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# The Effects of Passive Coordination on Distributed Separation Assurance

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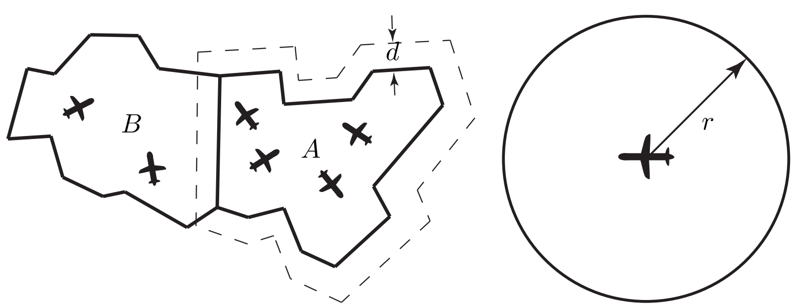
**This paper discusses an experiment to determine the effects of passive coordination on distributed separation assurance of aircraft. Both regionally centralized and airborne separation assurance paradigms are simulated in a common software testbed. In both of these cases, independent separation assurance agents do not communicate with one another. The surveillance range of each agent is varied to determine critical values. With no active coordination, both methods of separation assurance were able to resolve almost all conflicts. For the regionally centralized case, the extended surveillance range required to resolve all conflicts was approximately 20 nautical miles, and for the airborne case, the required sensing range was approximately 30 nautical miles.**

## I. Introduction

Separation assurance in the context of air traffic control means maintaining legal separation requirements between aircraft. There are generally two different paradigms for future automated separation assurance systems being discussed in the community: centralized separation management and airborne separation management.[1,2] In centralized separation management (sometimes referred to as “ground-based”), information about all of the aircraft in a region such as region $A$ or region $B$ in figure 1(a) is gathered by a central decision maker, and updated trajectories free of losses of separation are sent to the aircraft. For airborne separation management each aircraft is responsible for maintaining separation from other aircraft. The aircraft are generally responsible for identifying future possible losses of separation, know as conflicts, with aircraft within a certain range, as shown in figure 1(b), using on-board sensors.




(a) (b)

**Figure 1. Schematics of (a) two adjacent regions in the centralized problem and (b) the sensor radius for the airborne problem are presented.**

It is possible that the centralized separation management paradigm could have a single automated agent for the entire National Airspace System (NAS), but it may be necessary to divide the NAS into regions that are controlled by independent separation assurance systems. This division of responsibility may reduce computational complexity, ease the transition from the current system, or provide redundancy. If this division of the centralized case is chosen, multiple autonomous agents are required to maintain separation criteria for all aircraft in the NAS in both the airborne and regionally centralized separation assurance systems. In this sense, both are distributed control systems and are subject to synchronization and coordination issues.[3]

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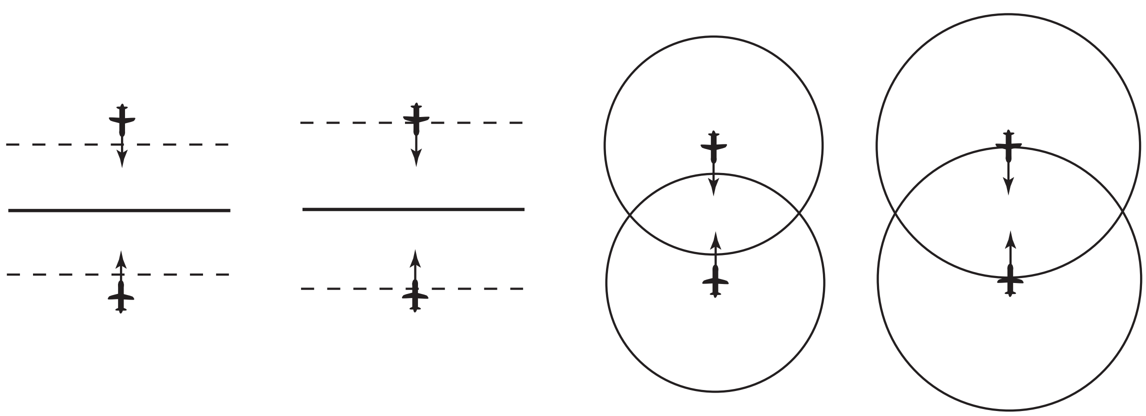
For a future automated system, coordination between agents will be necessary because all agents in the system will have limited knowledge of the states of the other agents. Lack of coordination may lead to losses of separation or resolutions that are suboptimal. Since this coordination is critical, it is important to determine the best way for it to be accomplished. The number of rules required for coordination should be kept to a minimum, because imposing extra rules unnecessarily constrains the system, making higher density operations more difficult. A system that is less complicated would also be easier to implement algorithmically and may even be provably safe mathematically under certain conditions.[4]

To begin to identify preferred coordination schemes, it is helpful to determine the magnitude of the coordination problem as defined by the number of losses of separation and by the quality of the resolutions that are implemented. The number and characteristics of losses of separation in the system that result from the lack of coordination are unknown and do not appear to be described in the literature. In this paper, the effects of a lack of active coordination are analyzed using the same conflict detection and resolution system for both regionally centralized and airborne separation assurance paradigms.

