Performance Analysis of a Horizontal Separation Assurance Algorithm for Short-Range Conflicts

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The concept of distributed air-to-air separation assurance envisions aircraft detecting and resolving conflicts autonomously without the need for a ground based air traffic service provider. Current automated conflict resolution algorithms that assume instantaneous heading changes without consideration of turn dynamics can result in unintentional loss of separation. A simulation of distributed conflict resolutions is used to evaluate a recently developed algorithm that implements realistic turn dynamics, i.e., without assuming instantaneous heading changes. In particular, the algorithm incorporates turn dynamics to resolve pair-wise, horizontal conflicts at close ranges. Examples of resolution trajectories generated by the separation assurance algorithm are shown. Data on the performance of this algorithm is extracted from the simulation. More importantly, analysis of these results indicates a need for coordination and communication between conflicting aircraft in order to guarantee a high level of safety in a distributed air-to-air separation assurance environment.

Nomenclature

V_A, V_B	=	Ground speed of both aircraft
X_{B0},Y_{B0}	=	Relative initial position of aircraft B after coordinate transformation
ψ_A ,ψ_B	=	Relative heading of both aircraft after coordinate transformation
D_{req}	=	Required horizontal minimum separation between any two aircraft
R_A, R_B	=	Turn Radius for both aircraft
$\Delta\psi_A$,$\Delta\psi_B$	=	Turn Angle for both aircraft.
ϕ	=	Bank Angle is chosen constant for both aircraft.
P_{AT}, P_{BT}	=	Position of the aircraft when the turn is complete
$t(\Delta\psi_A)$,$t(\Delta\psi_B)$	=	Y component of the resultant pressure force acting on the vehicle
D_{AB}	=	Distance between aircraft A and B at the end of the turn.
t_{smin}	=	Time to minimum separation in the straight-line segment beginning at the end of the turn
d_{smin}	=	Minimum distance achieved in the straight-line segment beginning at the end of the turn
D_{min}	=	Minimum distance achieved during the entire maneuver. This may occur during the turn, at the end of the turn, or in the straight-line segment beginning at the end of the turn

I. Introduction

THE concept of distributed air-to-air separation assurance envisions aircraft detecting and resolving conflicts without the need for a ground-based air traffic service provider. But without guidance from a ground-based system, a reliable method for distributed separation assurance needs to be developed. The Advanced Airspace Concept (AAC) describes a more automated air traffic control system in which automated separation assurance plays a central role.[1] With the idea of an automated and distributed method, an algorithm for horizontal separation assurance has been developed. This thesis presents the results from measuring this algorithm's performance in current and higher air traffic densities.

The separation assurance algorithm will detect and resolve conflicts for a time to first Loss of Separation (LOS) at three minutes or less. Current automated resolution algorithms, including the AAC auto-resolution algorithm implemented in ACES and CTAS, assume instantaneous heading changes.[2] This assumption can result in an

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unintentional LOS and so a trajectory engine checks the simplified resolution maneuver using realistic turn dynamics. If separation is lost, a new heading change is requested. For a close-range conflict greatly affected by turn dynamics, this will result in several iterations between the algorithm and the trajectory engine. Erzberger has derived a new algorithm to create a horizontal resolution plan by analyzing the turn dynamics for both aircraft.[3]

A simulation is used to measure the performance of the horizontal separation assurance algorithm developed by Erzberger.[3,4] While the simulation is running, certain events are recorded, counted, and classified into various types. Plotting measured data, drawing individual conflicts, and re-creating the simulation as an animation are used in this study to visualize events and measure the performance of the algorithm.

In the simulation, pair-wise conflicts are either detected at the time to first LOS parameter, or they are detected at an earlier time as the result of a secondary conflict. A pair-wise conflict resolution may result in a secondary conflict, specifically, when a maneuver is complete, either aircraft may become involved in a conflict with a third aircraft. Some secondary conflicts occur as an immediate result of the maneuver, possibly causing it to be detected at a time less than the time to first LOS, and potentially resulting in an unavoidable LOS.

At present, the algorithm is designed to resolve pair wise conflicts without considering any possible secondary conflicts. However, the simulation will attempt to resolve any secondary conflicts once the primary conflict has been resolved. The data from the simulation shows a conclusive need for coordination between aircraft to avoid secondary conflicts. Communication of intent is a necessary step; first it ensures both aircraft involved in a conflict choose the same maneuver and second, it informs other aircraft of their intentions. Communication by data-link could provide other aircraft's intentions. Future work will extend this algorithm to detect and resolve secondary conflicts.

II. Analytical Background

The following is a summary of the analytical formulation presented by Erzberger for horizontal separation assurance between two aircraft.[3] Understanding the derivation for this pair-wise separation assurance algorithm is a key step in the implementation and analysis process. Throughout this paper, winds are assumed negligible, thus air speed and heading is equivalent to ground speed and heading.

Separation Assurance Equations

(1) $X_A = X_A' + V_A \sin(\psi_A)$

(2) $Y_A = Y_A' + V_A \sin(\psi_A)$

(3) $\begin{bmatrix} X_{B0} \\ Y_{B0} \end{bmatrix} = \begin{bmatrix} \cos\psi_{A0}' & -\sin\psi_{A0}' \\ \sin\psi_{A0}' & \cos\psi_{A0}' \end{bmatrix} \begin{bmatrix} x_{B0}' - x_{A0}' \\ y_{B0}' - y_{A0}' \end{bmatrix}$

(4) $R_A = \dfrac{V_A^2}{g \tan\phi}, \; R_B = \dfrac{V_B^2}{g \tan\phi}$

(5) $\Delta\psi_A = \dfrac{t * g \tan\phi}{V_A}, \; \Delta\psi_B = \dfrac{t * g \tan\phi}{V_B}$

(6) $|\Delta\psi_B| = \dfrac{V_A}{V_B} |\Delta\psi_A|$

(7) $t(\Delta\psi_A) = t(\Delta\psi_B) = \dfrac{|\Delta\psi_A| * V_A}{g * \tan\phi}$

(8) $P_{BT} = [x_B, y_B] = \big[x_{B0} + R_B \,\mathrm{sgn}(\Delta\psi_B) * (\cos(\psi_B) - \cos(\psi_B + \Delta\psi_B)),$
$\quad y_{B0} + R_B \,\mathrm{sgn}(\Delta\psi_B) * (-\sin(\psi_B) + \sin(\psi_B + \Delta\psi_B)) \big]$

(9) $P_{AT} = [x_A, y_A] = R_A * \mathrm{sgn}(\Delta\psi_A) * [1 - \cos\Delta\psi_A, \sin\Delta\psi_A]$

(10) $P_{BT} = [x_B, y_B] = x_{B0} + t(\Delta\psi_A) * V_B * \sin(\Delta\psi_B)$

(11) $P_{AT} = [x_A, y_A] = [0, \; y_{A0} + t(\Delta\psi_B) * V_A]$

(12) $(\Delta_x, \Delta_y) = (x_B - x_A, y_B - y_A)$

(13) $D_{AB} = \sqrt{(\Delta_x)^2 + (\Delta_y)^2}$

(14) $t_{s\min} = \frac{-\left(\Delta_x * V_{Rx} + \Delta_y * V_{Ry}\right)}{|V_R|^2} \geq 0$

(15) $d_{s\min} = \sqrt{\left[\Delta_x + V_{Rx} * t_{s\min}\right]^2 + \left[\Delta_y + V_{Ry} * t_{s\min}\right]^2}$

These equations will be used to find the minimum distance between the two aircraft (A/C) during a maneuver. In a single aircraft maneuver, one A/C turns for a specified angle while the other aircraft flies straight. A cooperative maneuver is when both aircraft will turn for the same specified amount of time followed by straight-line flight. There are eight possible pair-wise maneuvers to check, four are cooperative and four are single aircraft. The goal is to maintain separation between the two aircraft. Separation is maintained if the minimum distance is greater than D_{req}.

Figure 1 illustrates the scenario to be resolved. The two aircraft involved are known as A and B, where the host aircraft assumes itself to be A, and the intruder aircraft is known as B. A coordinate and heading transformation is used to show the conflict scenario from the host's perspective by placing A at the origin with a heading of zero degrees. Aircraft B's position and heading, but not speed, are transformed into the relative coordinate system. Figure 2 through Figure 6 show the separation graph used to plot the maneuvers and Figure 7 is an example conflict resolution maneuver as extracted from the separation graph. A more detailed explanation of how maneuvers are extracted from the above equations has been made available by Erzberger[3] and Trapani.[4]

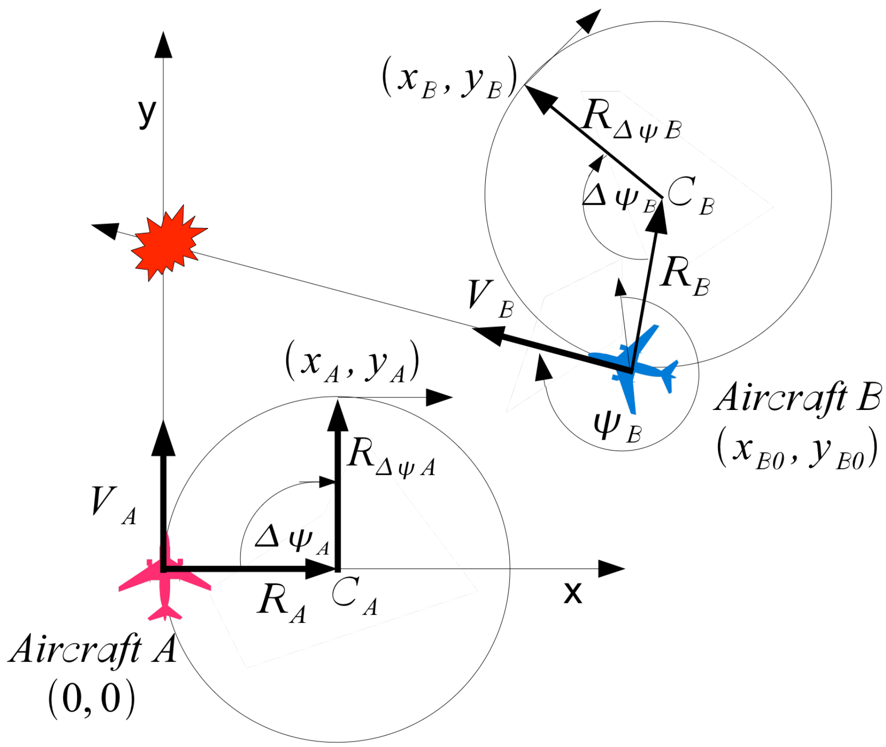

Figure 1: Figure 1 By [3]Erzberger. Shows a possible conflict scenario translated into A/C A's relative coordinate system.

