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Tactical Conflict Resolution using Vertical Maneuvers in Enroute Airspace

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An algorithm is presented for computing vertical resolution maneuvers to resolve imminent air traffic conflicts in which loss of separation could occur within two minutes. Several procedures are used, including rejection of altitude amendments that could cause a conflict, temporary altitudes, step altitudes, and critical-leveloff confirmation. These methods are tested on archived data from 100 actual operational errors (loss of separation due to controller error), which tend to be more difficult to detect and resolve than routine conflicts that get resolved successfully. Successful resolution was achieved in simulation for 84 of them using vertical maneuvers only. Augmented altitude amendments are then added to the input files to simulate altitude amendments that should have been entered by the controller but were not, or to correct amendments to make them consistent with the pilot's understanding. The number of successful resolutions increased to 94 of the 100 cases. The reasons for the failures are discussed.

I. Introduction

The large potential increase in air traffic in future decades is expected to require automation of the separation assurance functions that are currently performed by air traffic controllers using radar displays and voice communication with pilots. Separation assurance is a complex, real-time problem with many variables and uncertainties, and failure could be disastrous. The challenge is to develop an automated system that can keep the probability of collision acceptably low, despite the complexity and unpredictability of the traffic patterns, even as traffic doubles or triples.

NASA Ames is developing the Advanced Airspace Concept (AAC)[1,2] to meet that challenge. AAC comprises two stages of separation assurance, plus standard collision avoidance, which constitutes a third stage. The first stage is a strategic auto-resolver[3] that attempts to detect and resolve conflicts up to approximately 20 minutes in advance. The second stage is a simpler system called the Tactical Separation-Assured Flight Environment (TSAFE), which is intended to backup the strategic auto-resolver and handle any conflicts left undetected or unresolved with loss of separation (LoS) predicted to occur within approximately two minutes. If TSAFE fails to resolve a conflict, the Traffic Alert and Collision Avoidance System (TCAS)[4] is available on most commercial aircraft to prevent a collision using vertical maneuvers.

Because automated conflict detection and resolution are considered safety critical, TSAFE is intentionally designed to be as simple as possible, while still capable of resolving conflicts with high reliability. Thus, TSAFE generates relatively simple maneuvers consisting of altitude, heading, or speed changes, which could be used as controller advisories, but are intended ultimately to be automatically uplinked to the flight deck, possibly using the existing but underutilized Mode S datalink, as proposed by Erzberger.[5] For simplicity, TSAFE does not attempt to return the maneuvered flights back to their planned routes after the conflict passes. Because the conflicts are imminent, however, maneuver delays and flight dynamics must be accounted for. TSAFE must also guarantee that conflicts are resolved without creating new conflicts with nearby traffic. In addition, TSAFE must be designed to interact safely with TCAS, but that issue is outside the scope of this paper.

In addition to the far-term objective of tactical conflict resolution, TSAFE has also been developed and tested for a near-term application as a tactical conflict alerting aid for controllers.[6,7] The objective is to

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eventually replace Conflict Alert, the legacy system for alerting controllers to imminent conflicts in the US. Like Conflict Alert, TSAFE uses constant-velocity ("dead-reckoning") state projections, but unlike Conflict Alert, it also uses intent information in the form of the flightplan route and the assigned altitude. The details of TSAFE conflict detection are outside the scope of this paper. TSAFE has been tested extensively with actual air traffic data, including archived tracking data for 100 operational errors (losses of separation officially attributed to controller error). TSAFE provided timely alerts more consistently than Conflict Alert. TSAFE was also found to produce substantially fewer false alerts than Conflict Alert.

Conflicts must be detected before they can be resolved, and the resolution methods discussed in this paper build on the detection methods already in TSAFE. The conflict resolution capability of TSAFE using vertical (altitude) maneuvers was tested on the same set of archived operational errors that were used to test the conflict detection performance, and the results are presented in this paper. Horizontal resolution methods, such as those proposed by Erzberger,[5] are also currently in development for TSAFE, but they are beyond the scope of this paper.

Some of the vertical resolution methods used in this study have been used routinely by controllers for many years, some have been implemented by Erzberger in the auto-resolver,[3] and others are new. A vertical resolution algorithm was presented by Dowek,[8] in which vertical speed (as opposed to cleared altitude) is used as the control variable, but it was apparently not tested on actual traffic data. The main contribution of this paper is the integration of several vertical resolution procedures into an automated system and testing it on archived tracking data from actual operational errors.

The remainder of the paper is organized as follows. First, the basic maneuver simulation methods used to test TSAFE are outlined. Next, the vertical resolution methods are explained. Then the concept of augmented altitude amendments is discussed, in which altitude amendments are added to the input file to correct for omissions and errors by the controller. The results for simulated resolution of the archived operational error cases are then presented, followed by the conclusions.

II. Vertical Maneuver Simulation

When TSAFE predicts a loss of separation (LoS) to occur within two minutes, it attempts to compute a maneuver that will resolve the conflict. Those maneuvers can be altitude, heading, or speed changes, but in this paper they are restricted to altitude changes. The time threshold of two minutes is based on engineering judgment and could be refined in the future. TSAFE could be used to provide resolution maneuver advisories to the controller, but the ultimate objective is to automatically uplink the resulting maneuvers directly to the flight deck. In this study, maneuvers are simulated for archived operational error cases by "taking control" of the maneuvered flight and simulating an altitude profile to the specified flight level.

The simulation of vertical maneuvers in this study is fairly simple. A simulator, which is separate from TSAFE, takes control of the flight by intercepting and altering its radar track updates. The simulator imposes a specified maneuver delay to model the reaction time of a pilot, then it changes the vertical speed to a target value at a specified acceleration or deceleration rate until it reaches the target (or cleared) altitude and levels off. The target value of vertical speed is determined by a table lookup of the BADA (Base of Aircraft Data)[9] aircraft performance database developed and made available by Eurocontrol.

The maneuver delay and the vertical acceleration limit are parameters that are set to nominal values of 10 sec and 0.1 g, respectively (where g is the gravitational acceleration constant). In the 12 sec between radar samples, this allows the vertical speed to change by a maximum of ±386 ft/sec. That value is large enough that a smooth change in vertical rate is sometimes difficult to observe in the simulated maneuvers to be presented later in the paper (but the same is also true of the real data). The delay and acceleration parameters are based on engineering judgment and observation of actual traffic data. They are not intended to be precise but rather simply to add basic realism to the simulation.

In modeling the maneuver delay, the vertical speed was held constant for the duration of the delay, rather than letting the trajectory continue according to the tracking data. If a second vertical maneuver is issued within one minute of an earlier maneuver, the delay does not start over again, since the pilot is likely to be more alert and ready to respond faster. Also, an arbitrary decision was made not to discretize the simulated altitude profile in increments of 100 ft like the real baro-altitude data transmitted over Mode C.

BADA provides one descent and three climb rates, "slow," "nominal," and "fast," for each aircraft model at each flight level. These are nominal rates for heavy, nominal, and light loading of the aircraft. The fast and slow climb rates are used by TSAFE to establish a range of rates for conflict detection and also for testing candidate maneuvers for resolution. The nominal rate is used for the simulated vertical maneuvers.

III. Vertical Resolution Methods

Vertical conflict resolution methods in TSAFE can be classified into the following categories:

- Rejected altitude amendments
- Temporary altitudes
- Step altitudes
- Confirmations of critical leveloffs

Altitude amendments are rejected by TSAFE when it determines that they will cause a conflict. Temporary altitudes are temporary leveloffs used to avoid a conflict during a climb or descent. Step altitudes are offsets in the cleared altitude used to avoid conflicts. Confirmations of critical leveloffs occur when TSAFE detects that a failure to leveloff at the assigned altitude will result in an immediate LoS, so it reconfirms the altitude with the pilot. These methods are explained in more detail below, and examples are shown.

