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Relative Significance of Trajectory Prediction Errors on an Automated Separation Assurance Algorithm

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***Abstract*— Trajectory prediction is fundamental to automated separation assurance. Every missed alert, false alert and loss of separation can be traced to one or more errors in trajectory prediction. These errors are a product of many different sources including wind prediction errors, inferred pilot intent errors, surveillance errors, navigation errors and aircraft weight estimation errors. This study analyzes the impact of six different types of errors on the performance of an automated separation assurance system composed of a geometric conflict detection algorithm and the Advanced Airspace Concept Autoresolver resolution algorithm. Results show that, of the error sources considered in this study, top-of-descent errors were the leading contributor to missed alerts and failed resolution maneuvers. Descent-speed errors were another significant contributor, as were cruise-speed errors in certain situations. The results further suggest that increasing horizontal detection and resolution standards are not effective strategies for mitigating these types of error sources.**

Keywords*— *Separation Assurance, Trajectory Prediction, Prediction Errors, Separation Management

I. Introduction

Prediction of the future state and trajectory of an aircraft is central to many concepts being proposed to improve the efficiency and safety of the air transportation system. Accurate trajectory prediction plays an especially important role in automated concepts for separation assurance because it allows for reliable prediction of future losses of separation and for creation of safe resolution trajectories. Unfortunately, there will always be errors in any predicted trajectory since the model used to generate this prediction is only an approximation of the aircraft and the environment through which it is flying. Independent causes of the error of any trajectory prediction include, among many other things, a lack of accurate knowledge of the winds aloft, only partial information about how a pilot will execute any given maneuver, errors in the surveillance of the aircraft position and velocity, and inaccurate information about the weight and performance of the aircraft [1]. It is important to understand how robust an automated separation assurance system is to these prediction errors.

In the past there have been studies of the accuracy of specific trajectory predictors as compared to flight data [2, 3] as well as the effects of this accuracy on the performance of some decision support tools [4, 5]. These are, in general, studies conducted to evaluate how a specific design performs under specific types and levels of uncertainty. There have also been more general mathematical analyses of the effects of uncertainty on conflict detection and resolution [6, 7], but these either make limiting assumptions about the types of conflicts encountered or focus on detection only. An initial study of the effects of multiple cruise-speed errors on both conflict detection and resolution has been performed [8] using realistic conflict scenarios and high levels of cruise-speed prediction errors.

The purpose of the current study is to analyze the performance of an automated separation assurance system under the presence of various types and values of trajectory prediction error using realistic aircraft trajectories. Both detection alone and detection and resolution using the Advanced Airspace Concept Autoresolver [9] resolution algorithm are studied. The different prediction error sources to be analyzed are: wind prediction errors, cruise-speed errors, aircraft weight errors, top-of-descent prediction errors, descent-speed errors, and maneuver-initiation-time errors. These six trajectory prediction error sources affect trajectory prediction accuracy in multiple ways creating along-track, lateral and altitude errors.

This study is novel in that the different error sources are compared relative to each other for multiple different amounts of error and using the same baseline enabling a direct comparison of the effects of each source. Also, the simulation environment allows for precise definitions of missed and false conflict alerts. This study showed, among other things, that top-of-descent errors were the leading contributor to missed alerts and failed resolution maneuvers and that descent-speed errors were another significant contributor to these errors.

Section II will discuss the simulation environment used for this study. Section III discusses how the errors are modeled in this environment. The experiment setup is discussed in Section IV, and Section V presents the results for both the conflict detection algorithm alone and the separation assurance system composed of the detection algorithm and the Autoresolver.

II. Simulation Environment

For this study, the Airspace Concept Evaluation System (ACES) [10] was used to simulate the United States National Airspace System (NAS). The separation assurance algorithm evaluated in this simulation environment was the Advanced Airspace Concept [11] Autoresolver [9].

A. *Test Bed*

ACES is a non-real time simulation of the NAS that creates four-degree-of-freedom trajectories based on the aircraft performance models from the Base of Aircraft Data (BADA) [12] from departure fix to arrival fix. The routes and departure times for the aircraft in the simulation are derived from the actual routes flown on a specific day in the NAS.

In the base implementation of ACES the predictions of all aircraft states have zero error as compared to the trajectory that the simulated aircraft flies because both the trajectory predictor and the simulated aircraft use the same equations of motion and input data. Section III discusses modifications made to the trajectory prediction capability of ACES to include the different sources of trajectory prediction error for this study.

B. *Conflict Detection*

There are multiple types of conflict detection algorithms which could be used including geometric and probabilistic methods [13]. For this study, a basic geometric conflict detection algorithm, assuming all future intent is known, will be analyzed.

The predicted trajectories used for this process are composed of future latitude, longitude, and altitude values for the aircraft every five seconds up to a specified time. Points at the same future time for different aircraft are compared against each other to determine if the aircraft are within the prescribed distance and altitude for a predicted loss of separation.

In addition to this base conflict detection scheme, a horizontal detection buffer, Figure 1, can be used to extend the separation protection area and make the algorithm more robust to trajectory prediction errors. Increasing this detection buffer can lead to fewer missed conflicts and more separation between aircraft but also may result in more false alerts. No vertical buffers were included for this study.