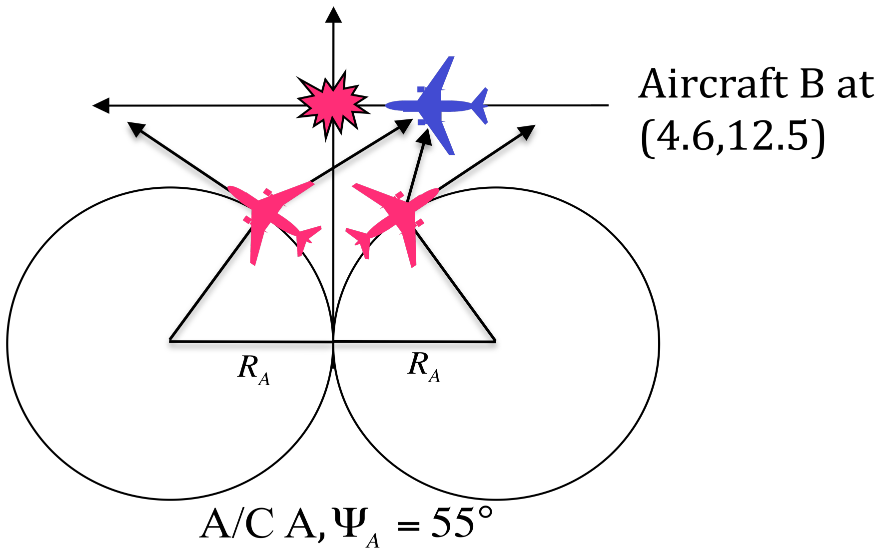

Figure 2: Distance between A/C's A and B after A turns left or right for 55° at a bank angle of 20°. B is at the same position because the time for both turns is the same. Note that A is no longer at (0,0), this is only used as the initial position and heading.

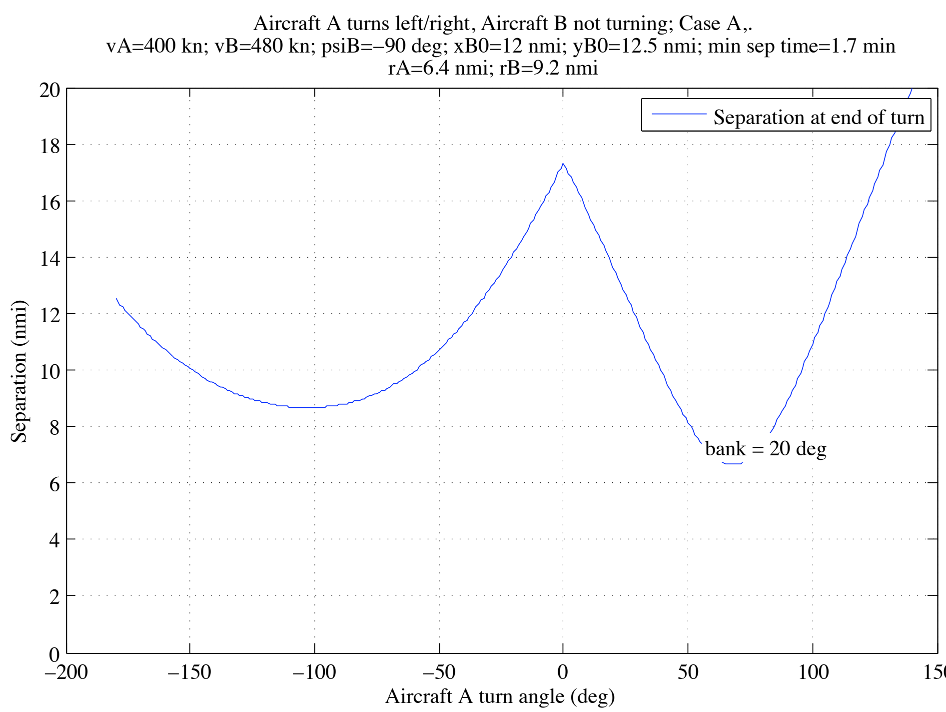

Figure 3: Distance at the end of every turn angle using Equation 13. Right turns are positive angles and left turns are negative angles. Generated by [3]Heere. As the turn angle increases, so does the time from the initial conflict position.

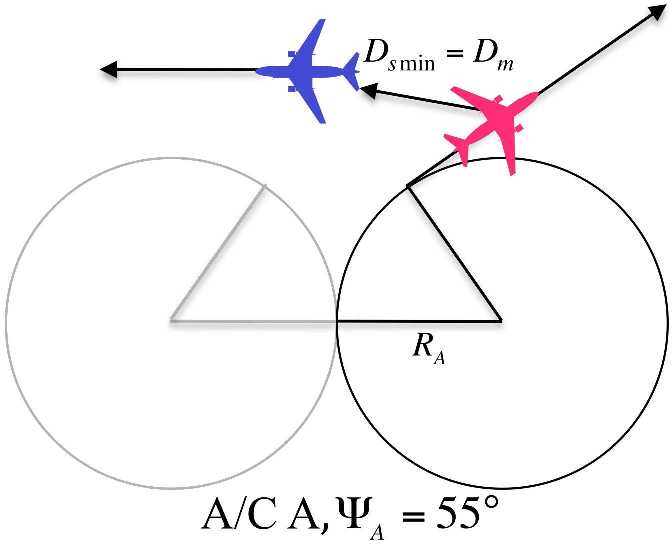

Figure 4: Minimum Distance on the straight-line after A/C A's turn is complete. This occurs shortly after the end of the turn.

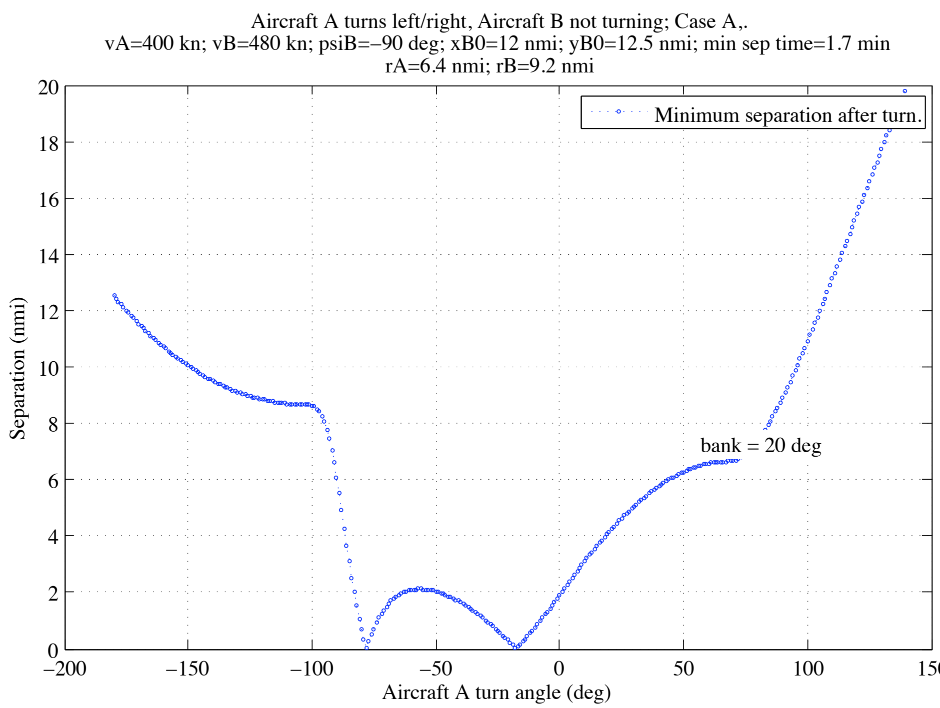

Figure 5: Minimum distance during the straight-line flight at each turn angle using Eq. 2.14. Right turns are positive angles and left turns are negative angles. Generated by [3]Heere. The time to the minimum distance after the turn may vary anywhere zero seconds up to several minutes.

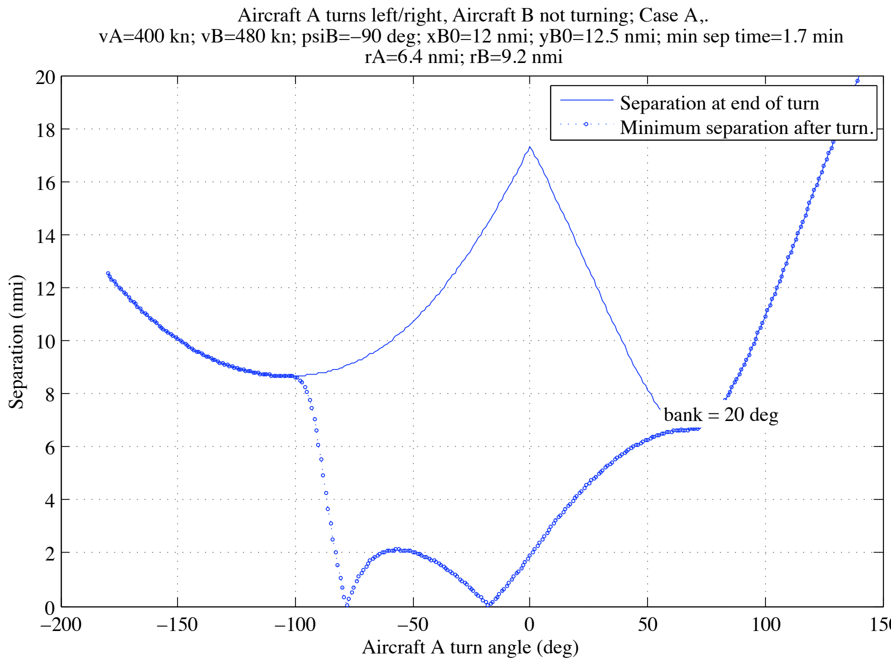

Figure 6: Plotting Figs. 3 and 5 on the same graph. Generated by [3]Heere. At a right turn of 55°, the distance at the end of the turn is slightly larger than the distance in the straight line after the turn.