Separation standards require either horizontal or vertical separation. However, a single, scalar metric defined as the "separation ratio" is used in this paper for rating separation performance. The separation ratio is defined as the greater of the horizontal and vertical separation ratios as illustrated in Fig. 1. The horizontal separation ratio is the ratio of the horizontal separation to the allowed horizontal separation minimum (HSM = 5 nmi). Similarly, the vertical separation ratio is the ratio of the vertical separation to the allowed vertical separation minimum (VSM = 1000 or 2000 ft, depending on the altitude). The usual rule applies for rounding to the cleared altitude within ±200 ft. In the interest of succinctness, the minimum separation ratio for an encounter will sometimes be referred to simply as the "separation ratio."

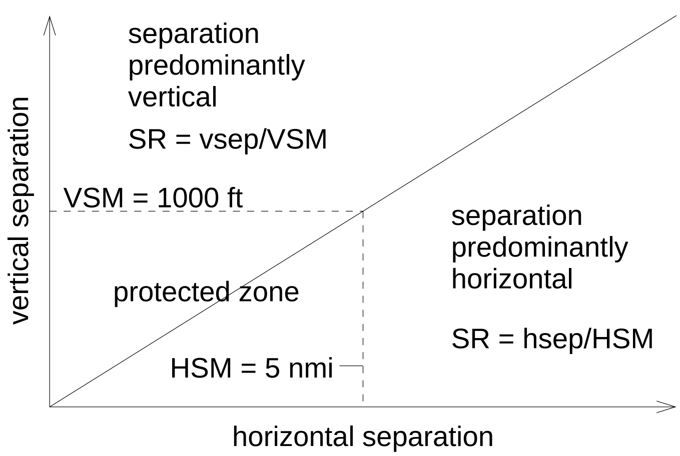


Figure 1. The separation ratio (SR) is the greater of the horizontal separation ratio and the vertical separation ratio (hsep/vsep: horizontal/vertical separation; HSM/VSM: horizontal/vertical separation minimum allowed)

If two flights are level at their cleared altitudes at adjacent flight levels, the separation ratio as defined above could be as low as 1.0, but that would be misleading because separation is assured as long as the flights stay within tolerance of their cleared altitudes. In that case, the flights are considered "separated by altitude clearance," and the separation ratio as defined above does not apply. Figure 2 shows how this criterion is defined in general. Assuming that neither flight is diverging from its cleared altitude, each flight is constrained to the altitude range between its current and cleared altitudes. If the separation between these two ranges meets or exceeds VSM, then the flights are considered “separated by altitude clearance,” and the separation ratio is considered arbitrarily large.

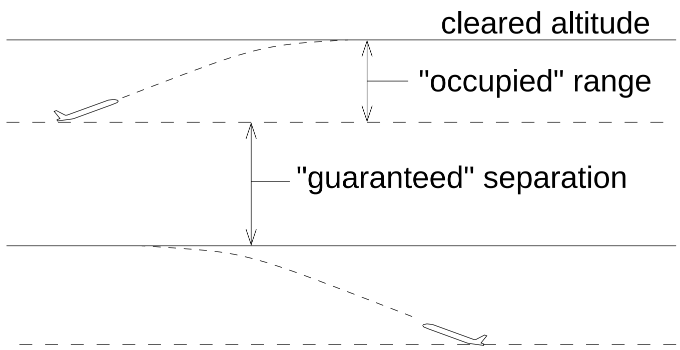


Figure 2. The encounter separation ratio does not apply when the flights are “separated by altitude clearance” (i.e., the “guaranteed” separation is greater than or equal to the separation standard)

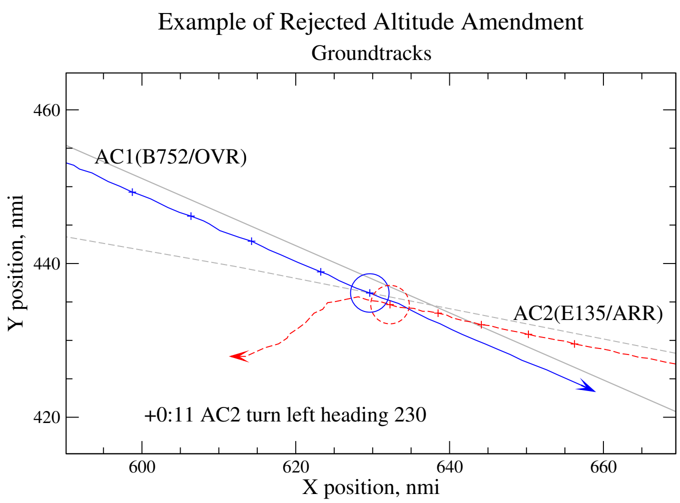
A. Rejected Altitude Amendments

The earlier work on TSAFE conflict detection[7] found that approximately 43% of the operational errors studied were caused by an air traffic controller issuing an altitude clearance that led directly to the loss of separation (LoS). An important feature of TSAFE is the ability in some cases to detect such conflicts as soon as the altitude amendment is entered, even before an aircraft that is flying level starts to climb or descend. Conflict Alert, the legacy operational tactical conflict alerting system, must wait for the climb or descent to begin, by which time separation could already be lost. An effective resolution procedure in TSAFE is to simply reject or block such clearances from being entered (accompanied perhaps by an audible warning to the controller).

In a future system with fully automated conflict resolution, altitude amendments should not need to be rejected except perhaps in the case of an error in the strategic auto-resolver (for which TSAFE serves as a backup). Until then, however, such rejection can be useful. If controllers had TSAFE and simply entered altitude amendments to be checked before issuing the voice clearance, many operational errors could be avoided. In any case, the results to be presented here can provide insight into some of the potential benefits of automation in preventing human error.

Figure 3 shows tracks of an operational error that could have been prevented by rejecting an altitude clearance. The top plot shows several minutes of the original, unmodified groundtracks leading up to the LoS. Aircraft 1 (AC1), represented by the solid line, was a B752 (Boeing 757-200) overflight (OVR) heading approximately southeast. Aircraft 2 (AC2), represented by the dashed line, was an E135 (EMBRAER RJ 135) overflight heading approximately west, nearly head-on with aircraft 1. The circles are five nmi in diameter at first LoS (more precisely, the first radar track after LoS). The “+” symbols are approximate minute markers going back to four minutes before LoS. The gray lines represent the flightplan route of the trajectory represented by the same line type (solid or dashed). The times shown for clearances are relative to the point of first LoS represented by the circles. Thus, at +0:11 (11 sec after LoS), AC2 was told to turn left to heading 230, but that was too late to resolve the conflict. (The voice clearances are taken from the official FAA reports on each operational error.)

The bottom plot of Figure 3 shows the altitude profiles. Time zero is the reference time of LoS corresponding to the circles on the groundtrack plot. The gray lines represent the cleared altitudes for the trajectory represented by the same line type (dashed or solid). In this case, the flights were at adjacent flight levels. Aircraft 1 (AC1) was flying nominally level at its cleared altitude of FL350 (with some noise or altitude variation at the Mode C discretization increment of 100 ft). Aircraft 2 (AC2) was flying level at 100 ft below its cleared altitude of FL360 (since it is within the tolerance of ±200 ft, its altitude is rounded to FL360 for separation requirements).