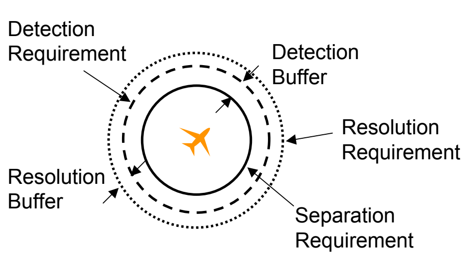


Figure 1: An illustration of the required separation standard and the detection requirement including buffer and the resolution requirement including buffer.

C. *AAC Autoresolver*

The Advanced Airspace Concept (AAC) is a concept for automating separation assurance in the future. A key feature of this concept is the use of multiple independent layers of separation assurance for increased reliability. One component of AAC is a strategic problem-solving tool known as the Autoresolver [9]. This algorithm was originally developed in the ACES environment taking full advantage of the zero-error trajectory prediction available, and many studies of the effectiveness of this algorithm in the zero-uncertainty environment have been performed [14]. It has also been integrated with, and evaluated in, other NAS simulations which have non-zero trajectory prediction errors [15–17].

The AAC Autoresolver uses an iterative approach to resolve all of the conflicts found by the conflict detection system. The algorithm attempts to generate many different types of resolutions for any conflict. The set of resolutions can include multiple horizontal, multiple vertical, and multiple speed resolutions. After the resolution trajectories have been generated, the successful resolution expected to impart the minimum airborne delay is chosen for implementation.

There are many different parameters of the Autoresolver that can be adjusted to mitigate the effects of uncertainty including a resolution buffer, an action time for conflicts, and a required clear time for resolutions. The resolution buffer (Figure 1) is the additional radius outside of the detection range that a resolution attempt must be clear of in order for it to be considered successful. This resolution buffer is designed to reduce the possibility of a conflict reoccurring, but a larger resolution buffer can cause greater average delays [18]. The action time for conflicts is a maximum look-ahead time which if a conflict is predicted outside this time, no action is taken. This look-ahead time is typically around 8 minutes, and limiting this time can reduce the number of false alerts acted upon by the system. The time for which a resolution must be clear of predicted conflicts is a similar parameter, and it is usually set to 12 minutes. This value should not be too long because there may be too many false alerts due to prediction errors.

III. Trajectory Prediction and Errors

In ACES, the exact same differential equations are used to propagate the state of the aircraft forward and to create predictions of its future trajectory for conflict detection and resolution. This allows for predictions with zero error, and modifications to this architecture allowing for small changes to the states of these equations allow for the trajectory prediction uncertainty to be varied smoothly from zero to any reasonable value. Typically, at each conflict detection and resolution cycle a single exact copy of these equations is made and used to create the trajectory prediction for that aircraft. For the current study, two copies of the equations were created; one of them was perturbed while the other was not. The unperturbed equations provided a base of perfect knowledge of how the aircraft would maneuver, while the perturbed equations were used for conflict detection and resolution. An explanation of the different types of errors and how they were implemented in ACES follows. The values used for the simulations are also discussed.

A. *Wind Prediction Errors*

To simulate wind prediction errors, two different wind fields are used. One is used to propagate the actual flight and one is used for conflict detection and resolution. The two wind fields differ only in terms of magnitude, not direction. The uniform wind error magnitudes studied were +10%, -10%, and +25%. The +10% error case indicates that for trajectory prediction a wind 110% of the actual wind was used. These values are within the range of errors found in a study of the accuracy of Rapid Update Cycle (RUC) 2 wind predictions [19].

B. *Cruise-Speed Errors*

To simulate cruise-speed prediction errors the cruise speed of the aircraft is perturbed for predicted trajectories. For the cruise-speed error simulations, a unique cruise-speed error was assigned to each aircraft and used for the entire simulation. This error was sampled randomly from a uniform distribution, and two different uniform distributions were used for different simulations; one from -2% to +2% and one from -5% to +5%. These cruise-speed errors are approximately the same as those seen in [20].

C. *Aircraft Weight Errors*

Aircraft weight errors are simulated by using two different weights for the actual and flown trajectories. In the simulation, the applied perturbation value is applied to the fuel weight only. So, a perturbation of +20% means that the fuel weight of the aircraft is increased by 20% to create the predicted trajectories.

The fuel weight error percentage was assigned to each aircraft for the entire simulation. This percentage was sampled from one of two uniform distributions, either $\pm10\%$ or $\pm20\%$ depending on which error case was being studied. These fuel weight errors produce overall aircraft weight errors in line with values examined in [1].

D. *Top-of-Descent Errors*

To determine the top-of-descent point for an aircraft, ACES determines an approximation of the descent slope based on the aircraft type, weight, cruise speed, and cruise altitude. To vary the top-of-descent point this descent slope approximation is perturbed by increasing or decreasing this slope by an angle sampled from a uniform distribution. Varying this slope only affects the point of top of descent. It does not affect the actual flown descent rate.

The increase or decrease in the approximate glide slope is applied per aircraft, and the distributions used for the simulation were $\pm0.3°$ and $\pm0.6°$. This glide slope perturbation resulted in top-of-descent errors of approximately ±5 nmi and ±10 nmi respectively. Errors in this range are similar to those discussed in [1] and [3].

E. *Descent-Speed Errors*

Descent-speed errors are simulated by taking the actual descent Mach and descent calibrated airspeed (CAS) and perturbing them by some value. As for most types of uncertainty in this study the descent-speed uncertainty is sampled from a uniform distribution for each aircraft. Both the descent Mach speed and the descent CAS were perturbed, and they were both sampled independently from the same uniform distribution. Two distributions were used: $\pm5\%$ and $\pm10\%$. These values are in line with the observed values in [20], which noted trajectory prediction descent-speed errors of roughly 7%.