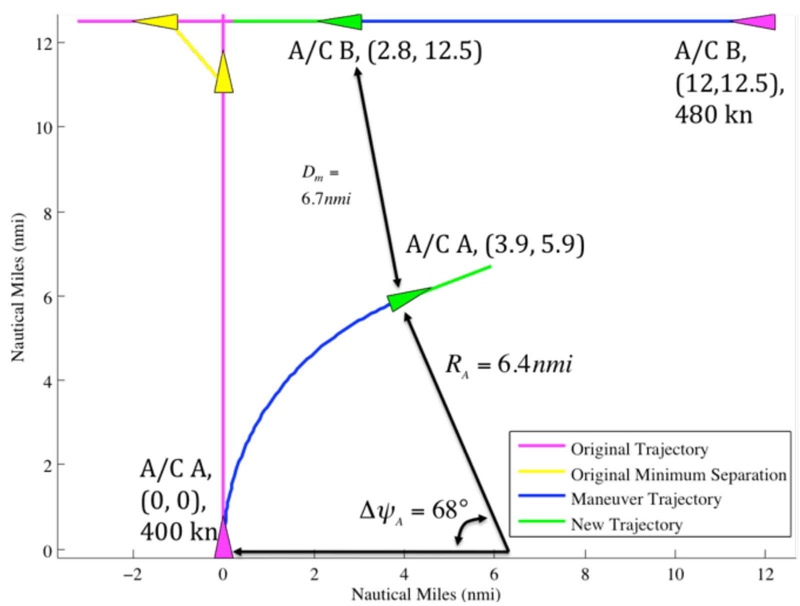

Figure 7: A/C A performs a right turn of 68° to maintain separation.

A. Significance of Turn Dynamics

Conflicts detected at two minutes or less time to first LOS are greatly affected by the turn radius and bank angle of each aircraft. At this range, changing speeds will generally have little effect in resolving a conflict.[3] However, the turn radius is greatly affected by the speed of an aircraft. Equation 4 shows the turn radius increases by the square of the speed. Any algorithm assuming instantaneous heading change for aircraft at this range will produce an inadequate resolution maneuver. The Automated Airspace Concept (AAC) contains a horizontal resolution algorithm that generates a maneuver assuming instantaneous heading change. The maneuver is passed to a trajectory engine to check the maneuver. If the resolution fails to maintain separation, an iterative process is used to revise the trajectory and check it again. However at such a close range, this iterative process is inappropriate. Figure 8 illustrates why this instantaneous heading change algorithm will not work.

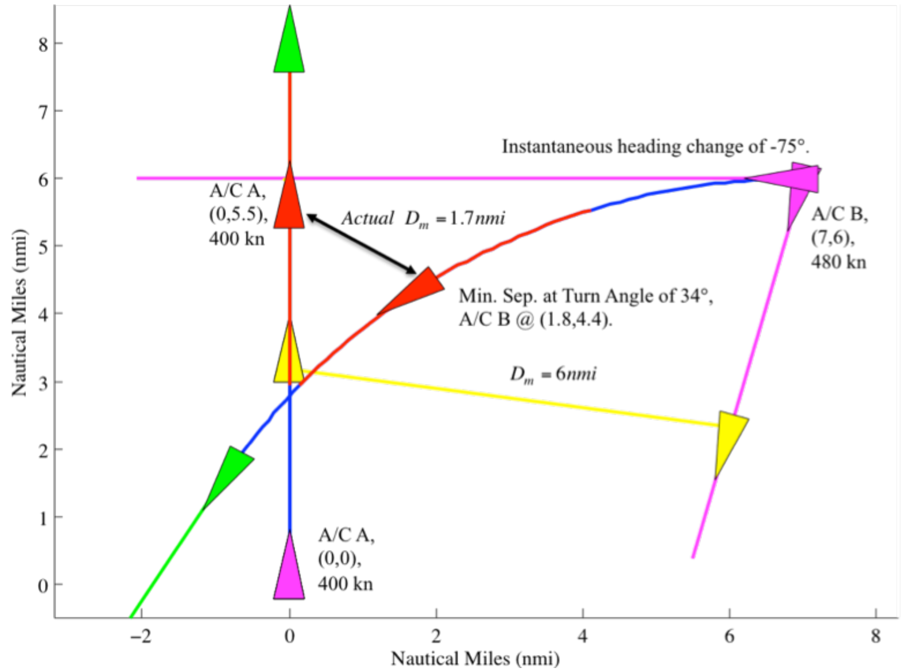

Figure 8: An instantaneous heading change algorithm claims separation is maintained, but when the maneuver is generated using turn dynamics, a LOS occurs. A larger turn angle will not make any difference in the minimum separation.

By examination of the turn radius formula in Equation 4, the greater the bank angle, the smaller the circle's radius becomes, increasing the potential distance between two resolving aircraft as seen in Figure 9. An improvement to the algorithm is to allow it to increase the bank angle when all cooperative maneuvers at a low bank angle result in LOS. [3] This method is not used for the simulations in this paper, but it is used in the performance analysis section.

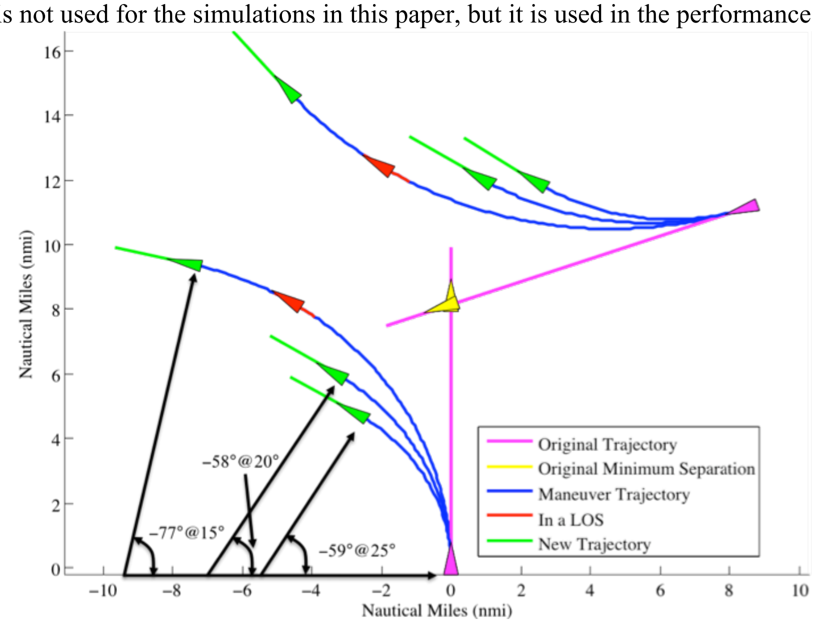

Figure 9: Shows the "turn angle @ bank angle" for one particular conflict. At a 15° bank angle, LOS is unavoidable for all maneuvers, while at greater bank angles separation is assured. These are minimum time maneuvers for 20° and 25° bank angles.

III. Simulation of a Pair-Wise Horizontal Conflict Detection and Resolution Algorithm

The goal of the simulation is to assess the performance of a pair-wise conflict resolution process in the presence of more than two aircraft. Having a variable amount of aircraft interact in one area will help measure the performance of this pair-wise separation assurance algorithm. The same dynamics used by the resolution algorithm are used to model the dynamics of the simulated aircraft. Aircraft are introduced one at a time into a square and single altitude airspace until a specified density is achieved. A single altitude is sufficient to investigate the performance of a horizontal resolution algorithm. Each aircraft flies on a straight path only altered by the separation assurance algorithm, with no attempt to return to original heading once a maneuver is performed. When an aircraft reaches the edge of the airspace, a new aircraft replaces it. Any new aircraft is introduced at a random position along the edge with new appropriate random values for speed and heading. There are many parameters available to this simulation, some are randomly generated during run time, some are set at the beginning, and some are constant throughout all runs. More details of the simulation are available by Trapani.[4] Table 1 lists the key parameters.

Delay Before Maneuver	By default this is zero. The simulation may assume all maneuvers will be performed at some time delay after detection unless LOS will occur as a direct result of this delay. In this case it will perform an immediate maneuver.
Required Separation	The required separation between any two aircraft is five nautical miles. If two aircraft are closer than this distance, it is recorded as a loss of separation (LOS). The pair-wise separation assurance algorithm requires six nautical miles to create a buffer handling discrete calculation errors in aircraft position.
Aircraft Density	The aircraft density is specified at the beginning of a simulation and it is maintained throughout the entire run. The default density is set to 25 aircraft.
Simulation Run Time	The run time is set at the beginning of each simulation. This is 50 hours by default.
Bank Angle ϕ	Set at a constant of 20° for all simulations.
Range of Speed	Each aircraft is randomly assigned a constant speed when it is initialized. This speed range is 300 knots to 500 knots.
Range of Heading	Each aircraft is assigned a heading appropriate for the border it will enter from. For instance, if it is entering along the west border, then it should be heading east, leaving a heading range from greater than zero degrees to less than 180 degrees.

Table 1: Simulation parameters. Some parameters are constant and some can be changed at the beginning of each simulation.

A. Conflict Resolution, Secondary Conflicts, and the Classifications of a LOS

Conflicts are detected and resolved when the time to first LOS is less than or equal to the parameter given at the start of the simulation. Any aircraft that are not currently performing a maneuver and are within detection range are a candidate for conflict detection.

During a simulation there are two types of conflict detections. A primary pair-wise conflict is always detected at the parameter time to first LOS. An attempt is made to resolve primary conflicts by passing the pair of aircraft to the separation assurance algorithm and generating a resolution maneuver. If a maneuver maintains separation, it will attempt to minimize the total time to complete the maneuver. If a maneuver results in a LOS, it will maximize the minimum separation.

A secondary conflict is detected when one or both aircraft have recently finished a resolution maneuver. An immediate secondary conflict occurs when an aircraft has finished a maneuver and is immediately in conflict with a third aircraft. This may result in a conflict detection at a time less than the parameter time to first LOS. The conflict detection and resolution algorithm does not look ahead and resolve for secondary conflict. It will detect, count, and resolve them once both aircraft are not currently maneuvering. While a secondary conflict is counted up to two minutes after a maneuver is finished, it will many times occur immediately at the end of a maneuver.

If an aircraft is maneuvering to resolve a conflict, it may lose separation with a third aircraft not involved in the conflict during its maneuver. This third aircraft may be flying straight or performing its own maneuver to resolve a separate conflict. These are not counted as conflicts as long as both aircraft are maneuvering while in LOS since a conflict is only counted when a resolution maneuver takes place.