## II. Background

With multiple agents making control decisions in a separation assurance system, it is important to determine what level of coordination is required between the agents to guarantee that there are no losses of separation. Figure 2 provides some examples of how this coordination between agents is important. Figures 2(a) and 2(b) illustrate two aircraft approaching a regional boundary. The dashed lines indicate areas of extended visibility between the two regions where the lower region can observe aircraft within the upper dashed line and the upper region can observe aircraft within the lower dashed line. In figure 2(a) neither region can observe both aircraft at the same time, and if this extended surveillance range is too small an automation system may be unable to maintain separation. Figure 2(b) shows the case where both regions can see both aircraft. The issue in this case is not surveillance, but rather determining which region should have authority and responsibility to resolve that conflict. In this case, explicit coordination and even iteration of solutions may be required. Figures 2(c) and 2(d) show the airborne analogues of these two cases.



(a) (b) (c) (d)

**Figure 2. An illustration of issues associated with distributed separation assurance and how they are common between regionally centralized and airborne cases is shown. In (a) and (c), no agent is aware of both aircraft. In (b) and (d), two agents are aware of both aircraft, and it may be important to determine which agent affects the outcome.**

The current system of separation assurance is a regionally centralized one. Air traffic controllers monitor a region of airspace and are responsible for maintaining separation in that region. To facilitate aircraft transitions across boundaries, controllers have surveillance for some distance beyond their region of responsibility (shown by the dashed line in figure 1(a)). While this distance is dependent on the local radar coverage and on the geometry of the region, a recent analysis of recorded data showed that hand-off of control across airspace boundaries is initiated approximately 35 miles before a boundary crossing.[5] This suggests a nominal value for the overlapping region in an automated airspace system. Once a flight has been identified as transitioning between regions, the system provides methods for communication and coordination of decisions between neighboring controllers as well as rule-based procedures that ensure that aircraft will not be in conflict when crossing airspace boundaries.

Fully automated systems cannot rely on ad-hoc decisions. Instead, a consistent and safe procedure for coordination must be included. A step towards realizing this goal has been discussed in terms of multi-sector planning for continuous descent approaches to airports.[6] In some of these approaches the controlling sector is determined automatically by comparing the airspace complexity of the two sectors. Current designs for airborne systems include priority rules to determine which aircraft maneuvers based on the geometry of the conflict and the procedures used for Visual Flight Rules operation.[7] This method is similar to the geometric rules used by the Traffic Alert and Collision Avoidance System (TCAS).[8] TCAS also uses the transponder code of each flight in a conflict as a coordination tool and includes active communication between the aircraft.

More generally, methods of coordinating independent agents are important to parallel and distributed computing applications.[3,9] The methodologies developed in those fields can be partially adapted to the current problem, but the distributed separation assurance problem has unique issues. For instance, in the airborne case, communication between aircraft may be limited to position and intent data. Also, it may be desirable to limit the overall number of messages required for safe functioning of the system to ensure robustness. The next section presents the methodology used to determine the specific issues associated with coordination in the distributed separation assurance problem.

# III. Simulation Environment

## A. ACES and AAC

For this study the Airspace Concept Evaluation System (ACES)[10] is used to simulate the NAS and to detect traffic conflicts, and the conflict resolution algorithm from a prototype of the the Advanced Airspace Concept (AAC)[11] operating concept is used to resolve conflicts. ACES is a non-real time simulation of the entire NAS. Inputs to the simulation include a list of flights with routes, an airspace configuration, and the location of airports in the system. The trajectory for each flight is created by numerically integrating a four degree of freedom model resulting in a realistic trajectory. ACES also has the capability to detect future conflicts in the system using the future intended route of the aircraft.

The conflict resolution algorithm from the prototype of AAC resolves a conflict by probing multiple instances of different classes of maneuvers for conflicts over a time horizon. Maneuver classes include path stretch maneuvers, temporary altitude maneuvers, and speed maneuvers for each aircraft. The best resolution is then selected based on which provides the minimum delay. AAC is capable of resolving all types of conflicts including conflicts in the en-route, climb, and descent phases of flight. The interface between ACES and AAC is known as a conflict list. This list of conflicts is generated by ACES which sends it to AAC, then AAC generates conflict-free resolutions for the list and sends the necessary maneuvers back to ACES to be implemented by each flight.