F. *Maneuver-Initiation-Time Errors*

To simulate the lack of precise knowledge of when a commanded maneuver will be executed, a nominal execution time is used for resolution maneuvers. Since it takes a somewhat uncertain amount of time for a maneuver message to be communicated to a pilot and for the pilot to act upon that message, the actual maneuver initiation time can be different than the nominal, assumed maneuver initiation time. For the next conflict detection cycle, if the aircraft has initiated the commanded maneuver, then the actual trajectory is used. If the aircraft has not started to maneuver yet, but it is before the nominal maneuver start time, then the nominal start time is used. Finally, if the aircraft has not started maneuvering and it is after the nominal start time, then it is assumed for detection and resolution purposes that the aircraft will start the maneuver immediately.

Based on the data presented in [21], for each maneuver that was executed, a nominal maneuver initiation time of 40 seconds for vertical and speed resolutions and 55 seconds for horizontal resolutions was assumed. Two actual maneuver-initiation-time error situations were studied, one with a broad variation in maneuver initiation time and one with a narrow spread in maneuver initiation time. For the broad variation case, a uniform distribution from 25 to 105 seconds is used for the horizontal maneuver actual start times, and a uniform distribution from 20 to 60 seconds is used for vertical and speed resolutions. For the narrow variation case the uniform distributions are 40 to 80 seconds for horizontal resolutions and 30 to 50 seconds for vertical and speed maneuvers.

IV. Experiment Setup

To compare the effects of different types of trajectory prediction errors on the performance of a separation assurance system composed of a geometric conflict detection algorithm and the AAC Autoresolver, the problem was decomposed into two related studies for each of the error types: a conflict detection study and a conflict resolution study.

A. *Conflict Detection Study*

The purpose of the conflict detection study was to compare the effects of the different types of trajectory prediction errors on a geometric conflict detection algorithm and to determine how effective a horizontal detection buffer is at mitigating these effects. To accomplish this, ACES was run without the

Autoresolver to allow every case to have the same conflicts. The required separation standard was 5 nmi horizontally and 1000 ft vertically, and for each error source, two simulations where performed, one with no detection buffer and one with a 2 nmi detection buffer. Since the Autoresolver was not used for this study, there were no conflict resolutions issued, and maneuver-initiation-time errors could not be studied. The other five errors were studied.

A geometric conflict detection scheme with no buffer will perfectly predict all conflicts in situations where there is no trajectory prediction error, so any conflict prediction errors in the no-buffer cases are purely a result of the trajectory prediction errors and represent the characteristics of that error source. Comparing each 2 nmi buffer case with the corresponding no-buffer case shows the relative ability of a horizontal detection buffer to compensate for each specific type of trajectory prediction error.

For each conflict detection cycle, two predicted trajectories were created for each aircraft: one perturbed and one unperturbed. The perturbed trajectories are compared against each other and if any two trajectory points from different trajectories come within the *detection requirement* distance of each other they are flagged as "in conflict". The unperturbed trajectories are also compared against each other to determine if any two trajectories come within the *separation requirement* distance of each other. If a conflict is predicted using the unperturbed trajectories, but it is not predicted using the perturbed trajectories, then this is a missed alert. On the other hand, if a conflict is predicted using the perturbed trajectories but it is not predicted using the unperturbed trajectories, then that conflict is a false alert. It is important to reiterate that when a detection buffer is used, for the unperturbed trajectories, a loss is defined by the actual separation standard, but for the perturbed trajectories a loss is based on the larger detection standard.

A flight data set with three hours of traffic from the peak traffic time of April 21, 2005 was simulated for the entire NAS. This data set had over 9000 flights in it, and there were over 5500 flights in the air at the peak. The conflict-detection function was run for all traffic across the entire airspace once every minute in the simulation.

B. *Conflict Resolution Study*

The conflict resolution study helps determine how the combination of the conflict detector and the resolver performs for the different trajectory errors. For this study, the AAC Autoresolver was active and resolving conflicts with a look-ahead time of 8 minutes for primary conflicts. All proposed resolution trajectories were required to be clear of conflicts for at least 12 minutes. These two parameters are related to the uncertainty of the trajectory prediction, but for this study they were held fixed.

The conflict detection buffer was used for these runs and set at 1 nmi for all cases. Conflict detection and resolution generation were performed every minute. The conflict resolution buffer was set to 0, 1, or 2 nmi. The same flight demand set was used for both the conflict detection study and the conflict resolution study. The 42 ACES runs encompassing all of the error cases as well as the baseline cases allowed for a comparison of the relative effects of each type of error on the resolution efficiency.

V. Results

The two different studies were performed to provide a parametric understanding of the effects of the different types of trajectory prediction errors on both conflict detection and conflict resolution performance. The results of these two studies are presented in the next two sections for the six different types of errors.