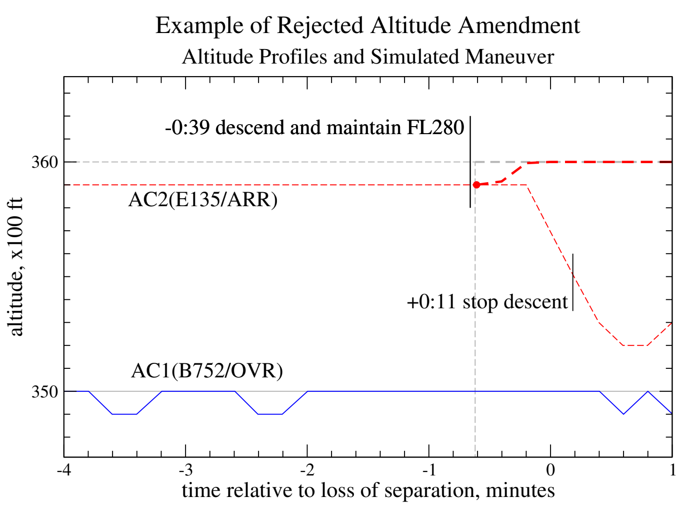


Figure 3. Groundtracks (top) and altitude profiles (bottom) for sample operational error that could have been prevented by rejecting an altitude clearance

At time –0:39 the controller cleared AC2 to FL280. The actual entry of that altitude a few seconds after the voice clearance is represented by the dashed gray vertical line going down to FL280 (off the plot). The resulting vertical vs. horizontal separation is shown in Fig. 4. The minimum separation ratio was 0.4 (2.0 nmi at 300 ft), which is considered fairly severe, particularly for this nearly head-on encounter. However, TSAFE detected the conflict as soon as the altitude amendment was entered and rejected the amendment, thereby preventing the LoS. The resulting continuation of the cleared altitude at FL360 is represented by the thick gray dashed line at that altitude. The maneuver simulator then took control of the flight and simulated the continued level altitude profile, which is represented by the thick, dark dashed horizontal line, beginning with the dot at the time the altitude amendment was entered.

Figure 5 shows the altitude profiles for another operational error that could have been prevented by rejecting an altitude amendment. The groundtrack and separation plots are not shown, but the horizontal encounter angle was approximately 120 deg and the separation ratio was 0.36 (1.8 nmi at 300 ft). Again,

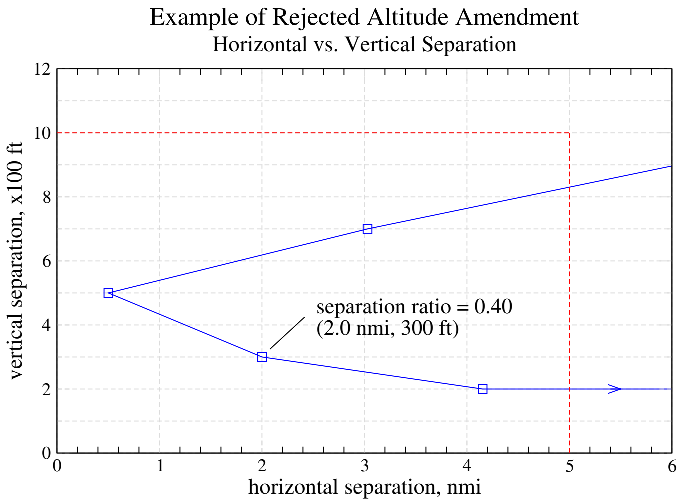


Figure 4. Vertical vs. horizontal separation (squares represent radar track updates)

that is fairly severe for an encounter at such a high relative speed. In this case, aircraft 1 (AC1) had leveled off at 8,000 ft after climbing, then at –0:21 it was cleared up to 14,000 ft. That clearance caused the LoS with aircraft 2 (AC2), which was flying level with an offset of 100 ft from its cleared altitude of 9,000 ft. The voice clearance follows the entry of the altitude amendment into the Host (represented by the vertical gray line) by approximately 10 sec.

As in the previous example, TSAFE detected the conflict as soon as the amendment was entered. The thick, dark horizontal line starting at the dot represents the simulated altitude profile with the altitude amendment rejected. (The dot appears to precede the altitude amendment by a few seconds because, for simplicity, it is placed at the last radar track preceding the rejected altitude amendment.) The reason for the short descending period shortly after LoS is not clear from the official report, but the minimum separation ratio occurred shortly after the climb resumed.

B. Temporary Altitudes

In the current air traffic system, "temporary" or "interim" altitudes are routinely used to resolve conflicts. As the name implies, a temporary altitude is simply a temporary leveloff at an intermediate flight level along a climb or descent. If the pair of flights are "separated by altitude" (i.e., are separated by 1,000 ft or more in altitude) when the conflict is detected, then a temporary altitude can often resolve the conflict simply and efficiently.

When a conflict is detected by TSAFE for a pair of flights that are currently separated by altitude, a list of candidate temporary altitudes is generated for each of the two flights. The list of candidates for each flight starts with the current cleared altitude and steps through each flight level (i.e., in increments of 1,000 ft in most cases) until it reaches the flight level closest to the current altitude, as illustrated in Fig. 6. (Because the maneuvers are intended to be short, the standard "altitude for direction" rule is ignored.) In principle, the "cost" of each candidate altitude is its absolute vertical distance from the current cleared altitude (which is assumed here for simplicity to be the desired altitude). To favor maintaining the current cleared altitude for one of the two flights, a large, arbitrary fixed "cost" is subtracted for the current cleared altitude. A list of all possible pairs of altitude candidates for the two flights is then generated and sorted according to the sum of the two associated costs.

TSAFE then steps through the ordered list of candidate altitude pairs and tests to see if they maintain altitude separation. To do that, TSAFE generates a fast and slow altitude profile for each flight using BADA and modeling a default maneuver delay of 10 sec and a default acceleration limit of 0.1 g (the same values used in the maneuver simulator discussed earlier). If the resulting altitude profiles maintain altitude

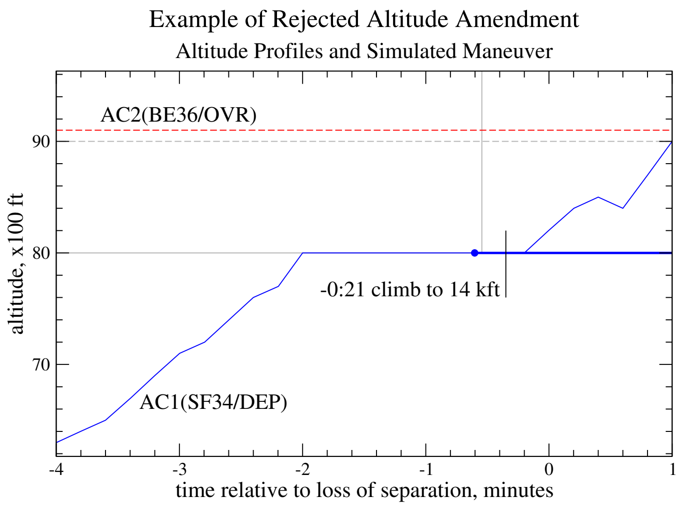


Figure 5. Altitude profiles for another sample operational error that could have been avoided by rejecting an altitude clearance (horizontal encounter angle approximately 120 deg; separation ratio 0.36)

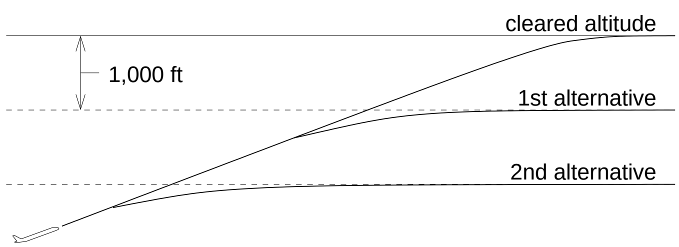
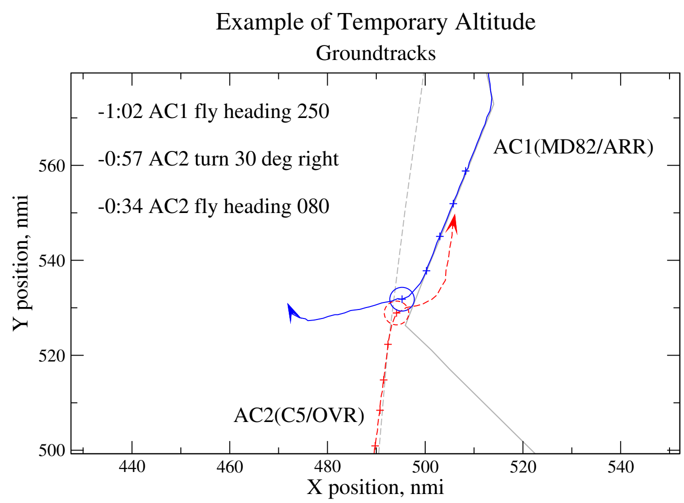


Figure 6. Preference order for temporary altitudes

separation for the entire duration of the prediction, which defaults to three minutes, then the conflict for that pair of flights is considered resolved. Horizontal separation is not checked, because altitude separation is required for the entire duration of the predicted altitude profiles. A check is then done for conflicts with all other flights. If a conflict is found with another flight, the candidate altitude pair is rejected and the next candidate is tried. Otherwise, the conflict is considered resolved and the altitude clearance or clearances are issued.