For this study, there is zero uncertainty in trajectory prediction for any entity, so there are no false alerts or missed alerts for any conflict. This is a large approximation on the actual system[12] because there are numerous issues associated with trajectory uncertainty, but this approximation should have a relatively minor impact on the effects of no coordination of independent agents. Furthermore, some precautions to deal with trajectory prediction uncertainty are embedded in the AAC algorithm such as a limited look-ahead time of 8 minutes for most resolutions as well as an additional 2 nmi horizontal buffer required for successful conflict resolutions.[11]

## B. Airborne and Multi-center Enhancements

The airborne and regionally centralized paradigms are simulated using ACES and AAC in the following manner. For the regionally centralized case, the current boundaries of the Air Route Traffic Control Centers (ARTCC) are used to divide the NAS into regions (figure 3). Each center has an independent AAC algorithm resolving all conflicts for aircraft within its boundaries.[a] To accomplish this, ACES creates a conflict list for each center comprised of all conflicts between aircraft in the set of aircraft inside that center's boundaries as well as aircraft within an extended surveillance region surrounding that center (figure 1(a)). This list of conflicts is then passed to AAC which generates trajectories free of losses of separation for each aircraft. If a maneuver is commanded for an aircraft in the center, that maneuver is sent to that aircraft to be

[a]A resolution of a conflict involving two aircraft inside a common center will be attempted even if the loss of separation is located outside the center boundary.

implemented. If a maneuver is required for an aircraft located in the extended surveillance region, that maneuver is not sent to the aircraft and is ignored.

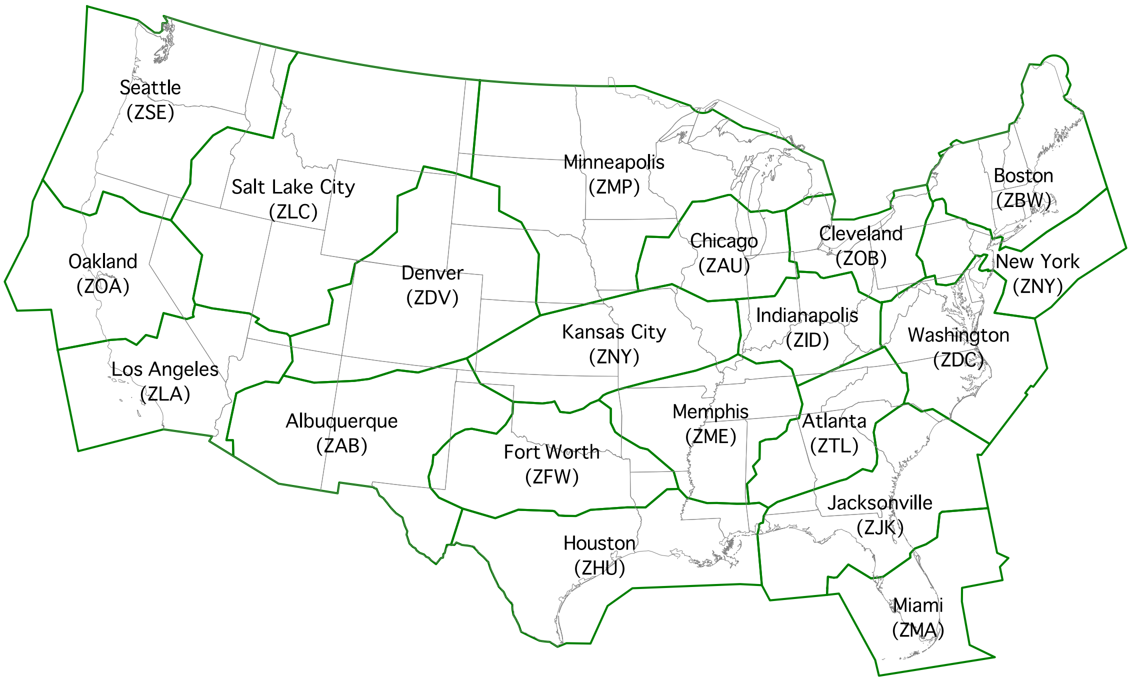



**Figure 3. A map showing the 20 centers, each of which has an independent separation assurance agent in the regionally centralized case is presented.**

The airborne case is simulated similarly. Each aircraft has an independent AAC algorithm resolving conflicts. To simulate the surveillance capability of each flight, ACES creates a conflict list comprised of all conflicts between aircraft within a certain radius of that flight's current position. This list is then sent to that flight's AAC algorithm for resolution. The resolutions are then filtered based on whether the aircraft that generated the conflict list is required to maneuver. If, for example, the AAC algorithm for aircraft $A$ provides a resolution trajectory that requires aircraft $A$ to maneuver, that resolution trajectory is implemented. If the resolutions require aircraft other than aircraft $A$ to maneuver, then no action is taken.