A. *Conflict Detection*

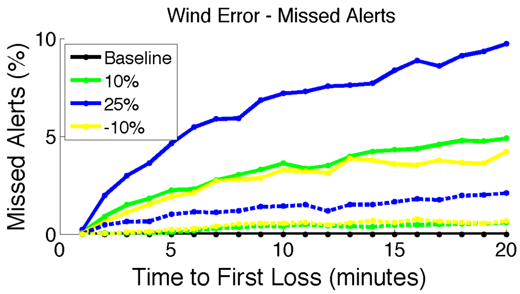
The main metrics for conflict detection are the percentage of missed alerts and the percentage of false alerts as defined in Section IV.A. These metrics are shown as a function of time before loss of separation for the different error types below and for two different conflict detection radii. In the figures, solid lines show the results for no conflict detection buffer (see Figure 1), and the dotted lines show the results for conflict detection with a 2 nmi horizontal buffer. Characteristic features of the effects of each type of error are discussed.

1) *Wind Errors*

The results of simulating wind errors of 10%, -10%, and 25% are compared to the baseline with no error in Figure 2. Figure 2(a) shows the percent of conflict detections which are missed as functions of time until first loss. Interestingly the results for +10% perturbation, which correspond to using winds 110% of the magnitude of the actual winds for conflict prediction, are very similar to the -10% perturbation, which corresponds to using winds 90% of the magnitude of the actual winds.

The results for the no-buffer case show that the wind errors increase mostly linearly as a function of time to first loss of separation and the largest wind error results in about 8% of the alerts being missed at 10 minutes before the loss of separation. Using a horizontal conflict detection buffer of 2 nmi reduces the missed alerts from about 8% to less than 2% at 10 minutes before the loss of separation. The detection buffer is even more effective for the smaller perturbation case resulting in less than 0.5% of the conflicts being missed. It is reasonable that the horizontal detection buffer is effective for wind errors because they largely affect aircraft in the along-track direction instead of affecting the vertical profile.

Figure 2(b) shows that the false alert percentage is affected by the wind prediction error for the no-buffer case, but when the buffer is included, the wind errors do not have much impact on false alerts. The large increase in false alerts between the no-buffer case and the 2 nmi buffer case is expected because more airspace is protected with the horizontal buffer.



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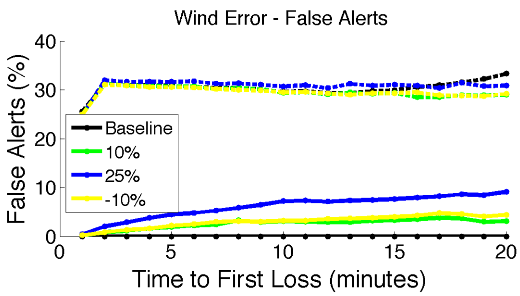


(b)

Figure 2: The results for wind prediction errors where solid lines represent no detection buffer and dotted lines represent a 2 nmi buffer. Percentage of (a) missed alerts and (b) false alerts as functions of time.

2) *Cruise-Speed Errors*

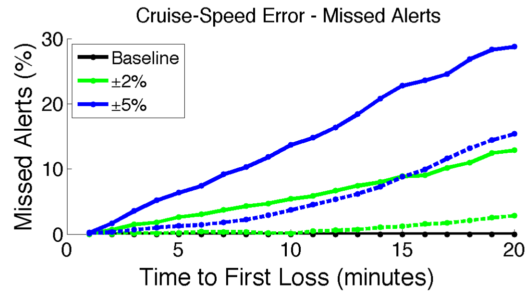
The results for the cruise-speed errors of $\pm 2\%$ and $\pm 5\%$ are shown in Figure 3. It can be seen from Figure 3(a) that the missed alerts are roughly a linear function of the time to first loss for the no-buffer case. The detection buffer is most effective for conflict detection times of less than approximately 8 minutes to first loss. Also, there are significantly more missed alerts caused by cruise-speed errors than due to wind errors. This is probably because wind errors affect nearby aircraft similarly while cruise-speed errors do not. False alerts, shown in Figure 3(b), are a strong function of both time to loss and cruise-speed error in contrast to the wind error simulations.

3) *Aircraft Weight Errors*

In Figure 4(a) the results for missed alerts for aircraft weight errors show an interesting trend. The percentage of false alerts increases as you get further from the loss until about 10 minutes and then it starts to decrease. Weight errors are the only source of trajectory prediction error studied here that mostly impact the beginning portion of the trajectory. Almost all of the longer-term predictions are not affected by weight errors while a larger portion of the nearer-term predictions are impacted by this source of error. This results in the non-monotonic nature of the missed alert results. Weight errors and time do not greatly influence the number of false alerts (Figure 4(b)).

4) *Top-of-Descent Errors*

The descent angle perturbation ranges of $\pm 0.3°$ and $\pm 0.6°$ both lead to significant amounts of missed alerts. For the no-buffer cases the shape of the missed alert curves are similar to



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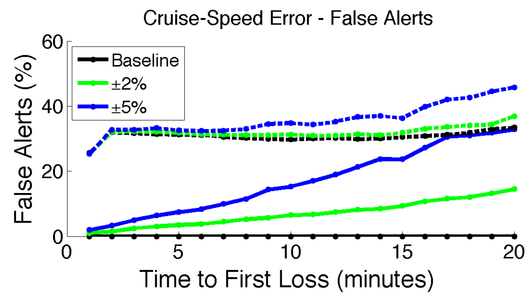

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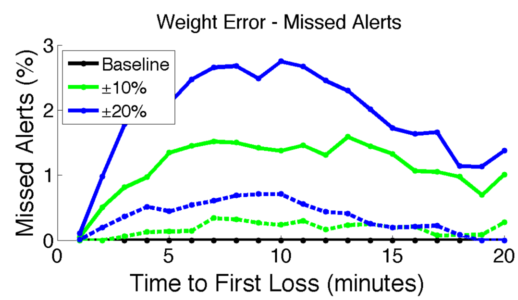
Figure 3: (a) The percentage of missed alerts and (b) false alerts for various cruise-speed errors. Solid lines indicate no detection buffer and dotted lines indicate a 2 nmi buffer.