Figure 7 shows an example of an operational error that was resolved in simulation by a temporary altitude amendment. The top plot shows the original, unmodified groundtracks. Aircraft 1 (AC1), represented by the solid line, was an MD-80 arrival (ARR) heading approximately south. Aircraft 2 (AC2), represented by the dashed line, was a C-5 overflight heading approximately north at a high encounter angle with aircraft 1. The circles are five nmi in diameter at LoS, as before, and the "+" symbols are approximate minute markers. The gray lines represent the flightplan route of the trajectory represented by the same line type (solid or dashed). At –1:02, AC1 was following its planned route closely when it was told to fly heading 250 deg in a failed attempt to resolve the conflict by turning in front of AC2. AC2 was closely following its planned route when, a few seconds later, it was told to turn 30 deg right, then it was later told to fly heading 080 deg to increase the angle of the turn. The minimum separation ratio was 0.62 (3.1 nmi, 400 ft).

The bottom plot of Fig. 7 shows the corresponding altitude profiles and the simulated maneuver. AC2 was flying level at its cleared altitude of FL230. AC1 was descending to FL240 when, at –3:02 it was told



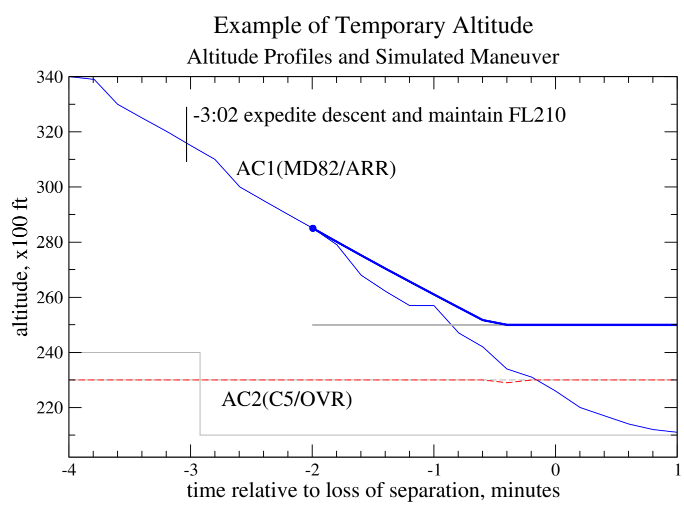


Figure 7. Groundtracks (top) and altitude profiles (bottom) for a sample operational error with conflict resolution by temporary altitude (separation ratio 0.62)

to expedite its descent and continue down to FL210. The altitude amendment entered into the Host is represented by the solid gray line that drops from FL240 to FL210 a few seconds after the voice clearance. At –2:00, TSAFE detected the conflict and issued a temporary altitude amendment to stop the descent at FL250, as represented by the thick gray horizontal line at that flight level. The thick, dark curve starting at the dot at –2:00 on the AC1 altitude profile represents the resulting simulated profile, which resolved the conflict.

Figure 8 shows the altitude profiles and maneuver for another operational error that was resolved in simulation by a temporary altitude amendment. The horizontal encounter angle was approximately 10 deg, so the relative velocity was fairly low. No horizontal maneuvers were used by the controller to resolve the conflict. The minimum separation ratio was 0.77 (3.85 nmi at 400 ft). Aircraft 1 (AC1), represented by the solid line, was climbing slowly to its cleared altitude of FL330, represented by the gray solid line. Aircraft 2 (AC2), represented by the dashed line, was climbing to its cleared altitude of FL230 when, at –1:57, it

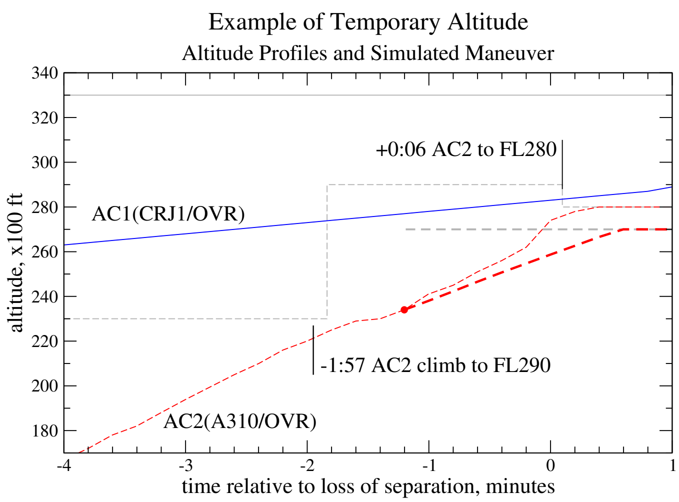


Figure 8. Altitude profiles for a sample operational error with conflict resolution by temporary altitude (horizontal encounter angle approximately 10 deg; separation ratio 0.77)

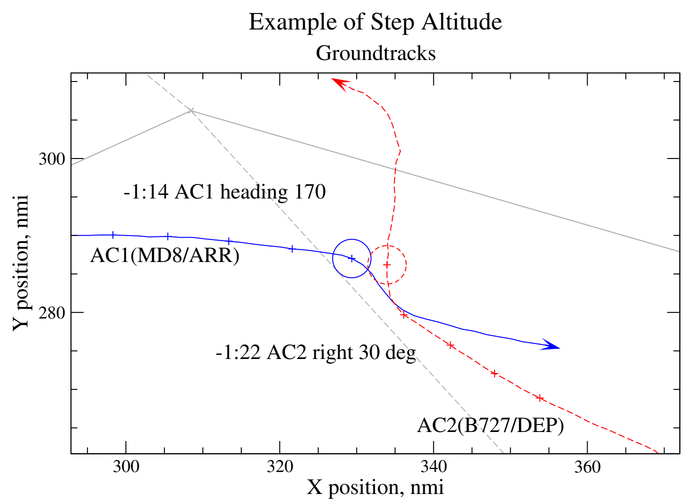
was cleared up to FL290. The dashed gray line that goes up from FL230 to FL290 represents the entry of that altitude amendment into the Host a few seconds later. At +0:06 the cleared altitude for AC2 was dropped to FL280 in an attempt to resolve the conflict, but that was insufficient, in part because the climb rate of AC2 had increased approximately 20 sec before that point. However, TSAFE detected the conflict at approximately −1:12 and generated a temporary altitude amendment of FL270 for AC2, which resolved the conflict. The thick, dark curve starting at the dot on the altitude profile of AC2 represents the resulting simulated maneuver.

C. Step Altitudes

When temporary altitudes cannot resolve a conflict, step altitudes are tried next. The procedure is similar to the procedure outlined earlier for temporary altitudes. The main differences are that (1) step altitudes are tried even if the two flights in conflict are not separated by altitude when the conflict is detected, (2) the ranges for the candidate altitude clearances are expanded by a default vertical distance of 2,500 ft in both directions, (3) vertical separation is not required for the entire duration of the prediction, so horizontal separation also needs to be tested, and (4) a record is kept of the altitude pair that produces the maximum predicted separation ratio so it can be used if the conflict cannot be resolved. (Heading resolution will be available when altitude resolution fails, but because this paper focuses on altitude resolution only, the best altitude maneuver will be selected even if it fails to resolve the conflict.)