Every LOS is recorded as one of two types. The first type occurs when a pair-wise resolution results in an immediate secondary conflict detection. This secondary conflict causes an unavoidable LOS, as shown in Figure 10, and is detected at less than the time to first LOS parameter. The other type, as previously explained, is shown in Figure 11 and Figure 12. In both cases, while one aircraft is turning as part of a resolution maneuver, it loses separation with a third, uninvolved aircraft. This third aircraft may be flying straight or it may be turning as part of its own conflict resolution.

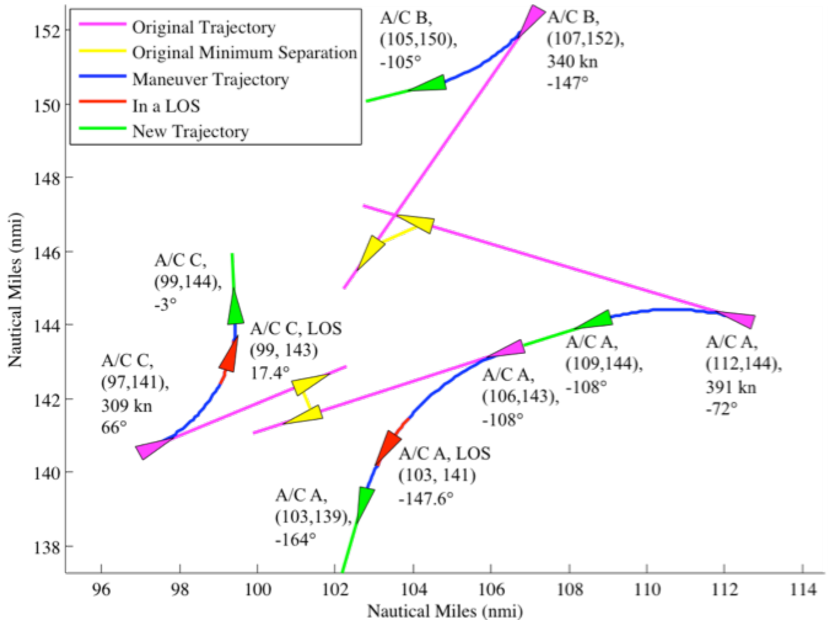

Figure 10: A/C A maneuvers into an immediate secondary conflict with A/C C, resulting in a LOS.

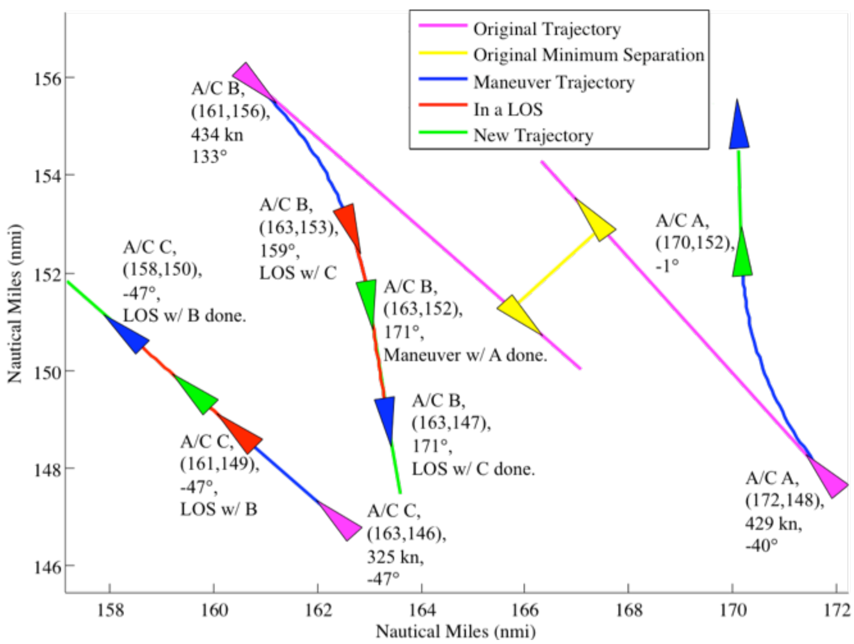

Figure 11: As A/C A and B maneuver to avoid each other, B loses separation with A/C C which is flying straight. B finishes its maneuver with A while still in a LOS with C.

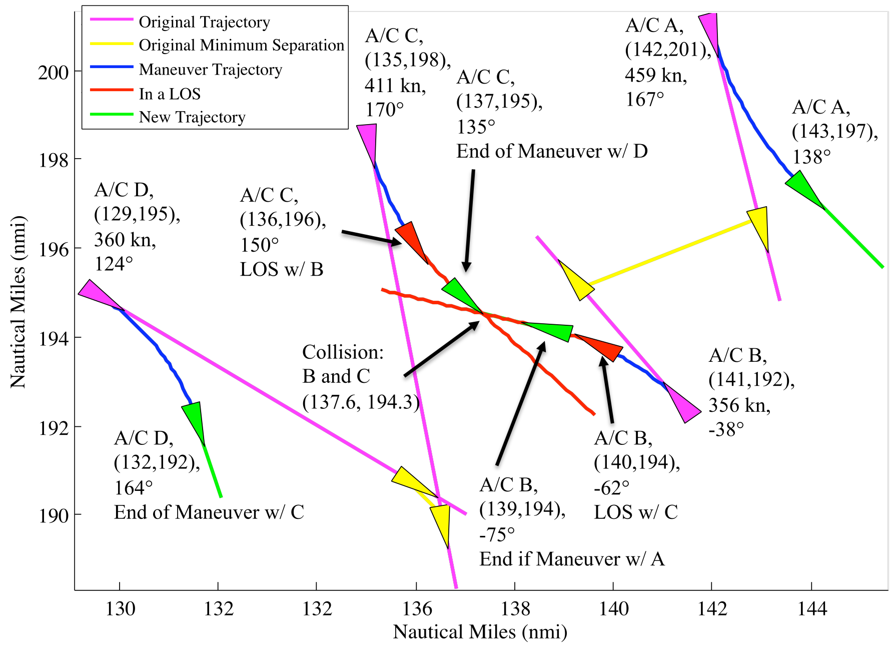

Figure 12: Two pair-wise conflicts resolve near each other resulting in a collision between A/C's B and C. When both B and C finish their maneuvers, they are 10 seconds from a collision.

IV. Analysis of Simulation Results

The performance of the separation assurance algorithm is being measured by varying key parameters of the simulation, analyzing the recorded statistics, visually confirming the results, and finally plotting collected data. Key parameters include time to first LOS, detection range, and aircraft density. Important results include the counted number of each type of LOS and conflict, the number of cooperative and single aircraft maneuvers, and the number of times the two aircraft fail two agree on the same maneuver.

A. Varying Time to First LOS

As the time to first LOS approaches zero, certain borders of the separation assurance algorithm are found. These borders include the time when single aircraft maneuvers can no longer maintain separation, causing the algorithm to switch to cooperative maneuvers, and the time when primary conflicts will result in unavoidable LOS.

When a single A/C maneuvering is no longer sufficient to maintain separation, the algorithm will attempt a cooperative maneuver. In order to find this point, the key parameter time to first LOS is varied from three minutes down to 3 seconds. At each time to first LOS, the simulation is run ten times. Each run is set at the default values found in Table 1 with an aircraft density of 25, equivalent to current air traffic density. The delay before the maneuver is set to zero seconds causing both aircraft to maneuver immediately after conflict detection. In addition, this simulation is repeated for each of the three bank angles 15°, 20°, and 25°. The time when cooperative maneuvers are required is reduced as the bank angle increases. The mean of the data for 10 simulations for each time to first LOS and bank angle is used to produce Figure 13 through Figure 15. This same method is used for all plots in this chapter.

A good indicator that primary conflicts are no longer being resolved by cooperative maneuvers is when the number of cooperative maneuvers drop below the number of conflicts detected at less than the time to first LOS parameter. One may note the number of secondary conflicts looks very similar to the number of conflicts detected at less than the time to first LOS. This is because all conflicts detected at less than the time to first LOS must be an immediate secondary conflict detected at the end of a maneuver. However, not all secondary conflicts are detected at less than the time to first LOS parameter, especially at higher times to first LOS.

Next, as the time to first LOS approaches zero seconds, there will be a point when primary conflicts result in unavoidable LOS. By counting the types of LOS that are occurring at each time to first LOS, the results will show when the algorithm predicts separation cannot be assured for primary conflicts using cooperative maneuvers. Figure 16 through Figure 18 show this threshold for different bank angles.

Once primary conflicts no longer result in LOS, the other two types of LOS are the result of more than two aircraft in a local area. As two aircraft finish a maneuver, each of them may become in an immediate secondary conflict, potentially resulting in an unavoidable LOS. As two aircraft maneuver to avoid each other, it is possible one of them will lose separation with a third aircraft. This third aircraft may even be maneuvering to avoid its own conflict. As the time to first LOS increases, it is more likely that the time when a secondary conflict is detected allows it to be resolved safely. This will reduce the number of LOS by immediate secondary conflicts. However, the total number of LOS is remaining approximately constant as the time to first LOS grows. The number of LOS by an uninvolved third aircraft increases in frequency. This increase is likely caused by maneuvering aircraft having a greater opportunity to breach the maneuver space of other primary conflicts. At a higher time to first LOS, most primary conflicts are resolved by a single aircraft maneuver. Recall both maneuvering aircraft will ignore other aircraft even during a single aircraft maneuver.

As time to first LOS is increasing, the number of LOS with aircraft un-involved in the pair-wise conflict is becoming more frequent. This trend supports an improvement to this algorithm. Both aircraft involved in a pair-wise conflict will generate the eight possible maneuvers. By using the same assumptions from the algorithm, each aircraft can check each of the generated maneuvers against all other aircraft within its detection range. This is a secondary conflict detection algorithm along each of the potential maneuvers trajectories. Once a set of safe maneuvers has been found, each aircraft can communicate its intent to all other aircraft and start performing the maneuver. If any other aircraft need to perform a conflict resolution, they will be able to use the same secondary conflict detection and see any aircraft's intent, whether it be flying straight or turning. By looking ahead, a secondary conflict resolution algorithm can avoid many LOS with third aircraft un-involved in the initial pair wise conflict. This algorithm is part of the future work by Professor Heinz Erzberger.

A final test for this section is to increase the aircraft density by a factor of two. At a bank angle of 20 degrees, the same trends occur for two times density in Figure 19 and Figure 20 as seen at one times density in Figure 14 and Figure 17. Further exploration of increasing air traffic density is presented in the next section.