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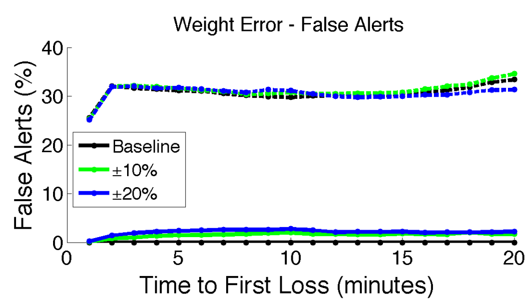
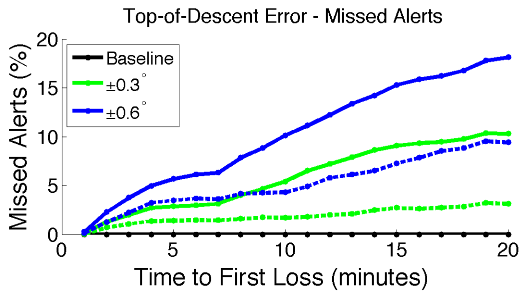


(b)

Figure 4: (a) The missed alerts and (b) the false alerts for aircraft weight errors.

those in the wind error cases, but with a larger percentage of missed alerts. The detection buffer does not lead to a significant reduction in the numbers of missed alerts. This makes sense because top-of-descent errors result in vertical errors in the trajectory, but since the buffer extends in the horizontal plane, the detection buffer is more effective on horizontal errors. False alerts seem to be a relatively strong function of time to first loss and the amount of top-of-descent error. The detection buffer reduced the number of missed alerts, but there are still many conflicts which are difficult to detect until late as indicated by the relatively steep slope of the missed alert curves near one minute to loss. Top-of-descent errors can lead to a moderate increase in the number of false alerts as can be seen in Figure 5(b).



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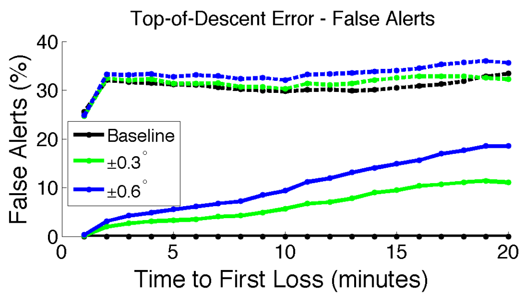


(b)

Figure 5: The missed alerts (a) and false alerts resulting from top-of-descent errors (b).

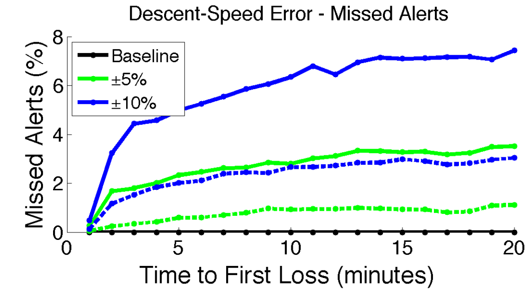
5) Descent-Speed Errors

Descent-speed errors in the range of $\pm5\%$ and $\pm10\%$, Figure 6(a), do not result in as many missed alerts as the top-of-descent error ranges studied. A significant feature of descent-speed errors are that they are not very sensitive to time to first loss. Down to about 1 or 2 minutes to first loss the percentage of missed alerts is still over 5%. This indicates that these types of errors result in losses of separation which are difficult to detect until very close to the loss of separation, and the horizontal buffer does not help much with this problem. Descent-speed errors do not lead to many false alerts (Figure 6(b)).

6) Detection Summary

The percentages of missed alerts for each type of error at 10 minutes and 5 minutes before loss of separation are shown in Figure 7 for the largest error ranges. In Figure 7(a) the values are for no detection buffer, and the error types resulting in the most missed alerts at 10 minutes to loss are top-of-descent errors and cruise-speed errors. At 5 minutes before loss, top-of-descent, cruise-speed, wind and descent-speed errors result in nearly the same percentage of missed alerts.

Figure 7(b) shows the detection results with a 2 nmi detection buffer included. At 10 minutes before loss the relative importance of each type of error is the same as for the no-buffer cases with the percentage of missed alerts generally reduced by about 60%. At 5 minutes before loss, top-of-descent and descent-speed errors have the highest percentage of missed alerts indicating that these two types of errors result in late detections which are not improved by including a horizontal detection buffer. A comparison of false alerts reveal trends similar to the missed alert trends.



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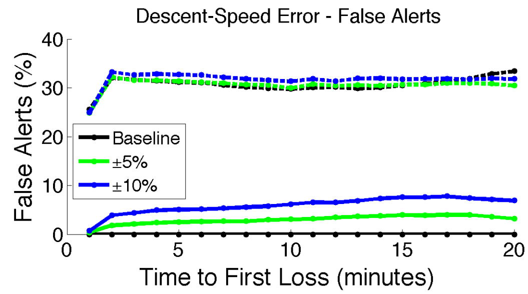

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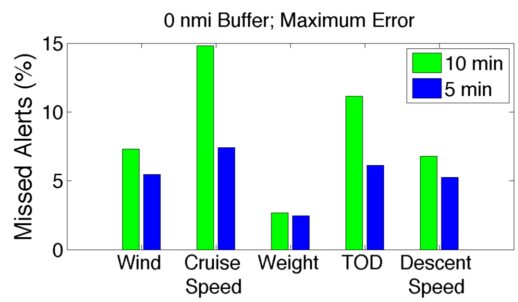
Figure 6: The missed alerts (a) and false alerts (b) for descent-speed errors.