In some cases, a pair of step altitudes are found to resolve a conflict when the same pair of altitudes failed as temporary altitudes. That is because temporary altitudes were implemented in TSAFE to require sufficient vertical separation for the entire duration of the prediction, whereas step altitudes require sufficient vertical separation only when horizontal separation is insufficient.

Figure 9 shows an example of an operational error that was resolved in simulation by a step altitude amendment. The top plot shows the original, unmodified groundtracks. Aircraft 1 (AC1), represented by the solid line, was an MD80 arrival heading approximately east. Aircraft 2 (AC2), represented by the dashed line, was an B727 departure heading approximately northwest at an encounter angle of approximately 135 deg with AC1. As before, the circles are five nmi in diameter at LoS, and the "+" symbols are approximate minute markers. The gray lines represent the flightplan route of the trajectory represented by the same line type (solid or dashed). Both flights were out of conformance with their flightplan routes, but AC2 was converging to its planned route when it was told to turn right 30 deg at −1:22. AC1 had been told to turn to heading 170 deg, a large right turn, at −1:14. The minimum separation ratio was 0.73 in this case (3.65 nmi at 1000 ft). (This case occurred before Reduced Vertical Separation Minimum (RVSM) was activated,



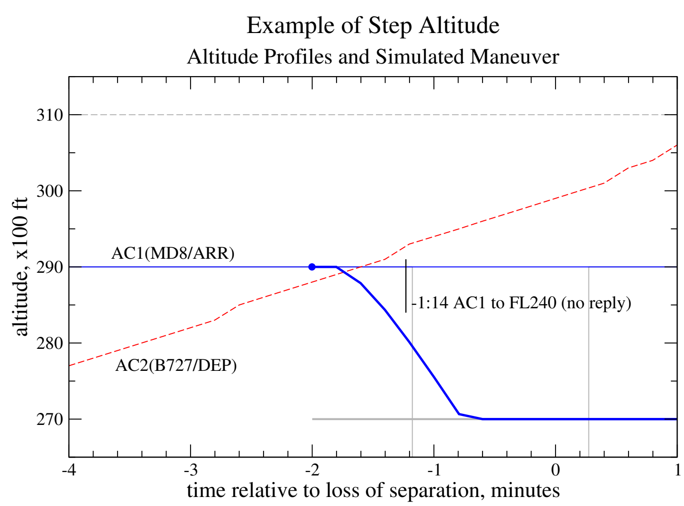


Figure 9. Groundtracks (top) and altitude profiles (bottom) for a sample operational error with conflict resolution by step altitude (minimum separation ratio 0.73)

which will be referred to as "pre-RVSM," hence the altitude separation standard was 2000 ft above FL290 and 1000 ft below.)

The bottom plot of Fig. 9 shows the altitude profiles and the simulated resolution maneuver. AC1 was flying level at its cleared altitude of FL290, and AC2 was climbing through FL290 to its cleared altitude of FL310. Some communication problems occurred in this case, and when the controller told AC1 to descend to FL240 at −1:14, the pilot did not respond. (The vertical gray line a few seconds after that voice clearance represents the entry of the corresponding altitude amendment into the Host, and the later gray line indicates that the controller set the altitude back to FL290.) The thick gray horizontal line starting at −2:00 at FL270 represents the simulated step altitude amendment, which descended AC1 by 2000 ft to resolve the conflict. The thick, dark solid line originating at −2:00 on the altitude profile of AC1 represents the resolution maneuver.

Figure 10 shows another operational error that was resolved in simulation by a step altitude amendment.

The top plot shows the original, unmodified groundtracks. Aircraft 2 (AC2), represented by the dashed line, was heading northwest and converging with its flightplan route. Aircraft 1 (AC1), represented by the solid line, was heading southeast well off its planned route when, at –2:31, it was told to fly heading 160 deg. The reason for that heading vector was not given in the official report, but it brought the two flights into conflict. As usual, the circles are five nmi in diameter at LoS, and the "+" symbols are approximate minute markers. The gray lines represent the flightplan route of the trajectory represented by the same line type (solid or dashed). The separation ratio was 0.67 in this case (3.35 nmi at 600 ft).

The bottom plot of Fig. 10 shows the altitude profiles and the simulated maneuver. AC2 was flying level at its cleared altitude of FL260. AC1 was climbing to its cleared altitude of FL260, but the altitude that had been entered into the Host was apparently FL270, as indicated by the gray line at that flight level. In this case, the discrepancy between the altitude cleared by voice and the altitude entered into the Host did not matter, because either altitude put the two flights into conflict. At –0:12, AC2 was told to "expedite to FL250," and at approximately the same time AC1 executed a TCAS Resolution Advisory (RA) to climb, but those maneuvers were too late to avoid the LoS. TSAFE detected the conflict at –1:12 and issued a step altitude amendment for AC1 to FL250, which was simulated as shown by the thick, dark solid line, thereby resolving the conflict. This case shows the effect of the maneuver delay of 10 sec and the altitude acceleration limit of 0.1 g. Although AC2 was not issued an altitude amendment, the simulation took control of it to block the effect of intervention by the controller in response to the original situation. That prevented AC2 from descending, which would have caused the resolution maneuver to fail. (The maneuver simulator always takes control of both flights, even if the cleared altitude is unchanged for one of them, but for simplicity the simulated altitude profile was not shown in the previous altitude plots, because the second flight was not maneuvered later by the controller.)

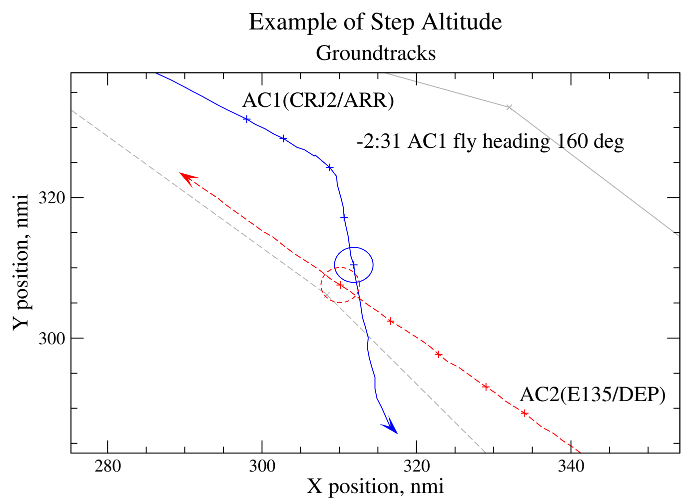
D. Critical-Leveloff Confirmation

In the earlier work on TSAFE conflict detection, approximately one in five of the operational error cases studied were found to be the result of miscommunication of an altitude clearance from controller to pilot. Pilots are required to "read back" each altitude clearance for confirmation, but occasionally they read it back incorrectly and the controller misses the error. In most cases the altitude itself is miscommunicated, but in some cases the callsign is misunderstood or misstated, so the wrong flight accepts the clearance. In yet other cases, the controller either misstates the altitude or enters the wrong altitude into the Host computer, thereby preventing Conflict Alert from detecting the conflict. Each of these cases can be particularly dangerous, because the controller and the pilot are typically unaware of the problem until separation is lost.

Altitude communication errors should be greatly reduced or eliminated when a datalink becomes available to uplink altitude clearances. In the interim, these errors could possibly be reduced by using voice synthesis on the ground to automatically deliver the clearance through existing voice channels. For now, TSAFE has an optional feature to detect situations in which failure to leveloff at the cleared altitude will result in an immediate LoS, as illustrated in Fig. 11. When such a critical leveloff is detected, TSAFE can prompt a reconfirmation of the cleared altitude. The effect of that reconfirmation was simulated in this study. Even if this feature is never used operationally, the following results provide insight into the benefits of a datalink or voice synthesis in reducing human error.