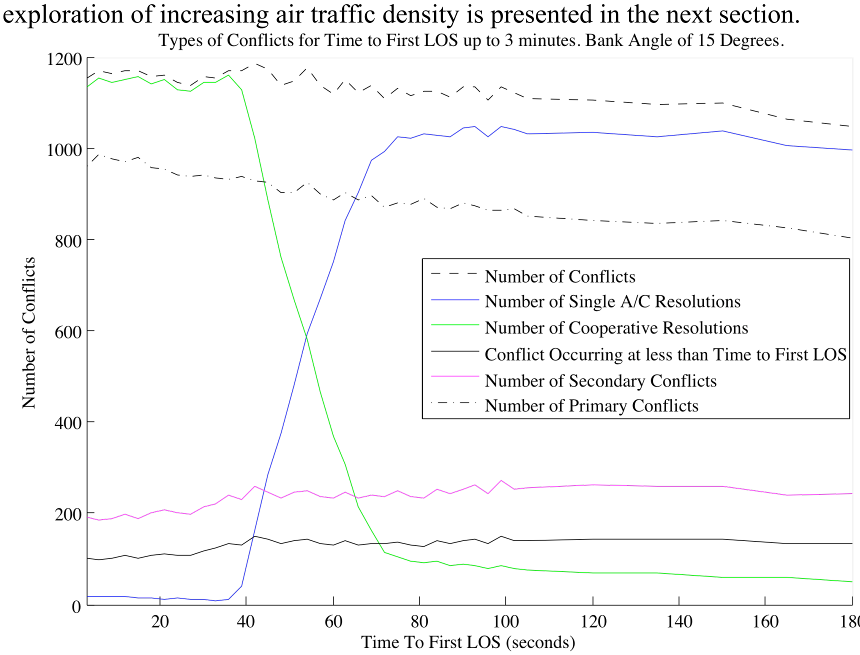

Figure 13: The number of cooperative and single aircraft maneuvers required flips and becomes approximately constant as the time to first LOS increases. For a 15° bank angle, primary conflicts are resolved by single aircraft maneuvers at greater than 72 seconds.

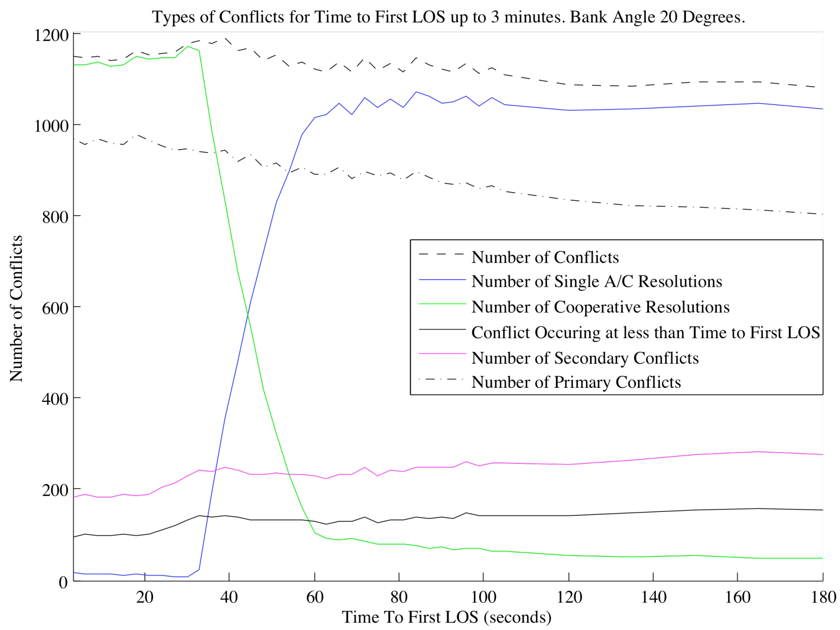

Figure 14: The number of cooperative and single aircraft maneuvers required flips and becomes approximately constant as the time to first LOS increases. For a 20° bank angle, primary conflicts are resolved by single aircraft maneuvers at greater than 57 seconds.

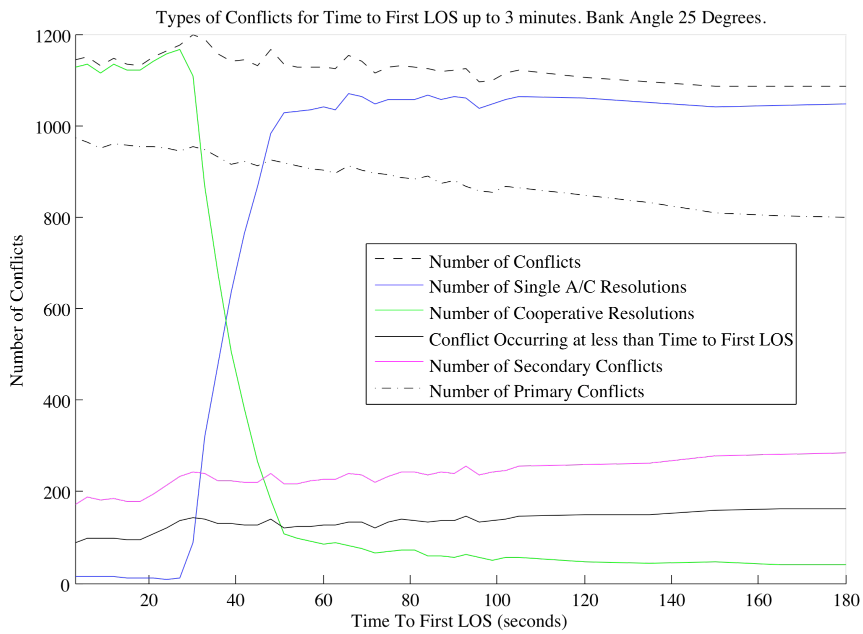

Figure 15: The number of cooperative and single aircraft maneuvers required flips and becomes approximately constant as the time to first LOS increases. For a 25° bank angle, primary conflicts are resolved by single aircraft maneuvers at greater than 51 seconds.

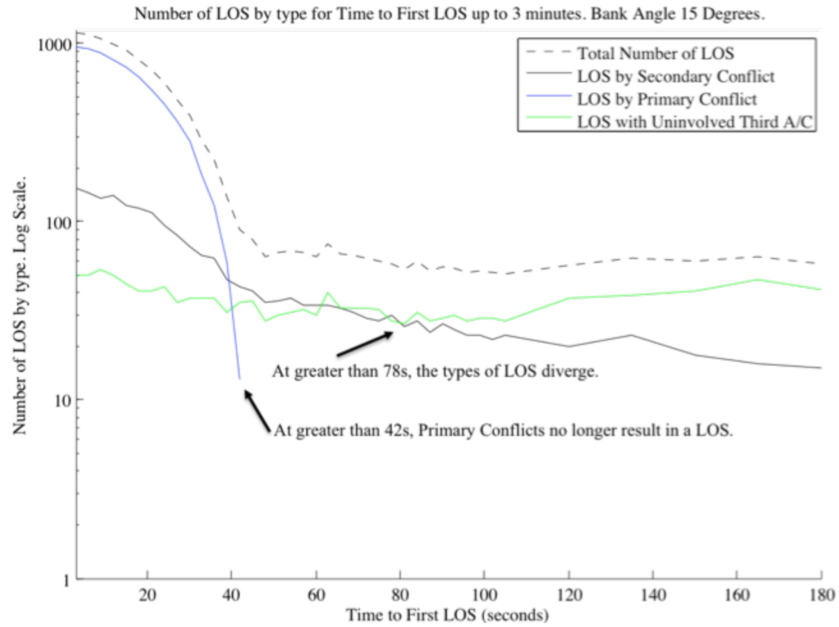

Figure 16: Primary conflicts may result in unavoidable LOS for a 15° bank angle when time to first LOS is less than 42 seconds.

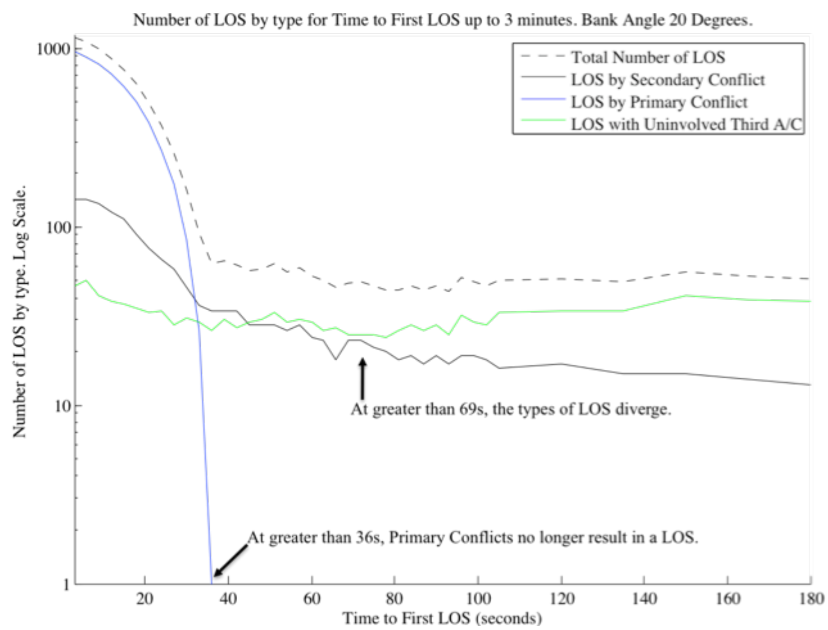

Figure 17: Primary conflicts may result in unavoidable LOS for a 20° bank angle when time to first LOS is less than 36 seconds.