It is important to note that for this experiment, there is no input into the AAC algorithm specifying which aircraft it is controlling. The algorithm proceeds as if it is in control of all aircraft, but the results are filtered as described above.

## IV. Experiment Setup

To study the effects of lack of active coordination between agents, one parameter is varied in each of the paradigms. For the center-based AAC algorithm, the size of the extended surveillance region around each center is varied from 0 nmi to 60 nmi. For the airborne case, the surveillance range is varied from 10 nmi to 60 nmi. The values chosen for both the airborne and the center-based cases do not necessarily reflect expected operational conditions, but instead were chosen to explore the coordination issue. In fact, airborne sensing equipment may be required to have a sensing range of 90 to 120 nmi.[13] The departures from the peak times of 1100 to 1300 Eastern Time on April 21, 2005 are used as the input for ACES resulting in about 9300 flights distributed realistically across the NAS. In the airborne case, the AAC algorithm is executed every 10 seconds of simulation time, and in the center-based case, the algorithm is executed every 60 seconds.

While the simulation is being performed, the trajectory states of all of the aircraft are recorded every five seconds, and the computed resolutions are collected. After the simulation is completed, the flight tracks are analyzed to determine if there are any remaining losses of separation between flights. Because ACES does not generate trajectories below 10,000 feet, losses of separation that occur below 11,000 feet are ignored. Also, in the current setup, flights are not constrained to be conflict free when they are initiated at the departure metering fix, so losses of separation that occur within the first two minutes from the metering fix are ignored.

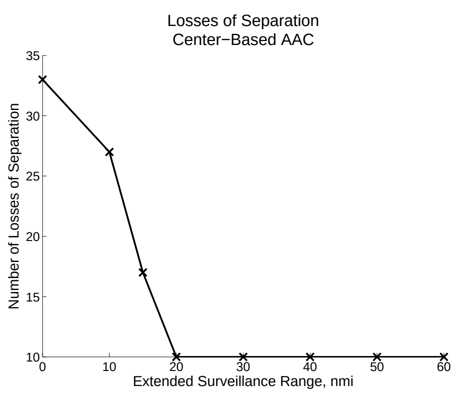
Simulations were performed using the three hours of current demand flight data set for the center-based case with extended surveillance ranges of 0, 10, 15, 20, 30, 40, 50, and 60 nmi. For the airborne case, simulations were performed for sensor ranges of 10, 20, 30, 40, 50, and 60 nmi. As a control, one simulation was run without AAC running to determine the baseline loss-of-separation properties.

# V. Results

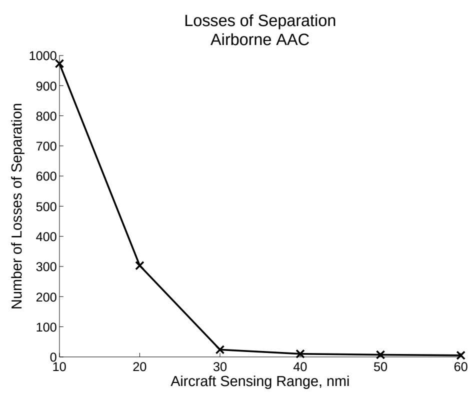
After running the cases discussed previously, the data were stored and analyzed. Results related to three different aspects of the problem are presented. The first is the overall system performance of both types of resolution as a function of the sensing range. Following that, the results of the respective minimum sensing ranges are analyzed to gather statistics related to what type of conflict is most difficult to handle. Finally, some aspects of the lack of coordination between agents are presented.

## A. System Performance

In the control case without AAC running there were 1,700 losses of separation. Figure 4(a) shows the number of losses remaining in the center-based case as a function of the extended surveillance range. The number of losses of separation decreases as the surveillance range increases until 20 nmi and then remains the same at 10 losses. An inspection of the 10 remaining losses of separation revealed that they fall into two categories. First are those with two international flights that come into conflict immediately upon entering the NAS. These conflicts would theoretically be resolved by an international controller before the flights were handed off to the centers. The second class of losses of separation are the result of software issues in ACES relating to the handling of international flights. No losses were found to result from lack of agent coordination in the center-based case.