Figure 12 shows the altitude profiles for an example of an operational error that was resolved in simulation by confirmation of a critical leveloff. The groundtracks and separation plots are not shown, but the horizontal encounter angle was approximately 10 deg and the separation ratio was 0.48, which is fairly severe even though the relative velocity was not high in this case. Aircraft 2 (AC2) was flying nominally level at its cleared altitude of FL200. Aircraft 1 (AC1) was climbing through 12,000 ft at –3:40 when the controller entered FL190 into the Host. A few seconds later at –3:33 the controller cleared AC1 by voice to FL230, apparently misstating the intended altitude of FL190. At approximately –1:30, TSAFE detected a critical leveloff at FL190 and issued a confirmation of the cleared altitude. At that point, the maneuver simulator took over and leveled the flight off at FL190, as represented by the thick, dark curve starting at the dot, thereby preventing the LoS.

Figure 13 shows the altitude profiles for another operational error that could have been avoided by confirmation of a critical leveloff. Again, the groundtracks and separation plots are not shown, but the horizontal encounter angle was approximately 100 deg and the separation ratio was 0.36 (1.8 nmi at 100 ft), which is severe. Aircraft 2 (AC2) was flying level at its cleared altitude of FL220. Aircraft 1 (AC1) was descending through FL250 at –2:20 when the controller entered FL230 into the Host. A few seconds



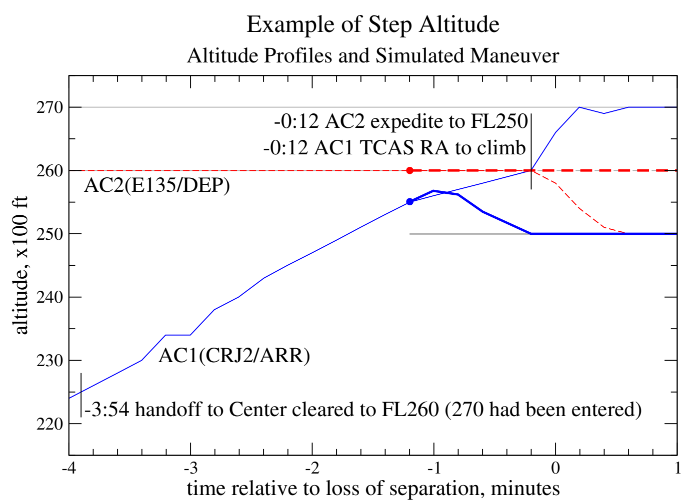


Figure 10. Groundtracks (top) and altitude profiles (bottom) for another sample operational error with conflict resolution by step altitude (separation ratio 0.67)

earlier at −2:25 the controller had cleared AC1 by voice to FL210, again apparently misstating the intended altitude. At approximately −1:10, TSAFE detected a critical leveloff at FL230 and issued a reconfirmation of the cleared altitude. At that point, the maneuver simulator took over and leveled the flight off at FL230, as represented by the thick, dark curve starting at the dot, preventing the LoS.

IV. Augmented Altitude Amendments

For some of the archived operational error cases, the conflict could not be detected by TSAFE (or any other ground-based automated system) in time to resolve it, because the necessary information was not available. The missing or erroneous information is usually a cleared altitude for which the controller either did not enter an altitude amendment or entered it incorrectly. The problem could also be an altitude clearance that was misunderstood by the pilot. In some of those cases, the critical-leveloff-confirmation

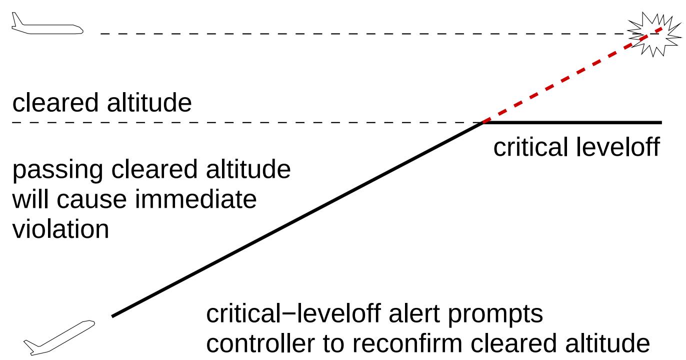


Figure 11. Illustration of a critical leveloff

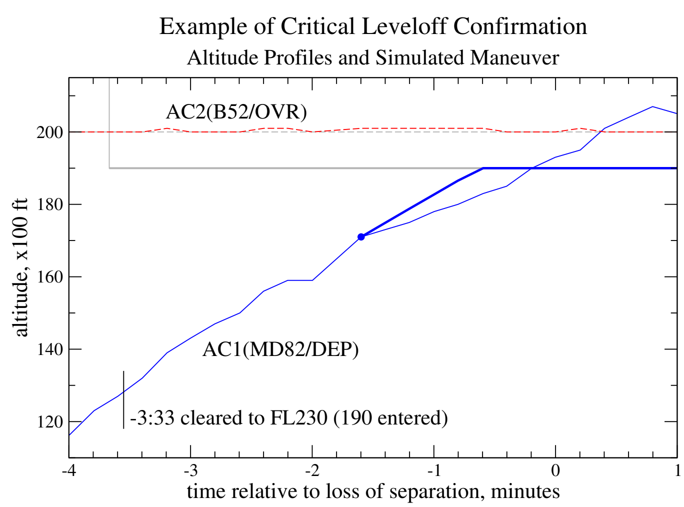


Figure 12. Example of critical-leveloff confirmation (horizontal encounter angle approximately 10 deg; separation ratio 0.48)

method discussed earlier can prevent the LoS, but in other cases even that cannot prevent it.

Because such conflicts cannot be detected early enough to resolve them, the idea of an "augmented" altitude amendment was conceived. The idea is to determine what would have happened had TSAFE known the correct flight level at which the pilot intended to level off. Several operational error cases were found that could benefit from such augmented amendments, and the amendments were manually inserted into the input file. Such additions were clearly identified and distinguished from real altitude amendments, and a switch was provided to use them or not. Hence, the benefits derived from them will be clearly identified, and they can be used to highlight the importance in the future of guaranteeing that the pilot and TSAFE have consistent and correct inputs. In the future, aircraft equipped with ADS–B (Automatic Dependent Surveillance – Broadcast)[10] will broadcast intent information (including altitude intent), and the augmented altitude amendments in effect simulate the use of that information by TSAFE.

Figure 14 shows an example of an operational error in which an augmented altitude amendment was used. The groundtracks are not shown, but both flights were following their planned routes closely, and the horizontal encounter angle was approximately 45 deg. The separation ratio was 0.30 (0.89 nmi at 300 ft), which is severe. The two flights were level within tolerance (±200 ft) of their cleared altitudes at adjacent

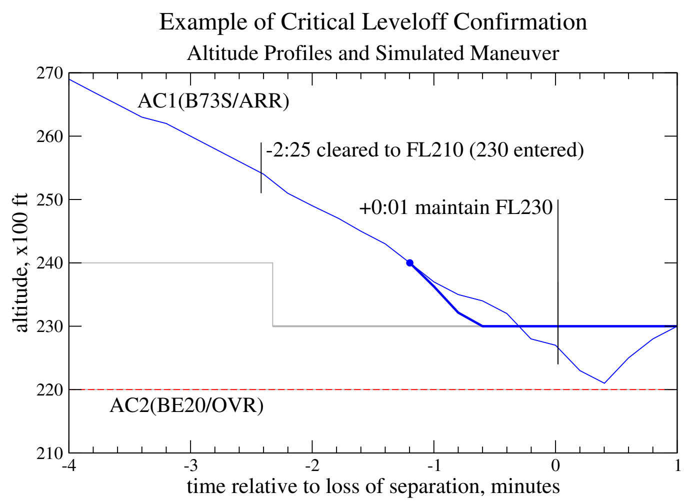


Figure 13. Another example of critical-leveloff confirmation (horizontal encounter angle approximately 100 deg; separation ratio 0.36)