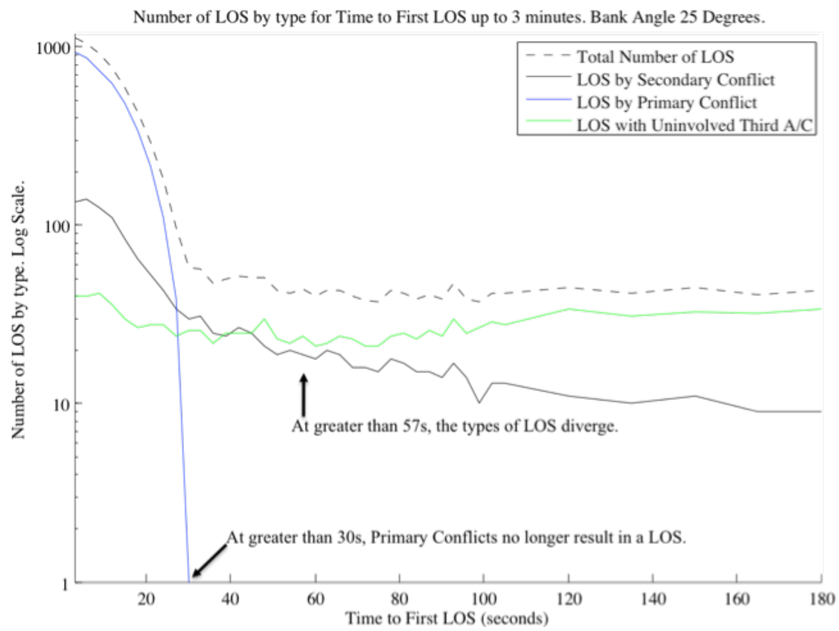

Figure 18: Primary conflicts may result in unavoidable LOS for a 25° bank angle when time to first LOS is less than 30 seconds.

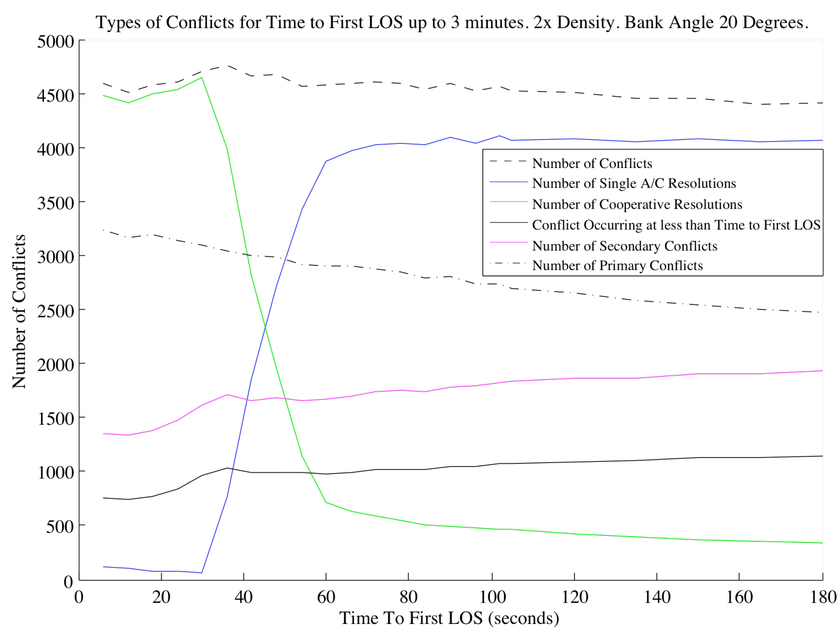

Figure 19: The same trends occur at two times density as in Figure 14 at one times density. Few primary conflicts before 57 seconds require cooperative maneuvers.

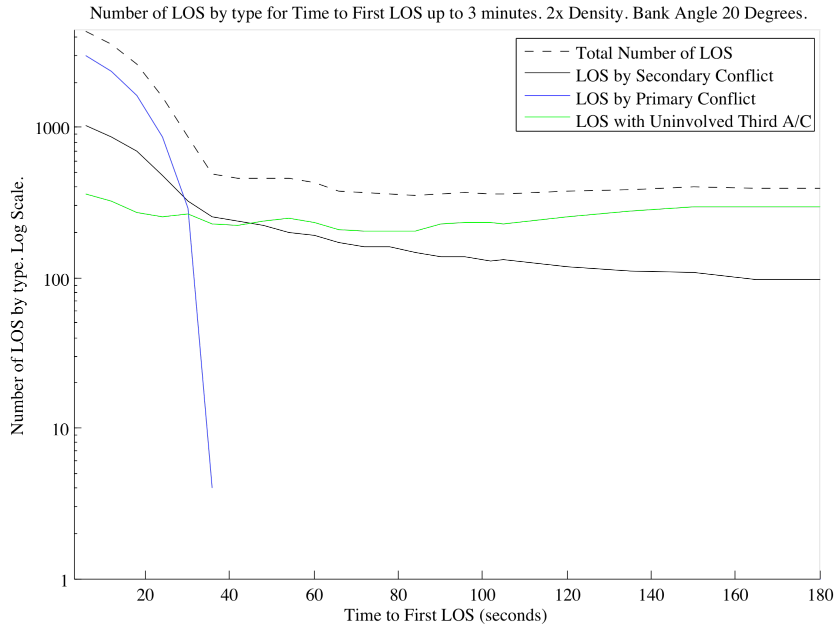

Figure 20: The same trends occur at two times density as in Figure 17 at one times density. Primary conflicts no longer result in LOS after 36 second.

B. Increasing Aircraft Density

One goal of implementing this simulation was to be able to check the effects of increased aircraft density upon this pair-wise separation assurance algorithm. The simulation is run thirty times at each aircraft density, ten times for one, two, and three minutes time to first LOS. The default values are used from Table 1. Figure 21 through Figure 23 show the number of each type of conflicts. As air traffic density increases, the total number of conflicts grows quadratically, the percentage of secondary conflicts increases, and the percentage of conflicts resolved by cooperative maneuvers also increases. However, as the time to first LOS increases, the number of conflicts requiring a cooperative maneuver is reduced, even though the percentage of conflicts resolved by a cooperative maneuver is higher at three times density, 75, than at one times density, 25. This is a result of primary conflicts no longer using cooperative maneuvers and more secondary conflicts being detected at the max time to first LOS range.

As the aircraft density grows, Figure 24 through Figure 26 show the number of LOS by an uninvolved, third aircraft grows faster than the number of immediate secondary conflicts resulting in an unavoidable LOS. As there are more aircraft in the airspace, the chance of running into other aircraft increases, causing more LOS by aircraft not involved in the conflict. This again is showing secondary conflict detection and resolution is an important next step in developing this algorithm.

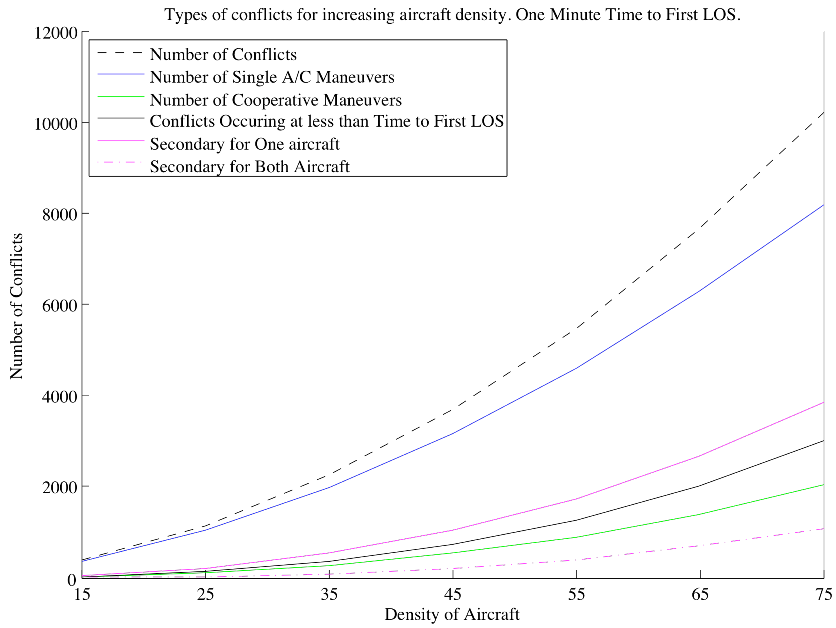

Figure 21: As aircraft density increases, the percentage of secondary conflicts increases. At one-minute time to first LOS and a 20° bank angle, there are few primary conflicts requiring a cooperative solution.

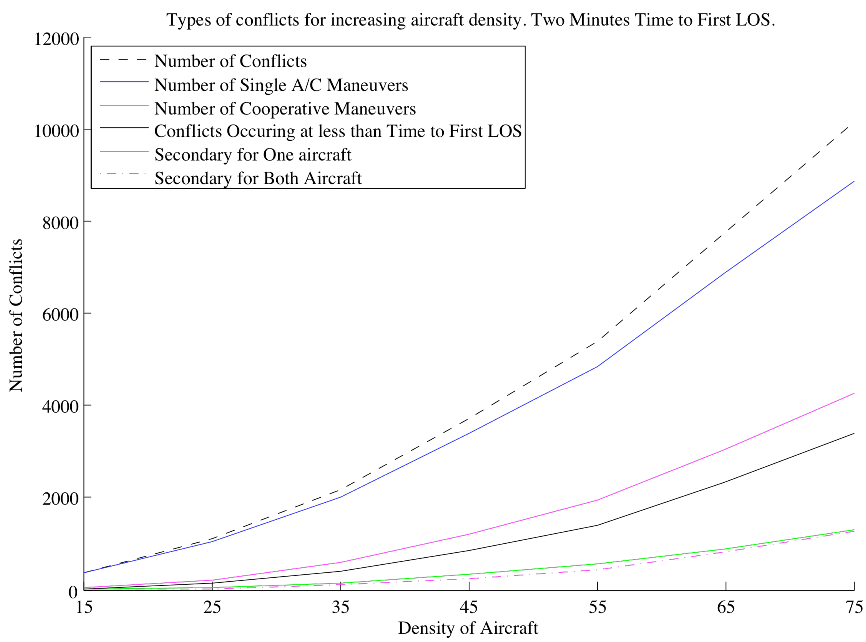

Figure 22: At two minutes, the percentage of conflicts that are secondary and the number of cooperative maneuvers is smaller than for one minute time to first LOS.