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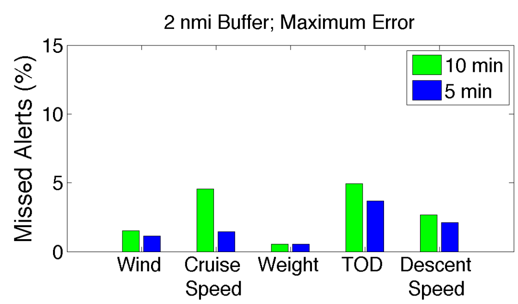


(b)

Figure 7: A summary of the missed alerts at 10 minutes (green bars) and 5 minutes (blue bars) before loss of separation for the largest error ranges and (a) no detection buffer and (b) a 2 nmi detection buffer.

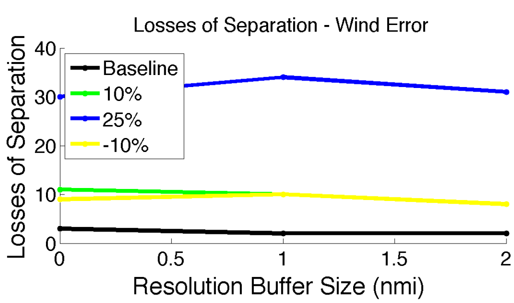
B. Conflict Resolution

For the next studies the AAC Autoresolver was enabled and attempted to resolve any detected conflicts. The Autoresolver made all decisions based on the perturbed trajectories. Three different resolution buffers were studied for all of the different uncertainty ranges. The main metrics computed were the actual losses of separation and the total delay resulting from conflict resolutions. The losses of separation were computed by taking the flown trajectories and comparing them point wise. The delay was computed by comparing the flying time of each aircraft before the resolution and after.

Each simulation is compared against a baseline simulation in which there is no uncertainty. For the baseline cases there are around 25 losses of separation. These losses are artifacts of the ACES simulation environment resulting from aircraft entering the simulation at the simulation boundaries with a very near-term loss of separation. Using this same input with no conflict resolution there are over 1800 losses of separation. The total baseline delay ranged from around 800 minutes to about 1200 minutes depending on the resolution buffer size.

1) Wind Errors

Wind prediction error results are shown in Figure 8. The number of losses of separation, Figure 8(a), are approximately symmetric for +10% errors and for -10% errors. There are not significantly more losses in those cases than in the baseline. For 25% errors there are about twice as many losses of separation than in the baseline case. Increasing the resolution buffer size seems to have a small impact on the number of losses.



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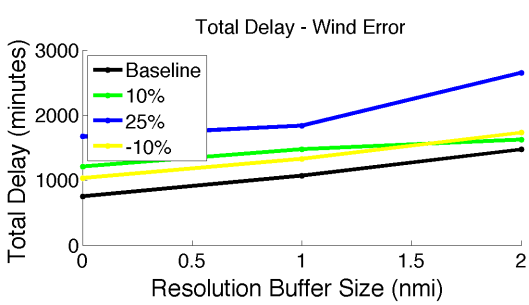


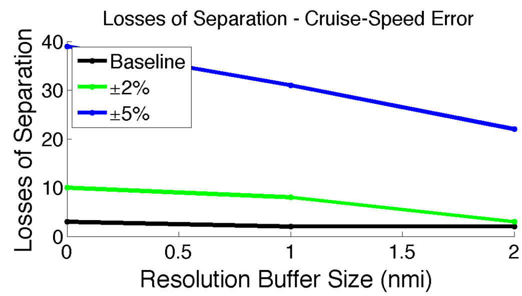
(b)

Figure 8: (a) The number of losses of separation and (b) the total delay in the simulation for a baseline case and three different wind prediction error levels as a function of the resolution buffer size.

Increasing the wind error from the baseline to 25% increases the delay significantly from about 750 minutes to over 1600 minutes (Figure 8(b)). Also, increasing the buffer size increases the total delay from around 1600 minutes to over 2600 minutes in the 25% error case. Additionally, the results for delay seem to be symmetric between the +10% and -10% cases.

2) Cruise-Speed Errors

Cruise-speed errors ranging between $\pm 2\%$ and $\pm 5\%$, Figure 9, result in approximately the same numbers of losses of separation as the wind-speed errors. Increasing the resolution buffer seems to decrease the number of losses though.



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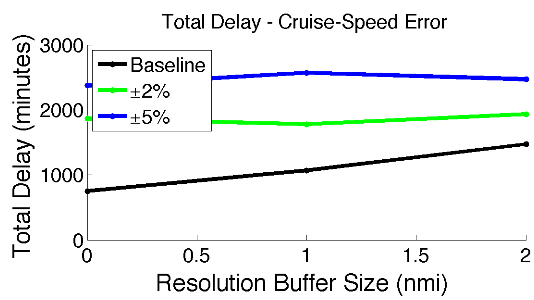


(b)

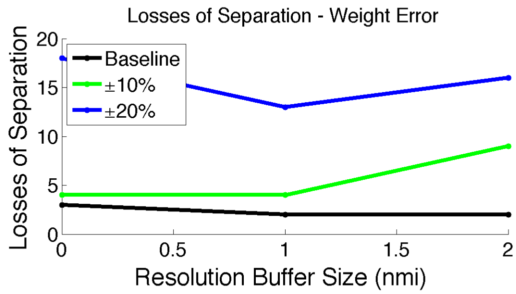
Figure 9: The losses of separation (a) and total delay for different cruise-speed errors.