(a)

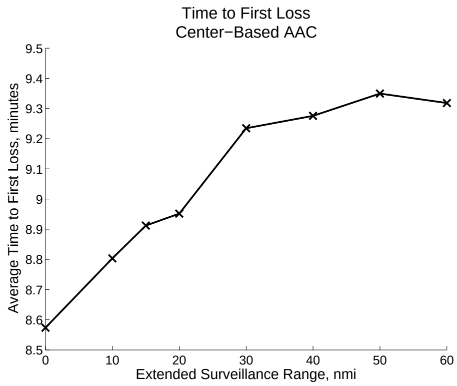



(b)

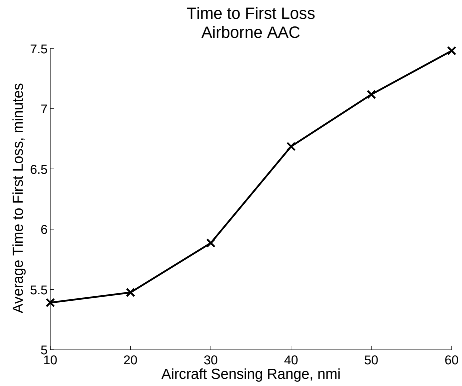
**Figure 4. The losses of separation that were not resolved for (a) the center-based case as a function of the extended surveillance range and (b) the airborne case as a function of the sensor range are shown.**

The airborne case is shown in figure 4(b). For these simulations the number of losses of separation decreases rapidly as the sensor range increases to 30 nmi and then slowly decreases with only 5 losses remaining in the 60 nmi sensing case. The losses of separation in the 60 nmi case are the result of an ACES issue related to the sensor range. In the 40 or 50 nmi sensing cases, there are a small number of losses resulting from a lack of coordination between the aircraft. In some cases, both aircraft think the other will maneuver every iteration, and in some cases both aircraft maneuver, but are immediately in conflict again.

Figure 5(a) shows the average time to first loss when resolutions are implemented for the center-based case. The time to first loss increases as the extended surveillance range size increases, but since this value only ranges from about 8.6 minutes to 9.3 minutes, the time to first loss is not heavily dependent on the size of the extended surveillance range. This is reasonable because most of the resolutions in the center-based case occur in the interior of centers and are not affected by center boundaries. Figure 5(b) shows the average time to first loss for the airborne case. In this case, the average time is heavily dependent on the sensor range because every resolution is affected by this range. As the sensing range increases, the average time to first loss for the airborne case approaches that of the center-based case.




(a)

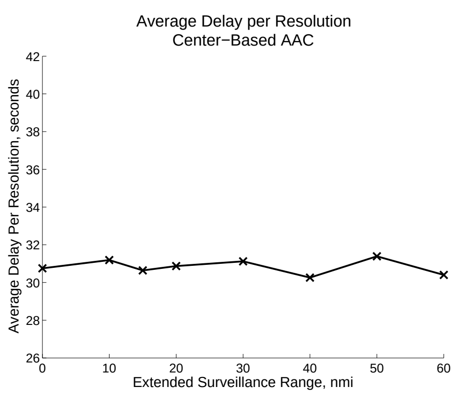



(b)

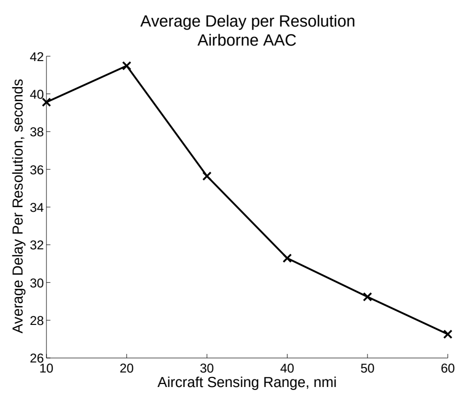
**Figure 5. The time to first loss when the resolution occurred for (a) the center-based case as a function of the extended surveillance range and (b) the airborne case as a function of the sensor range is depicted.**

The average delays per resolution for both cases are shown in figure 6. It is important to note here that for this study the AAC algorithm was configured such that it preferentially selected horizontal resolutions over vertical ones. The algorithm was also configured so that instead of trying all different classes of resolution for each conflict, the algorithm chose the first successful resolution it found. If that were not the case, delays per resolution would be on the order of 7 seconds instead of 30 seconds.

