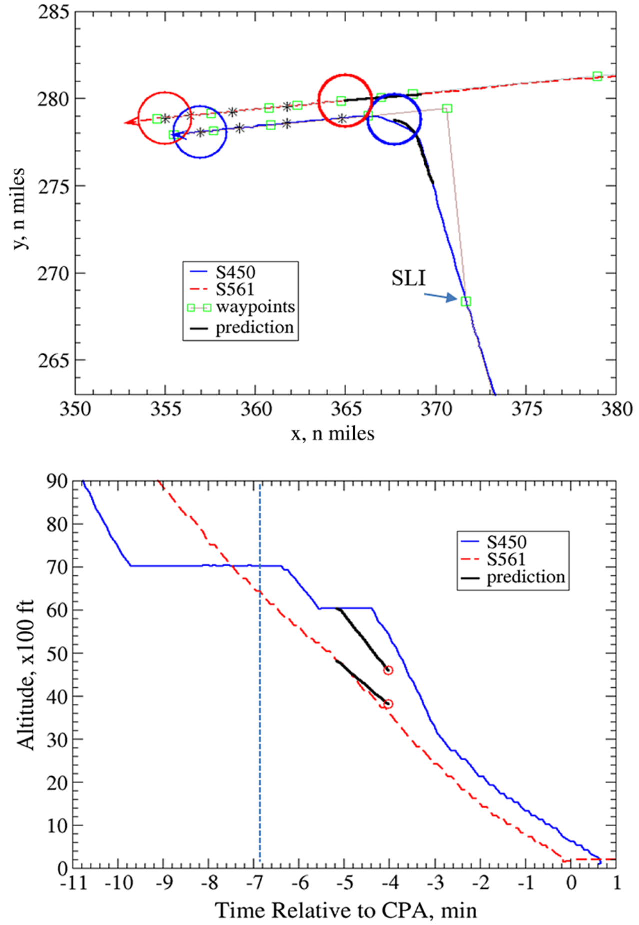

Fig. 6 Ground tracks and altitude profiles of aircraft involved in a non-LOS ALR-only alert with a nonattributable leveloff.

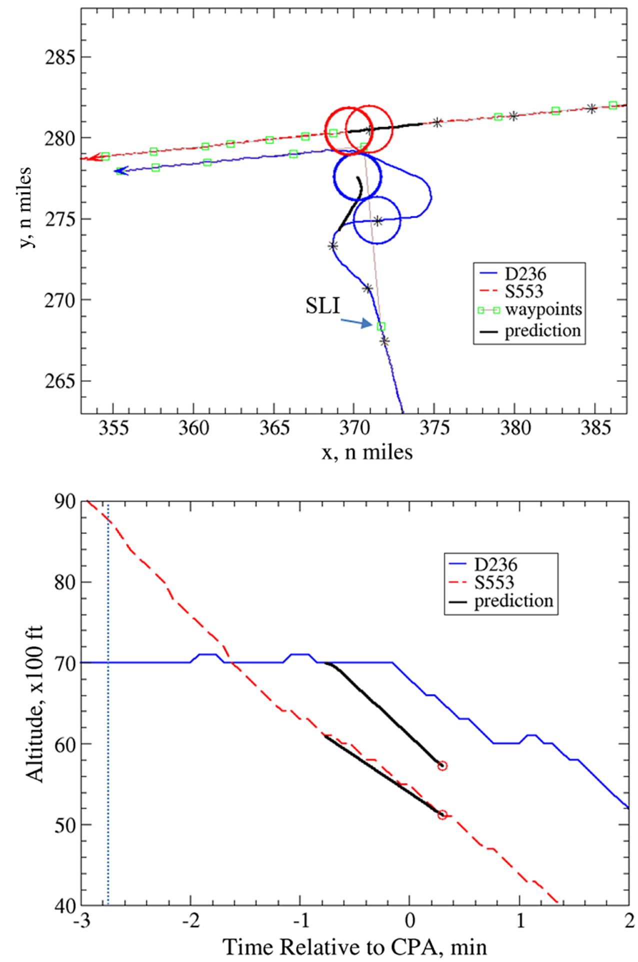

Fig. 7 Ground tracks and altitude profiles of aircraft involved in a valid non-LOS ALR-only alert with vectoring.