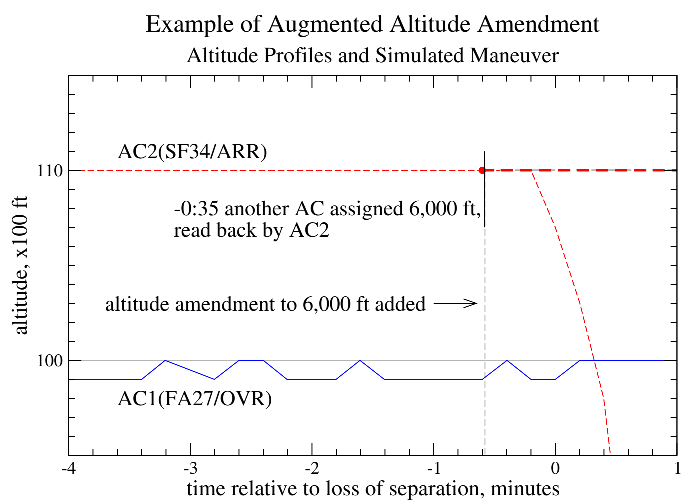


Figure 14. Example of augmented altitude amendment (horizontal encounter angle approximately 45 deg; separation ratio 0.30)

flight levels. At –0:35, a clearance to 6,000 ft issued to a third flight was erroneously accepted and read back by AC2, and the controller did not notice the mistake. When AC2 descended a few seconds later, an immediate and severe LoS resulted.

With no knowledge of the pilot's intent to descend, TSAFE could not predict this conflict in time to resolve it, nor would any other ground-based alerting system be able to do so. But what if TSAFE somehow knew that the pilot of AC2 intended to descend? To answer that question, an augmented altitude amendment to 6,000 ft was added. The result is that TSAFE immediately detected the conflict and blocked the amendment. The simulation then took control of the flight and kept it level at the original cleared altitude, thereby preventing the LoS.

Figure 15 shows another operational error in which an augmented altitude amendment was used. The

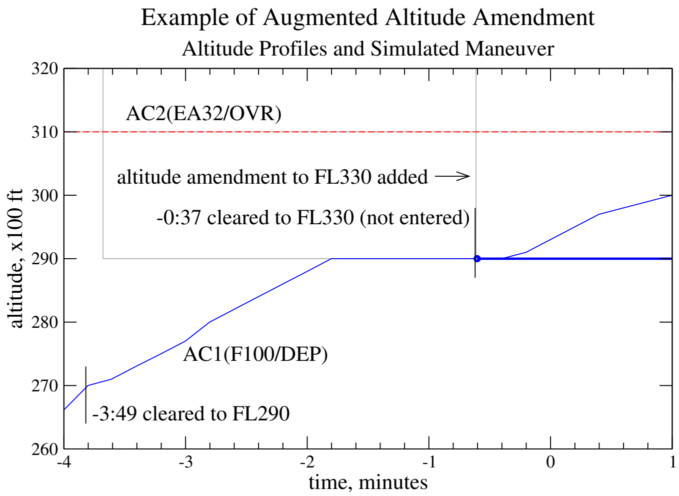


Figure 15. Example of augmented altitude amendment (horizontal encounter angle approximately 135 deg; separation ratio 0.75)

groundtracks are not shown, but both flights were following their planned routes closely, and the horizontal encounter angle was approximately 135 deg. The separation ratio was 0.75 (3.75 nmi at 1500 ft, pre-RVSM). AC2 was flying level at its cleared altitude of FL310. AC1 had leveled off after climbing to its cleared altitude of FL290. At –0:37, the controller issued a voice clearance to FL330 for AC1 but neglected to enter an altitude amendment into the Host. Separation was lost immediately after AC1 climbed past 200 ft above FL290.

Again, with no knowledge of the pilot's intent to climb, TSAFE could not predict this conflict in time to resolve it. To simulate what would have happened had an altitude amendment been properly entered by the controller, an augmented altitude amendment to FL330 was added at the same time as the voice clearance. It is represented by the gray line going up to FL330 (off the plot). As in the previous example, TSAFE immediately detected the conflict and rejected the altitude amendment. As before, the simulation then took control of the flight and kept it level at the original cleared altitude, preventing the LoS.

V. Results

The vertical resolution methods outlined above were tested on the entire archived set of 100 randomly selected operational error cases. Setting up these cases for detailed analysis and batch runs was very time consuming. Although much more testing is certainly needed before the methods proposed in this paper can be considered ready for operational implementation, these tests provide a level of operational realism that would be difficult to match by pure simulation.

Actual operational error cases tend to be more difficult to detect and resolve than routine conflicts that get resolved successfully, so the results to be presented should not be considered representative of routine operations. Note also that 57 of the 100 archived operational error cases occurred before RVSM was activated, and 29 of those occurred above FL290. Because the vertical separation requirement for those cases was 2,000 ft rather than 1,000 ft, resolution by altitude is more difficult.

Figure 16 shows plots of the cumulative separation ratios, which will be explained in the following paragraphs. Table 1 shows selected points from those plots for convenience. The row of Table 1 labeled "no resolution" shows the baseline results before conflict resolution was attempted. The second column from the

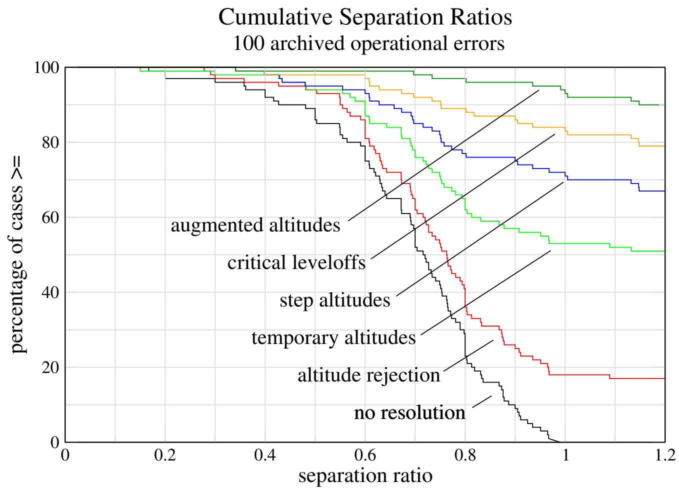


Figure 16. Cumulative separation ratio as percentage of archived operational error cases

right shows that 0% of cases had a separation ratio greater than or equal to 1.0, meaning that separation was lost in all cases (as required by the definition of an operational error). The third row from the right shows that 29 of the 100 cases had a separation ratio greater than or equal to 0.8, and so on, in increments 0.2 in separation ratio. (No collisions occurred, so all separation ratios were greater than zero.)

	separation ratio (≥), %					
	0.2	0.4	0.6	0.8	1.0	1.2
no resolution	99	94	75	29	0	0
altitude rejection	100	96	81	41	18	17
temporary altitudes	100	98	87	65	53	51
step altitudes	100	98	93	77	72	67
critical leveloffs	100	98	97	89	84	79
augmented altitudes	100	99	99	97	94	90

Table 1. Cumulative separation ratio as percentage of archived operational error cases

For the first test, the archived set of operational error cases was run with altitude-amendment rejection only. The results are given in the row labeled "altitude rejection" in Table 1 and the corresponding curve of Fig. 16. The second column from the right shows that for 18% of cases the separation ratio was greater than or equal to 1.0. In other words, 18 of the 100 cases were resolved successfully in the simulation using altitude-amendment rejection only. The second column from the right shows that 41% of cases had a separation ratio greater than or equal to 0.8, and so on. The right column shows that 17 of the 18 cases that were resolved had a separation ratio of 1.2 or greater. Whereas a separation ratio of 1.0 is right on the edge, this 20% buffer or margin adds robustness to error in trajectory prediction.