Similar to the time-to-first loss results, the average delay per resolution for the center-based case (figure 6(a)) is not dependent on the extended surveillance range. The value varies in the range of 30.5 seconds per resolution. The average delay per resolution for the airborne case (figure 6(b)) on the other hand is sensitive to the sensing range. As the sensing range increases from 20 to 60 nmi, the average delay per resolution decreases from 40 seconds to 28 seconds. This indicates that the resolutions required for the smaller sensing radii are more severe than those for the larger sensing radii because late conflict detection generally requires a larger maneuver.




(a)



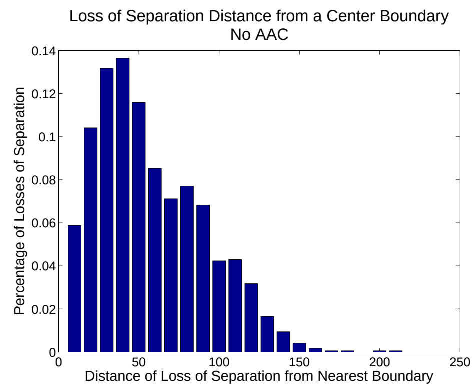

(b)

**Figure 6. The average delay per resolution for (a) the center-based case as a function of the extended surveillance range and (b) the airborne case as a function of the sensor range is shown.**

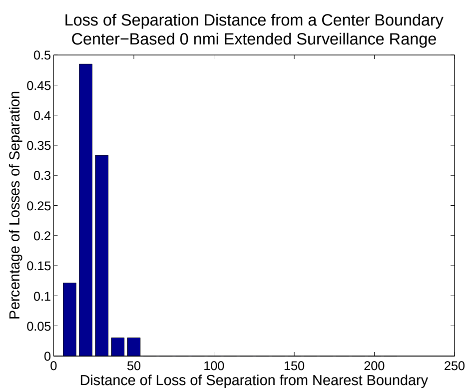
### B. Characteristics of Difficult Conflicts

To characterize the types of conflicts that are difficult to resolve in the airborne and center-based cases, the results of the minimum sensing ranges studied (10 nmi and 0 nmi respectively) for both are compared to the open-loop case. While neither of these sensing ranges is expected to be encountered operationally, they allowed for valuable statistics to be generated. The losses of separation in the minimum sensing cases are analyzed to determine the angle of incidence and the distance of the loss of separation from a center boundary with the results presented below.

Histograms showing the distance of losses of separation from the nearest center boundary are shown in figure 7. The control case without AAC is shown in figure 7(a). The distance of the losses from center boundaries are distributed in approximately a log-normal fashion. In the center-based case with no extended surveillance region, figure 7(b), the losses of separation are clustered at the center boundaries and are mostly the result of late or no sensing depicted in figures 2(a). The losses in the airborne case with 10 nmi sensor range, figure 7(c), are not clustered at the boundary, and are distributed in a similar fashion to those in the control case indicating that the losses of separation are not correlated with the geographical boundaries in the airborne case. The causes of the losses of separation are also mostly related to late or no detection, while separation agent disagreement about which aircraft should maneuver also plays a role.




(a)

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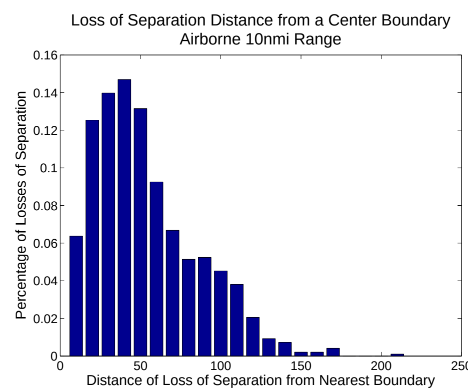
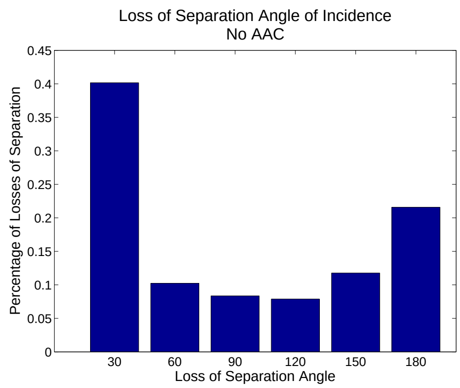



(c)

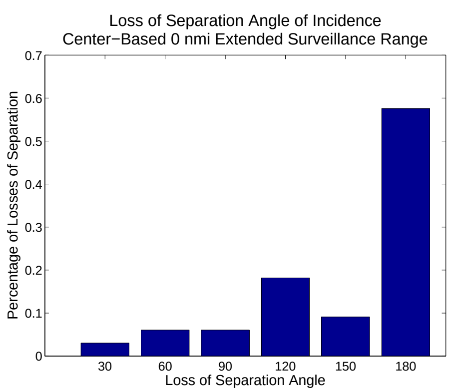
**Figure 7. The histograms show the percentage of losses of separation that occur various distances from the nearest boundary for (a) the simulation with AAC off, (b) the center-based case with no extended surveillance region, and (c) the airborne case with 10 nmi sensor range.**