containing a leveloff that was not attributable to an altitude restriction. Figure 6 shows the ground tracks and altitude profiles. Aircraft S450 was turning from the base onto the final segment of its NIR to LAX runway 25L, while S561 was already established on its final to LAX runway 24R. The symbols mean the same as before. The circles are 3 n miles in diameter with the light ones at the CPA and the dark ones at the predicted LOS points. The dark lines are predicted horizontal tracks. The base segment for S450 starts from the indicated waypoint SLI, which has an altitude restriction at or above 7000 ft. The end waypoint of the base segment has an altitude restriction at or above 5000 ft. The vertical dotted line in altitude-profile plots indicates the moment when S450 reaches waypoint SLI.

Without any further flight-intent information, we assume aircraft follow their runway descent profiles even when they are still on the base segment (may not be on the final approach yet). As a result, altitude restriction on the runway descent profile also requires S450 to stay at or above 5000 ft before reaching the final segment. In practice, S450 may stay level (7000 ft in this case) beyond the starting waypoint of the base segment without requiring the controller's further instruction. However, we assume that aircraft would start to climb or descend as soon as they have passed through the waypoint of an altitude restriction. This assumption is generally justified based on observations. For example, with the current traffic data, we observed that, among a large number of daily flights through all routes with this base segment, only three alerts were related to the extension of the leveloff at 7000 ft. Aircraft S450 did not begin its descent out of 7000 ft until about 2 n miles beyond SLI, or about 30 s after SLI as seen in the plot of altitude profiles. Furthermore, as can be seen, S450 made an additional leveloff at 6000 ft not attributable to an altitude restriction. Being unaware of this leveloff led to a non-LOS alert from the ALR method. Because we expect that the ALR method should be augmented with altitude entry of nonattributable altitude clearances, which would eliminate the alert, we consider the leveloff as a controller or pilot intervention and categorize this as a valid non-LOS alert.

The third example involves an ALR-only valid non-LOS alert caused mainly by an aircraft making unusual vectoring to achieve proper spacing. Figure 7 shows the ground tracks and altitude profiles of the aircraft involved in the alert. The notations are the same as before. Aircraft D236 was approaching LAX runway 25L while S553 was already established on the final approach course on LAX runway 24R. Aircraft D236 was being vectored by the controller for spacing before merging onto the final approach. Vectoring is currently treated as uncertainty in the flight-intent information in the NIR. For lack of the vectoring flight-intent information, the predicted horizontal trajectory deviated from the actual trajectory noticeably. This unusual vectoring appeared late and abrupt. As in Fig. 6, there was an altitude restriction of 7000 ft at waypoint SLI before the next restriction at 5000 ft on the runway descent profile. The dotted vertical line in the plot of the altitude profile also indicates the time when D236 reached waypoint SLI. Although we assumed D236 to descend right away after passing SLI, the altitude profile shows that it maintained 7000 ft for 2.6 min while performing the vectoring before being able to merge onto runway 25L, which avoided the potential LOS. Even though vectoring is expected to occur generally near the base segment, the fact that the vectoring occurred close to the initial alerting suggests that a controller intervention occurred, and thus the alert is classified as valid. This alert should be useful to help the controller be aware of the situation and take proper action as well. The controller may make an altitude entry of 7000 ft to remove the alert. In fact, there was another non-LOS alert involving D236 with a different aircraft on runway 24R as well. Note that these were ALR-only alerts since the aircraft would remain on the inferred altitude clearance at 7000 ft in the IAC method until a descent was detected.

Overall, six of the 12 valid ALR-only non-LOS alerts involved nonattributable altitude clearances as in the second example mentioned previously. These would not be alerted if the controllers entered nonattributable altitude clearances. Otherwise, these alerts would help remind the controllers of the potential conflicts as well, and they are thus valid non-LOS alerts. These ALR-only alerts did not appear when the IAC was used since the aircraft remained at the altitudes of the inferred altitude clearances until a descent was detected. The six other valid ALR-only non-LOS alerts involved speed or vectoring maneuvers that made the predicted losses of separation not materialized as in the third example. So, they still are valid, and they might still occur after additional entries of nonattributable altitudes are made.