The total delays for cruise-speed errors are greater than the total delays resulting from wind-speed errors (Figure 9(b)). The delay does not increase as a function of the resolution buffer size for cruise-speed errors. This is probably because the resolution buffer reduces the number of resolutions which are executed.

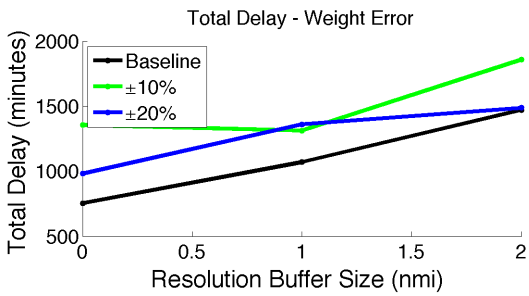
3) Weight Errors

Aircraft fuel weight errors ranging between $\pm 10\%$ and $\pm 20\%$ result in fewer losses of separation than either cruise-speed or wind errors (Figure 10(a)). In fact, the lower weight error range has approximately the same number of losses as the baseline case. The number of losses resulting from weight errors may be fewer than the number resulting from wind and cruise-speed errors because weight errors mostly impact prediction in the climb portion of the trajectory. There does not seem to be any relation between losses of separation and the resolution buffer size.

Similar to losses of separation, the total delay due to these weight error ranges are lower than the total delays resulting

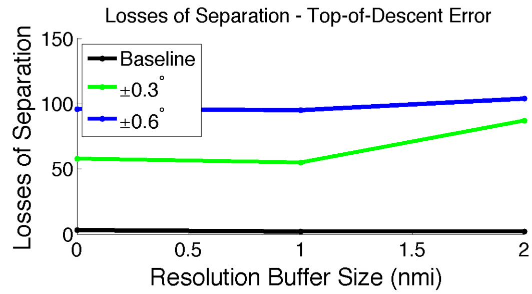


(a)

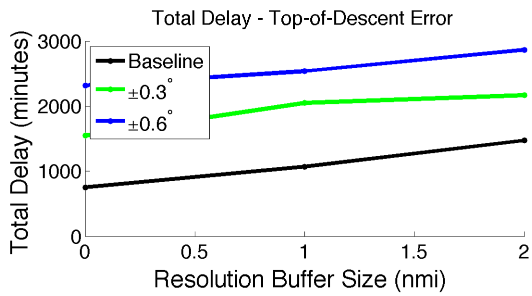


(b)

Figure 10: Losses of separation (a) and total delay (b) as a function of resolution buffer for aircraft weight errors.



(a)



(b)

Figure 11: Losses of separation (a) and total delay (b) for two top-of-descent error ranges.

from wind and cruise-speed errors. The delays do seem to increase as a function of resolution buffer size.

4) Top-of-Descent Errors

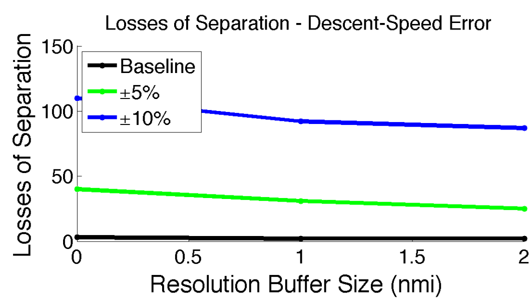
Top-of-descent errors in the range of ± 5 nmi result in over 80 losses of separation and errors in the range of ± 10 nmi result in around 120 losses of separation (Figure 11(a)). This is the most losses of separation of any type of error in this study. Since top-of-descent errors only affect the descent portion of the flight, this indicates that these types of errors are not dealt with well by the current trajectory error buffers. There is not a clear relationship between the number of losses of separation and the resolution buffer size.

Top-of-descent errors result in delay numbers comparable to the other sources of error in this study (Figure 11(b)). The delay increases as a function of the resolution buffer.

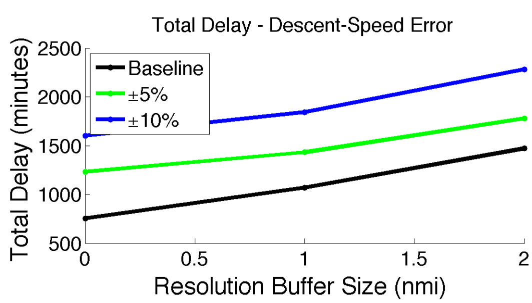
5) Descent-Speed Errors

Figure 12(a) shows the number of losses of separation for descent-speed errors in the range of $\pm 5\%$ and for descent-speed errors in the range of $\pm 10\%$. Descent-speed errors of $\pm 5\%$ result in a relatively moderate 50 losses of separation. Errors of $\pm 10\%$ on the other hand result in over 110 losses of separation. This is the second highest number of losses of any type of error studied. The number of losses seemed to decrease as a function of the resolution buffer size.