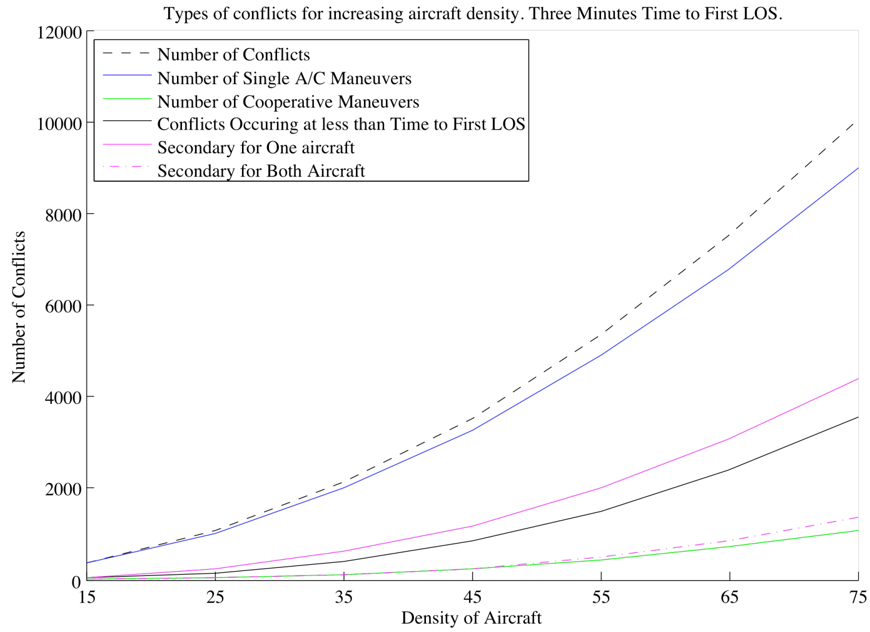

Figure 23: As aircraft density increases, the percentage of secondary conflicts is even smaller for three minutes time to first LOS and fewer conflicts require a cooperative maneuver.

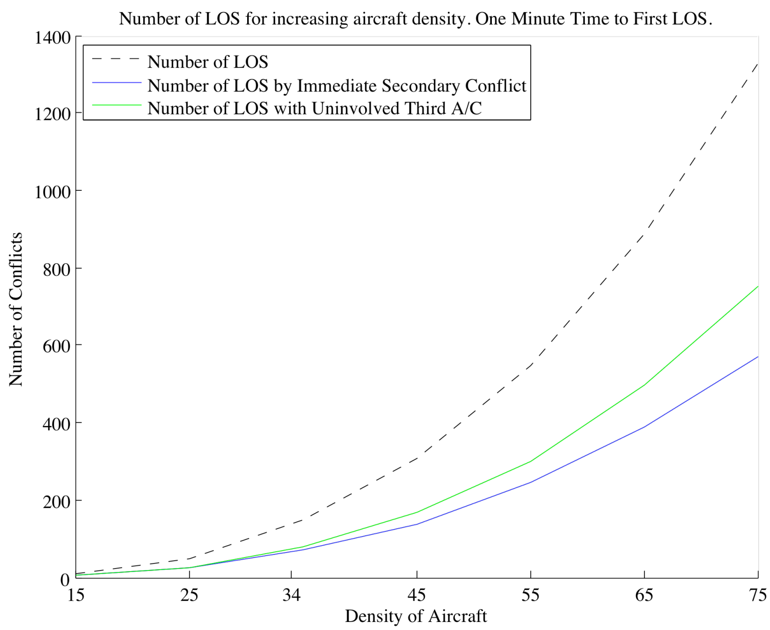

Figure 24: As aircraft density increases, the number of LOS due to an aircraft not involved in the conflict is increasing faster than the number of LOS by immediate secondary conflict. One minute time to first LOS.

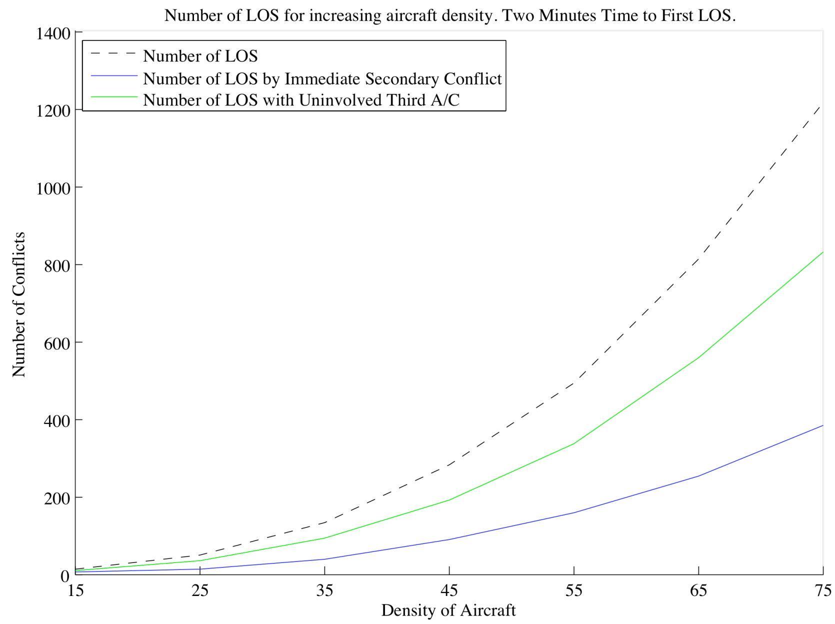

Figure 25: As aircraft density increases, the number of LOS due to an aircraft not involved in the conflict is increasing faster than the number of LOS by immediate secondary conflict. Two minutes time to first LOS.

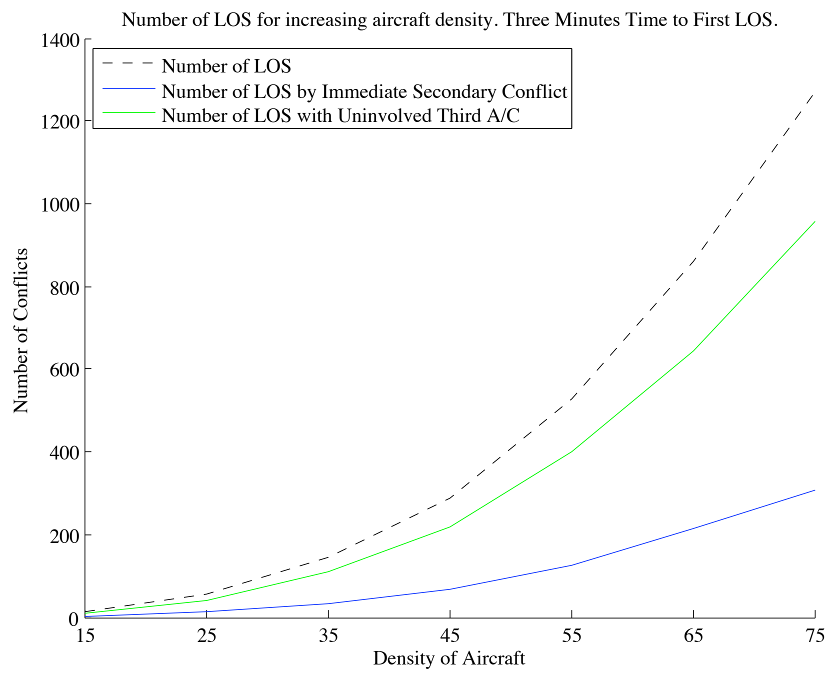

Figure 26: As aircraft density increases, the number of LOS due to an aircraft not involved in the conflict is increasing faster than the number of LOS by immediate secondary conflict. Three minutes time to first LOS.

C. Varying Detection Range

The detection radius of an aircraft defines the area in which it can see other aircraft and obtain their speed, heading, and position. By default this radius is 50 nmi. In a distributed manner, each aircraft updates its set of aircraft within its detection radius at each time step of the simulation. As the detection radius approaches the minimum separation required between two aircraft, the number of unavoidable LOS will approach the total number of conflicts detected. The detection radius has been varied from 100 nmi down to 5 nmi using a two minutes time to first LOS and otherwise default values from Table 1. For each detection radius, the simulation is run ten times and the mean is taken to produce the following figures.

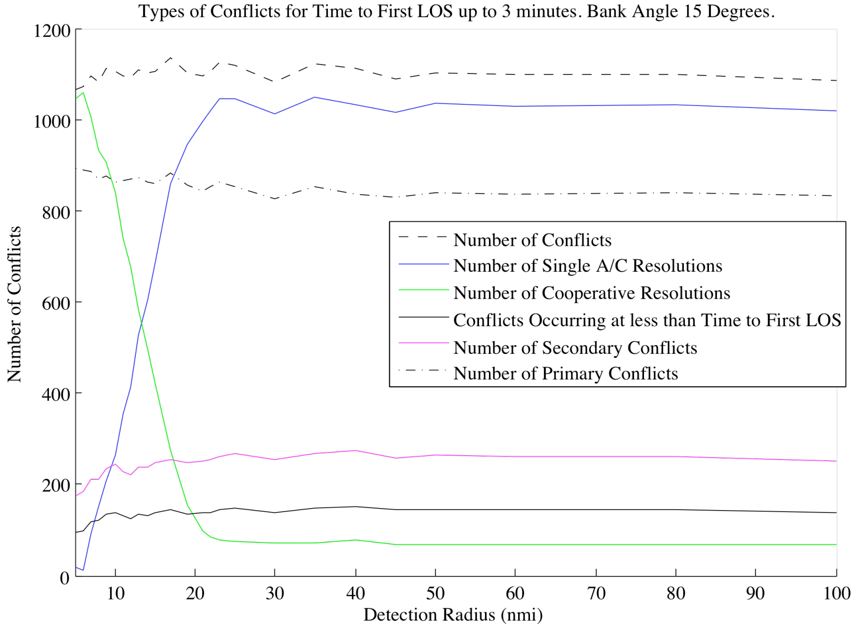

Figure 27: Number of conflicts as the detection radius approaches zero for a 15° bank angle. Primary conflicts do not require cooperative maneuvers after a 22 NMI detection radius.