Histograms representing the loss of separation incidence angle are shown in figure 8. The incidence angle ranges from 0 degrees to 180 degrees, where the two aircraft are in-trail at 0 degrees and are flying directly towards each other at 180 degrees. In the control case, figure 8(a), a majority of the losses occur between 0 and 30 degrees. Similar data are shown by previous researchers for a different simulation software[14] and for conflict estimations based on flight tracks.[15] Figure 8(b) shows that for the center-based case with no extended surveillance region, the remaining losses of separation are mostly clustered between 150 and 180 degrees. This is expected because head-on conflicts are harder to detect and resolve across the center boundary.

The remaining losses of separation in the airborne case with 10 nmi range, figure 8(c), are distributed more towards head-on conflicts as well. This indicates that for the airborne case as the angle of incidence increases, the difficulty of resolving the conflict increases as well. The relative velocity between the aircraft




(a)

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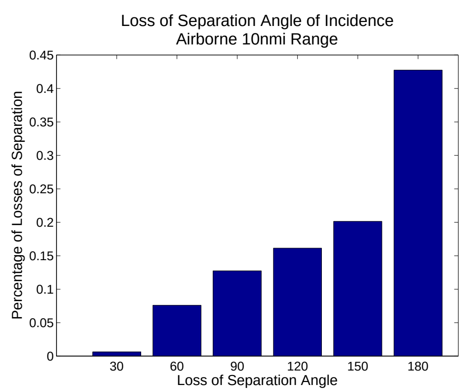



(c)

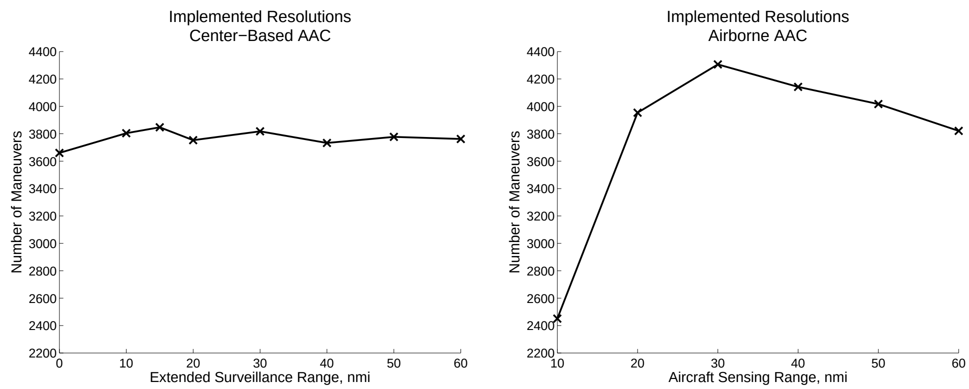
**Figure 8. The histograms show the percentage of losses of separation that occur at various angles of incidence for (a) the simulation with AAC off, (b) the center-based case with no extended surveillance region, and (c) the airborne case with 10 nmi sensor range.**

increases as the angle of incidence increases, so the time to first loss when the conflict is detected would decrease as the angle of incidence increases.

## C. Agent Coordination

In order to characterize how the lack of coordination between agents affects the efficiency of the system, figure 9 shows the number of resolutions that are implemented for each case. In general, more resolutions would be required in two ways because of lack of coordination between two agents controlling two different flights in conflict: first, if both flights are commanded to maneuver to resolve the same conflict, and second, if both flights are commanded to maneuver, but this command results in them being in conflict again.

In the center-based case (figure 9(a)), the number of implemented resolutions decreases as the sensing range increases, but the range of variation is only approximately 100 maneuvers. For the airborne case (figure 9(b)), the number again decreases as the sensing range increases with a total variation of about 600 maneuvers. Comparing the center-based case and the airborne case it can be seen that for small to medium-sized sensing ranges there are more maneuvers executed than strictly necessary. This indicates the need for coordination to ensure efficiency. As the sensing range increases though, the number of resolutions approaches the center-based case, and coordination is less important.