The total delay, Figure 12(a), increases as a function of the resolution buffer size even as the number of losses decreases. The delays are relatively less severe than the top-of-descent errors, ranging from around 1200 minutes to 2300 minutes.



(a)

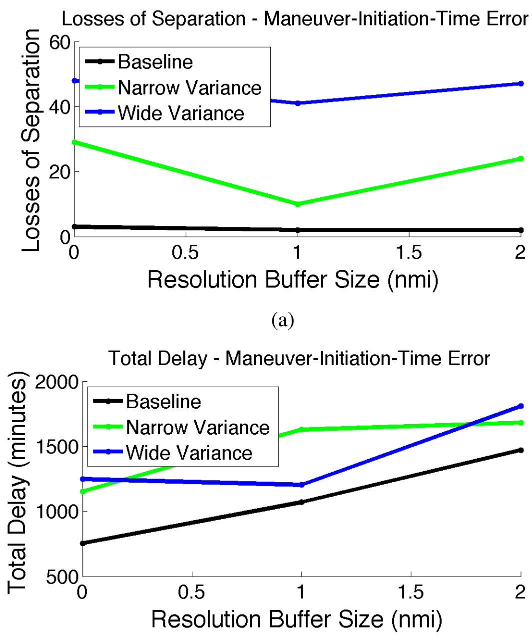


(b)

Figure 12: Losses of separation (a) and total delay (b) for descent-speed errors.

6) Maneuver-Initiation-Time Errors

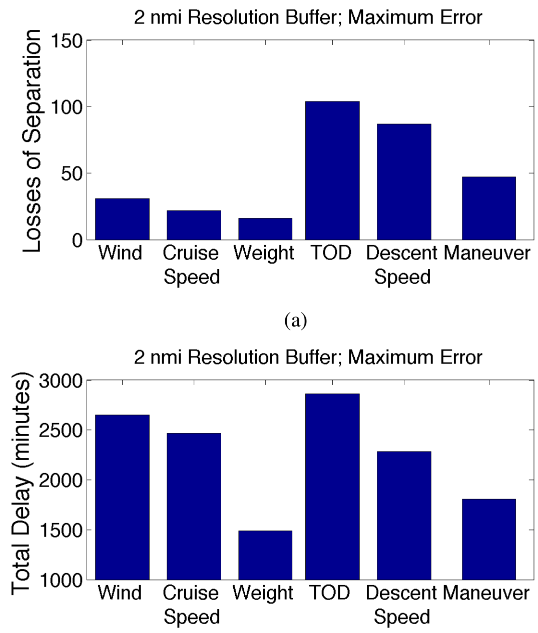
The results for the maneuver-initiation-time error simulations are shown in Figure 13. For the narrow variance maneuver-initiation-time cases the losses of separation are not much greater than the baseline cases. The wide initiation time variance cases show around 50 losses of separation. There isn't a clear trend for losses of separation as a function of resolution buffer.



(a)

(b)

Figure 13: Losses of separation (a) and total delay (b) for maneuver-initiation-time errors.



(a)

(b)

Figure 14: A summary of the losses of separation for the the largest buffer sizes and the largest error ranges.

The total delay due to maneuver-initiation-time errors is fairly close to the baseline for both the wide and narrow time variance cases. This is probably because this type of error does not affect all aircraft in the simulation. It only affects aircraft that are directed to maneuver, but have not yet begun the maneuver. The total delay increases as a function of the maneuver resolution buffer size.

7) *Resolution Summary*

Figure 14(a) shows a comparison of the number of losses of separation for each type of trajectory prediction error when the largest error range and the largest resolution buffer were used. It is clear from the figure that the two error types that result in the largest vertical errors also result in the greatest number of losses of separation. These two error types also resulted in the most missed conflict alerts close to the time of loss of separation (Figure 7(b)).

Though the top-of-descent errors and the descent-speed errors resulted in the most losses of separation, the wind and cruise-speed errors result in a comparable total delay (Figure 14(b)). This is because these error sources impact most resolutions while the descent errors only impact aircraft in the descent portion of flight.

VI. Conclusions

Six different sources of trajectory prediction errors have been individually evaluated against the same baseline in terms of both their effect on conflict detection alone and conflict detection and resolution. The conflict detection results show that top-of-descent errors can have a major impact on the number of missed alerts and that the impact is relatively insensitive to a horizontal conflict detection buffer. The detection results also show that cruise-speed errors can have a large effect on the number of missed and false alerts and that descent-speed errors tend to result in late predictions of conflicts.

The conflict resolution results show that when using a conflict detection buffer size of 1 nmi, any form of prediction error results in an increase in the number of losses of separation and an increase in the total delay in the system. The maximum number of losses resulting from any one error source was around 150, and the base situation with no resolutions performed had over 1800 losses. So, even with no vertical detection buffer the system was able to resolve over 90% of the conflicts.

Similar to the conflict detection study, the two error sources that had the greatest impact on resolution performance were the top-of-descent errors and the descent-speed errors. The fact that both of these types of error sources result in altitude prediction errors leads to the conclusion that a vertical detection and resolution buffer should be added to increase the robustness of the system. Another important result is that the performance of the resolution algorithm is very dependent on the robustness of the conflict detection algorithm. Future studies will examine the combined impact of the sources of trajectory prediction error, the effects of enhancements of the conflict detection algorithm on the robustness of the system, and the acceptability of this performance for different concepts of operations.

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