The IAC-only non-LOS alerts were mostly false as they mainly resulted from short-duration level altitudes at altitude restrictions that were not identifiable as IAC altitudes similar to the first example. This is the artifact in the IAC method for simulating the effect of controller entry of level altitudes. The ALR method of obtaining level-altitude flight-intent information through altitude restrictions avoids such drawbacks. If additional entries of nonattributable altitudes were made, most of the ALR-only alerts would not be issued by T-TSAFE. Thus, we conclude that the ALR method augmented with entries of nonattributable altitudes may work as well as when entries of all level altitudes are made.

3. *Analyses of Alerts at DFW TRACON*

The same analyses were done for the simulation that used the D10 traffic data. Table 4 shows the comparison between the ALR and IAC methods for the DFW-DAL and non-DFW-DAL alerts grouped in terms of common and distinctive alerts. A DFW-DAL alert is one with at least one of the aircraft involved being a DFW or DAL arrival or departure. As mentioned earlier, the weather conditions and the traffic pattern for the specific day suggested mostly visual approaches but all arrivals were assumed to be on ILS approaches instead so the standard separation criteria could be used. This allowed more alerts to be compared between the ALR and IAC methods.

Among the 478 DFW-DAL LOS alerts, only two were safety alerts. As before, the differences between alerts in the two methods lie again in the distinctive alerts. Compared to the case for the SCT data, there were slightly more ALR-only and IAC-only alerts: 24 and 18% of their respective non-LOS alerts. The 32 IAC-only alerts were all false alerts for reasons similar to the IAC-only LAX alerts. That is, the intended leveloffs that would otherwise prevent the alerts were not recognizable either because they were too short or the altitude ascended slowly for some departures near a published 10,000 ft altitude restriction. As a result, these alerts were generated in the IAC method, but altitude restrictions prevented them from appearing in the ALR method. Notice that there were more DFW-DAL alerts compared to the LAX alerts in general, resulting from the fact that most aircraft were not actually subject to the standard separation minima for being on visual approaches.

Among the 44 ALR-only non-LOS alerts, there were 31 valid and 13 false alerts. Among the valid alerts, 22 resulted from leveloffs nonattributable to altitude restrictions, and 9 were resolved later from speed maneuvers. Seven of the false alerts were grouped as false because they lasted one or two radar cycles and often corresponded to the level altitudes being extended slightly (say 10 s) beyond the waypoint of altitude restriction; nevertheless, they appeared to be resolved by speed maneuvers. The single IAC-only LOS alert was similarly due to small altitude fluctuations about an unrecognizable leveloff at the 10,000 ft altitude restriction.

Table 4 Number of alerts of different types with the IAC and ALR methods for D10

	DFW-DAL		Non-DFW-DAL	
Method	LOS	Non-LOS	LOS	Non-LOS
IAC and ALR	478	143	17	8
IAC only	1	32	0	2
ALR only	0	44	0	7

Table 4 also shows alerts involving aircraft that are not DFW or DAL arrivals or departures. As can be seen, nonmajor airports for D10 play an insignificant role. This makes sense since there were only eight nonmajor airports involved in the alerts, as compared to 29 for SCT.

Thus, the same conclusion as from the SCT data can be drawn that the ALR method with controller entry of altitude clearances nonattributable to altitude restrictions may work as well as when entries of all level altitudes are made. Recall that, as mentioned in Sec. II.C, altitude clearances from controller entries take precedence over the altitude restrictions.

C. Altitude Entry and Controller Workload

While it appears that no supporting analysis is found in the literature, SMEs suggest that the workload could be too high if TRACON controllers were required to make entry of all altitude clearances. A first such analysis is provided here.