(a) (b)

**Figure 9. The number of resolutions implemented for (a) the center-based case as a function of the extended surveillance range and (b) the airborne case as a function of the sensor range are presented.**

Another way to analyze the effects of coordination is to look at the results of the cases where two different agents control the two flights in a conflict. There are three possible results when this occurs. In the first case, only one of the aircraft is maneuvered. This is the desired outcome because it should resolve the conflict with a minimum amount of aircraft deviation. In the second case, neither aircraft is maneuvered because both agents think the other flight will divert resulting in the conflict remaining. In the third case, both aircraft are maneuvered because each agent calculates that it needs to maneuver its aircraft. This can either result in the conflict being resolved or both aircraft being in conflict again. There are several possible methods to disambiguate which agent should resolve the conflict using passive coordination such as using a "rules-of-the-road" approach, but selecting the best method that puts the least constraint on a solution is an area for future study.

The percentage of times that each outcome occurs for airborne and center-based cases are shown in figure 10. In the center-based case shown in figure 10(a), approximately 80% of the time only one aircraft is maneuvered. This number increases gradually with the sensing range. There is no data for the 0 nmi case because there are never times when two agents control different aircraft in a conflict. Two aircraft are maneuvered about 6% of the time in the center-based case. This and the fact that there are fewer cases where two aircraft are controlled by different agents accounts for the relatively fewer number of maneuvers shown in figure 9(a).

The outcomes of multiple agents resolving a conflict for the airborne case are shown in figure 10(b). Approximately 65% of the time one aircraft is maneuvered in this case, no resolutions are implemented 30% of the time, and two resolutions are implemented approximately 9% of the time. This is basically constant as a function of sensing range. The decrease in implemented resolutions as a function of sensing range shown

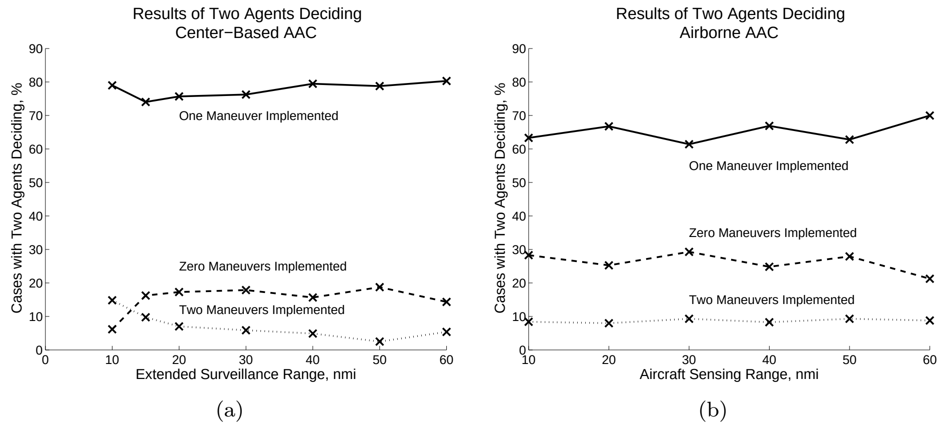



**Figure 10. The percentages of the three possible outcomes when two agents can resolve the same conflict for (a) the center-based case as a function of the extended surveillance range and (b) the airborne case as a function of the sensor range are shown.**

in figure 9(b) is caused by a decrease in the number of cases where two agents are attempting to resolve a conflict. The number of cases decreases because first resolution attempts are successful more often.

Since the same resolution logic is used by both agents in the conflict, if they are both aware of the same aircraft they will both agree on what resolution to implement. Comparing figure 10(a) and figure 10(b) shows that one maneuver is implemented more often in the center-based case than in the airborne case. This results from information being somewhat more “asymmetric” in the airborne case due to the surveillance geometry.

# VI. Conclusions

This paper presented results of a study simulating both airborne and regionally centralized paradigms of automated separation assurance. The AAC separation assurance algorithm and the ACES NAS simulation tool were used for both cases. For the regionally centralized case, each of the 20 continental ARTCC regions was controlled by a single separation assurance agent. The extent of visibility of these agents beyond their geographical boundary was varied. For the airborne case, each aircraft had its own separation assurance agent, and the sensing range of the aircraft was varied. There was no active coordination between separation assurance agents in either case.

For the center-based case, there are no important losses of separation remaining in the system when the extended surveillance range is greater than 20 nmi. For the airborne case, almost all losses of separation are resolved when the sensing range is greater than 30 nmi. The most difficult conflicts for both cases to resolve involved flights approaching head-on. While the center-based case had more losses of separation along center boundaries, the losses of separation in the airborne case were not correlated with those boundaries. The lack of coordination in both cases resulted in cases where both aircraft in a conflict are maneuvered or where neither aircraft is maneuvered, creating inefficiencies. The simulation environment used for this study can be used for future work to help develop efficient methods of coordination by analyzing the effect of the coordination on specific losses of separation and cases where multiple agents are attempting to resolve a common conflict.

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