For the next test, the set of operational errors was run with temporary altitudes in addition to altitude-amendment rejection. The results are given in the row labeled "temporary altitudes" in Table 1. The second column from the right shows that 53 of the 100 cases were resolved successfully in the simulation. The third column from the right shows that 65% of cases had a separation ratio greater than or equal to 0.8, and so on. The right column shows that 51 of the 53 resolved cases had a 20% or greater margin in separation ratio.

Step altitude maneuvers were added next, and the results are shown in the row labeled "step altitudes."

The right column shows that 72% of cases were resolved in simulation using altitude rejection, temporary altitudes, and step altitudes. Of those, 67 cases had at least a 20% margin in separation ratio.

When critical-leveloff confirmation was added, 84% of the operational error cases were resolved, as shown in the row labeled "critical leveloffs." Of those, 79 had at least a 20% margin in separation ratio.

Finally, when augmented altitude amendments were added, the number of successful resolutions in simulation rose to 94%, as shown in the row labeled "augmented altitudes." As explained earlier, augmented altitude amendments are added to the input file to tell TSAFE the flight level at which the pilot intended to level off in cases where the controller either neglected to enter it or entered it incorrectly. Of those cases, 90 had at least a 20% margin in separation ratio.

In eight of the 100 cases, a third flight in the vicinity of the encounter forced the selection of another altitude amendment different than the altitude that was selected based on the original pair alone. In no case, however, did a third flight actually prevent resolution of the conflict.

The conflicts that were not successfully resolved were all detected late and involved two flights that were either flying level at the same altitude or were close to the same altitude when the conflict was detected. Figure 17, for example, shows a case of two merging arrivals flying level at 8,000 ft and approaching the southeast arrival fix of the TRACON (Terminal Radar Approach Control, the approximate boundary of which is indicated by the dotted lines in the upper left corner of the plot). Both flights were far off of their planned routes, which are represented, as before, by the gray lines on the groundtrack plot. Aircraft 2 (AC2) was apparently rerouted to the southeast arrival corner of the TRACON, but it was not spaced far enough behind aircraft 1 (AC1) to maintain the required separation. A speed maneuver could have been used to slow AC2 and resolve the conflict, but only vertical maneuvers were allowed in this study. As earlier, the thick lines beginning at the dot at approximately –0:24 represent the simulated maneuvers. The altitude plot shows that TSAFE issued step altitude amendments to 7,000 and 9,000 ft, but the conflict was detected too late to be resolved vertically. This conflict was detected late because separation was lost only slightly, and also because speed is difficult to estimate accurately due to radar noise (which is very bad in this case, as is evident by the "kinks" in the groundtracks).

The other five unresolved conflicts involved flights at or near the same altitude, in which one or both of the flights are in a holding pattern. These conflicts tend to be detected late because the holding patterns are not currently indicated or represented in any way in the Host computer, so as far as TSAFE (or any ground-based conflict detection system) is concerned, they are unexpected or unplanned turns. Improved methods for detecting conflicts involving holding patterns are being developed for TSAFE, but they are outside the scope of this paper. Even without those methods, horizontal turn maneuvers should be able to resolve at least some of the unresolved cases, but those are also beyond the scope of this paper.

Finally, to get an indication of the sensitivity to pilot delay, the simulated delay of the pilot reaction to an altitude clearance was changed from its nominal value of 10 sec to 15 sec. With all vertical resolution methods and augmented altitude amendments in use, the number of successfully resolved conflicts dropped by two from 94 to 92.

VI. Conclusions

Several procedures have been introduced in this paper for tactical conflict resolution using vertical maneuvers in enroute airspace. These procedures build on the conflict detection capability of TSAFE (Tactical Separation Assured Flight Environment), which was presented in earlier papers. TSAFE computes simple resolution maneuvers, such as altitude or heading changes, when it predicts loss of separation to occur within two minutes. It is intended as a backup for a more complex, strategic system that attempts to detect and resolve conflicts up to 20 minutes in advance.

The focus of this paper was restricted to altitude maneuvers, which were tested on archived tracking data for 100 actual operational errors. A basic simulation that modeled climb and descent rates, maneuver delay, and a vertical acceleration limit was used to test the effectiveness of the TSAFE resolution maneuvers.

The vertical resolution procedures presented and tested in this paper included the rejection of altitude amendments that are predicted to cause a conflict, temporary altitudes, step altitudes, and reconfirmation of critical leveloffs. Those methods were able to resolve 84 of the 100 archived operational error cases in simulation.

In some cases, conflicts cannot be detected in time to resolve them because the controller either neglected to enter an altitude amendment or entered it incorrectly. Augmented altitude amendments were added to

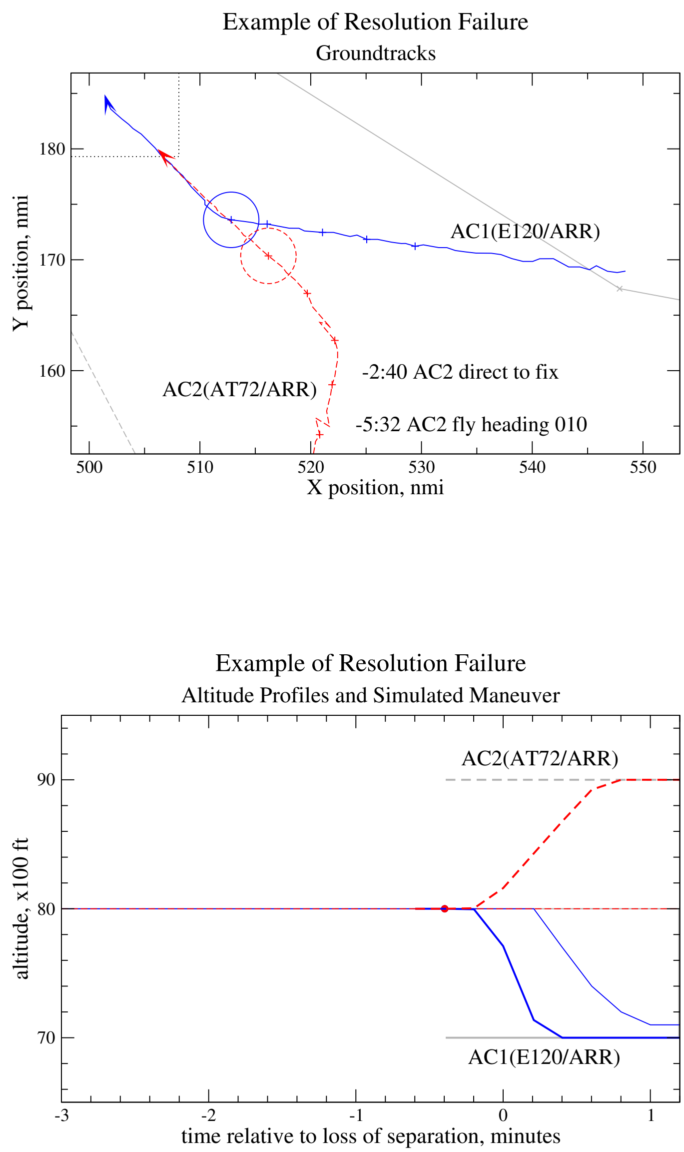


Figure 17. Groundtracks (top) and altitude profiles (bottom) for sample operational error that was not successfully resolved

the input file for several operational error cases to determine what TSAFE could do if it had the necessary information. In effect, this simulates the use of altitude intent information broadcast from the flight deck via ADS-B. The number of successful resolutions increased from 84 to 94 of the 100 cases, clearly showing the value of the broadcast intent information.

Operational error cases tend to be more difficult to resolve than routine encounters that get resolved successfully, so these results should not be considered representative of routine operations. Much more testing is needed before the methods presented in this paper can be considered ready for operational implementation, but the results presented here are a good first step toward establishing operational credibility. In future work, horizontal resolution methods will be developed and tested, primarily turns to a specified heading or course angle.

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