The numbers of level altitudes attributable and nonattributable to altitude restrictions were determined for the busy hours between 8:00 a.m. and 9:00 p.m. local time for the SCT data on 24 February 2012. It was found that 39% of level altitudes (354 out of 904) for LAX arrivals were nonattributable. That number for LAX depatures is 80% (287 out of 359) and that for non-LAX flights is 90% (2172 out of 2412). The high number for non-LAX flights is due to the lack of, or aircraft not following closely, the NIRs and RNAV DPs. As seen earlier, a leveloff attributable to altitude restriction can be too short to be recognizable by the IAC method, while this would not be the case for a nonattributable leveloff as it results from a specific clearance that the aircraft would not penetrate until another clearance is received. Thus, the number of attributable leveloffs for LAX arrivals may well be underestimated. Note that the leveloffs nonattributable to altitude restrictions were unavailable in the ALR method by definition; however, only six distinctive alerts in the ALR method corresponded to nonattributable level altitudes. Thus, less than 3% of the nonattributable level altitudes of LAX arrivals led to alerts.

If controllers were to enter all of the nonattributable LAX-arrival level altitudes, it would amount to only seven entries per hour per controller position, averaging over 13 work hours and four arrival controller positions at LAX: two feeder sectors of East Feeder and Zuma and two approach sectors of Downe and Stadium. By slicing the time into 15 min intervals, we extracted the number of leveloffs as a function of time for each controller position, approximately defined based on arrival runways and the distance to LAX. We found only three isolated bursts of eight or nine leveloffs within 15 min for the full-day traffic, one for each of the three controller positions of Stadium, Downe, or East Feeder. The rest were mostly between zero and four leveloffs in 15 min. Thus, making entry of nonattributable leveloffs did not significantly increase controller workload for LAX arrivals.

The same conclusion may not apply for attributable leveloffs as they could be well underestimated. Consider the straight-in arrivals of parallel runways 24R and 25L at LAX with the single approach controller position at Downe; there are seven and eight altitude restrictions for runways 24R and 25L, respectively, in the runway descent profiles between 2000 and 10,000 ft, as seen from the IAP charts. In busy hours on a typical day with simultaneous parallel approaches to the two runways, we find a typical throughput to be 60 aircraft per hour. The number for four-runway simultaneous approach could be larger. Thus, the Downe controller would need to make eight altitude entries per minute in peak hours if all leveloffs attributable to altitude restrictions were required to be entered. Since controllers are busy merging and separating aircraft, requiring them to make an additional 500 altitude entries per hour could be excessive. The altitude-restriction method of obtaining level-altitude flight-intent information augmented with controller entry of nonattributable altitude clearances may resolve this issue.

The altitude-restriction method should work well with LAX departures as the number of leveloffs is small. For non-LAX flights, controllers either may enter the level altitudes when they are not too busy or could wait until alerts are being generated. The same conclusion can be drawn from similar analysis on the DFW data.

VI. Conclusions

In this Paper, algorithms for trajectory generation and tactical conflict prediction and declaration have been summarized. Altitude restrictions from runway descent profiles and waypoints on the NIRs and RNAV departure procedures were incorporated as flight-intent information in the altitude profiles. Parameters were adjusted with real-world air traffic data from operational-error cases and two large TRACON facilities. The alert lead time, number of different types of alerts, and effect of controller altitude entries on controller workload were studied.

Simulation experiments were performed through playback of recorded real-world air traffic data. With real-world operational error data, the altitude-restriction method of gaining level-altitude flight-intent information showed an improvement of average alert lead time by 16% over the baseline of no altitude restrictions. With full-day air traffic data from two TRACONs, it was shown that for major airports where NIRs and RNAV DPs are available and are followed closely the altitude-restriction method, augmented with controller entries of only those altitude clearances not attributable to altitude restrictions, would work as well as if all altitude clearances were entered into the system by controllers. This was done by analyzing the differences between alerts in the altitude-restriction method and the previous IAC method. The distinctive alerts (different aircraft pairs for the two methods) in the IAC method were mostly false; they resulted from artifacts of the method itself and would not have occurred if the controller had entered the relevant level altitudes, which were attributable to altitude restrictions. On the other hand, the distinctive alerts in the altitude-restriction method were mainly due to level altitudes not attributable to altitude restrictions; they would not have occurred if the altitude clearances were entered. It was shown that the workload increase is insignificant in the altitude-restriction method, enhanced with controller entries of altitude clearances not attributable to altitude restrictions for major airports. For nonmajor airports where the NIRs and RNAV DPs are not followed closely or not available at all, the controllers might make the entries after alerts are triggered or when they are not busy.

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