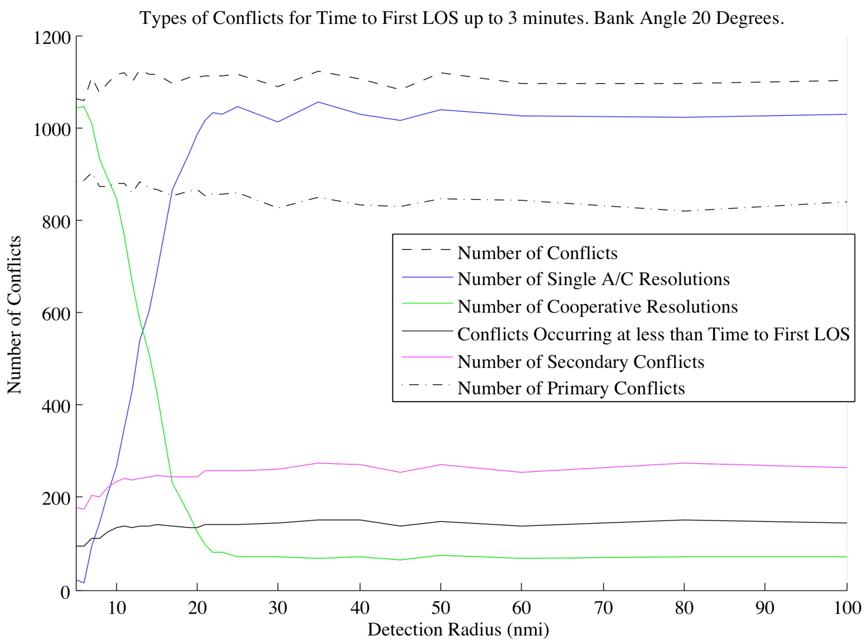

Figure 28: Number of conflicts as the detection radius approaches zero for a 20° bank angle. Primary conflicts do not require cooperative maneuvers after a 21 NMI detection radius.

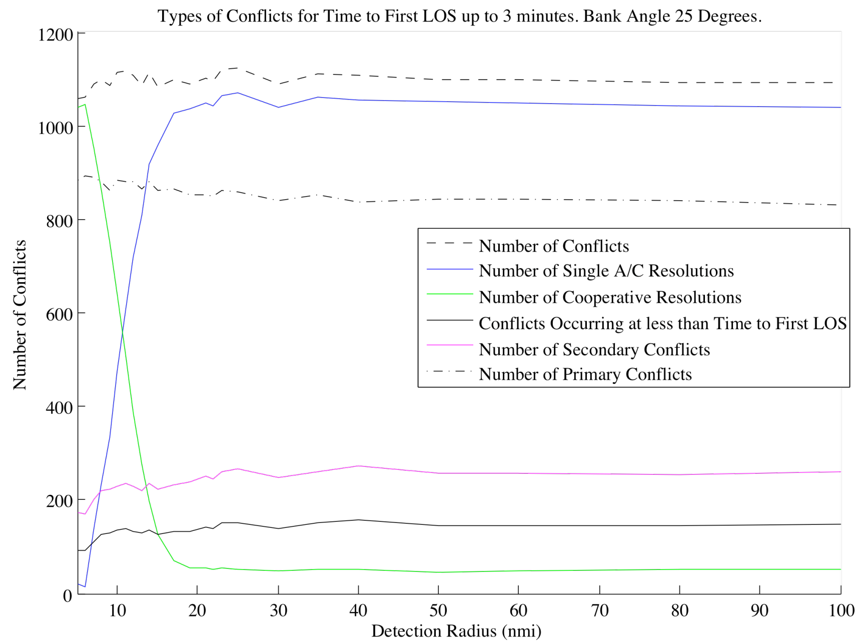

Figure 29: Number of conflicts as the detection radius approaches zero for a 25° bank angle. Primary conflicts do not require cooperative maneuvers after a 17 NMI detection radius.

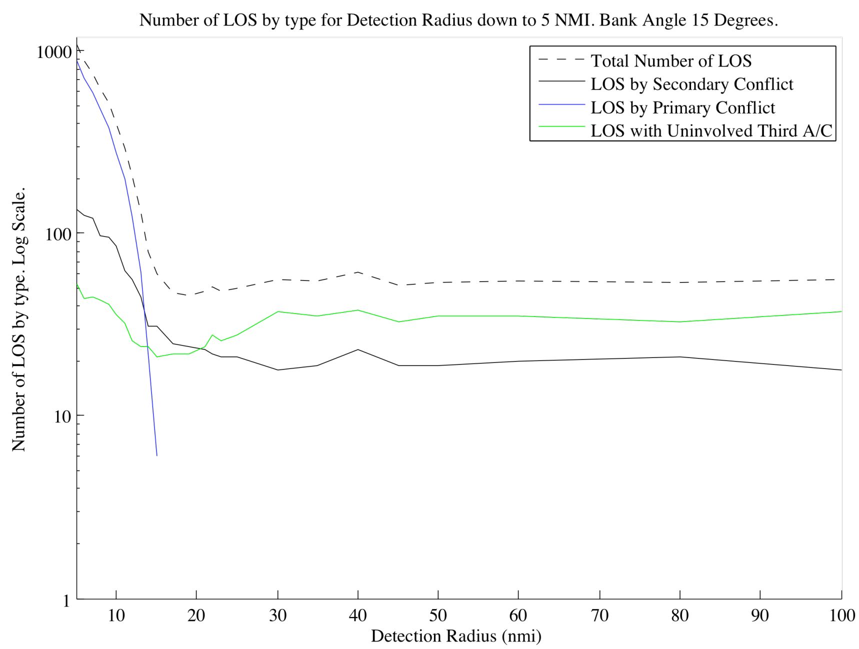

Figure 30: At a 15° bank angle, primary conflicts no longer lose separation after a 16 nmi detection radius.

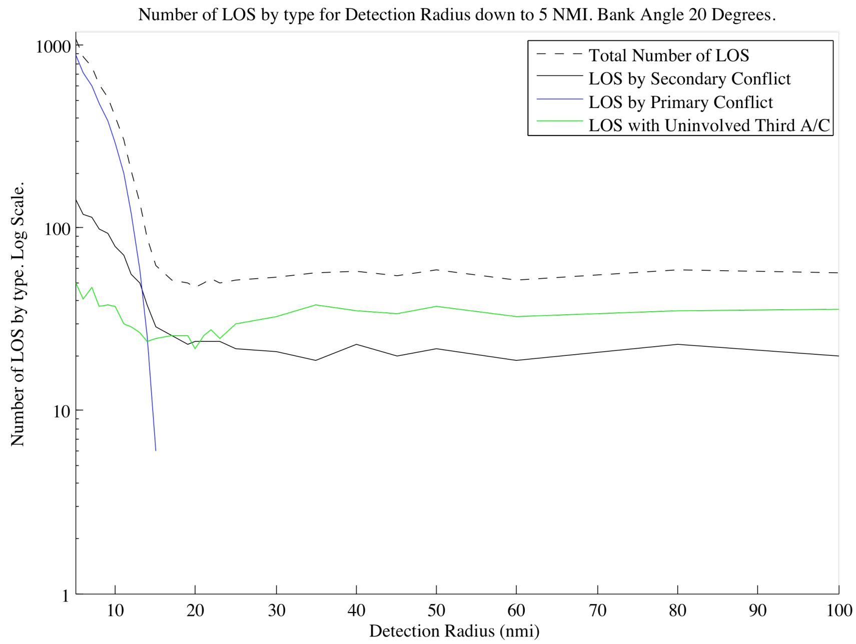

Figure 31: At a 20° bank angle, primary conflicts no longer lose separation after a 15 nmi detection radius.

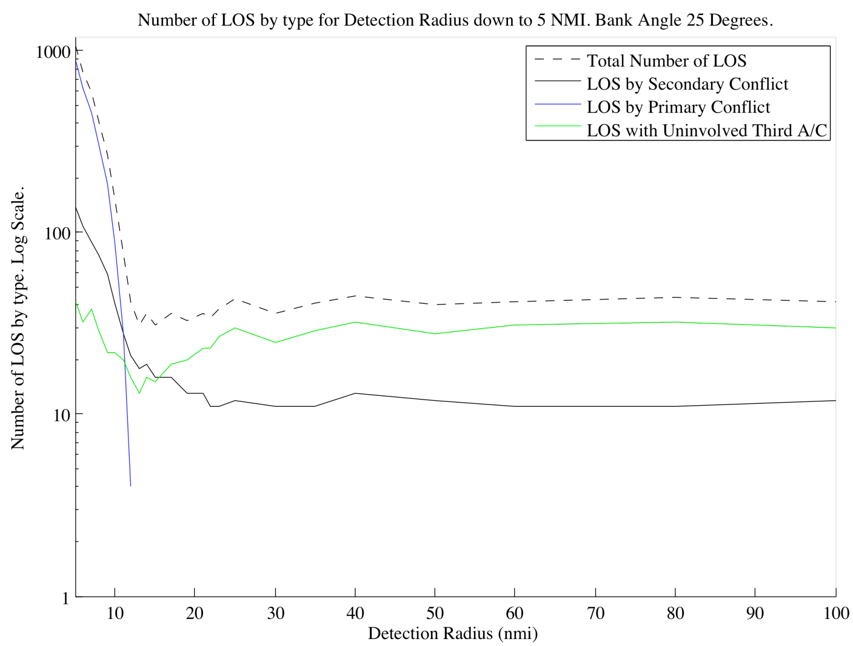

Figure 32: At a 25° bank angle, primary conflicts no longer lose separation after a 12 nmi detection radius.

Type of Relation	Bank Angle	Minimum Time to first LOS	Minimum Detection Range
Primary conflicts no longer require cooperative resolutions.	15°	72s	22 nmi
	20°	57s	21 nmi
	25°	51s	17 nmi
Primary conflicts result in unavoidable LOS.	15°	42s	16 nmi
	20°	36s	15 nmi
	25°	30s	12 nmi

Table 2: The relationship between bank angle, time, and detection radius showing the performance of the separation assurance algorithm.

As the detection range approaches zero, the same trends occur as when the time to first LOS approaches zero. This allows a relation between distance and time given varying air speeds shown in Table 2. Time was measured at a higher resolution than distance, causing the relationship to be an approximation.

D. Constraints on the Separation Assurance Algorithm

This implementation of the separation assurance algorithm tries to minimize total time to minimum separation without consideration of returning to original path or for secondary conflicts. It will first select a single aircraft maneuver if it assures separation, else it will use a cooperative maneuver. While an aircraft is performing a maneuver, either turning or flying straight, it will ignore all other conflicts until it has reached minimum separation.

Ignoring all other aircraft until it has completed a maneuver will cause many immediate secondary conflicts and LOS with uninvolved third aircraft. Secondary conflict detection and resolution (CD&R) solves many of the problems found in the previous sections. However, there will still be cases where a secondary CD&R algorithm will not be able to avoid a LOS. This may occur because of two conflicts resolving simultaneously in the same local area, or perhaps there are simply too many aircraft and resolving the situation is beyond the capabilities of pair-wise secondary CD&R.

When the algorithm minimizes for total time, it will usually select a larger turn angle for which the minimum separation occurs at the end of the turn. When the algorithm chooses a single aircraft maneuver, it is possible it could take well over double the time a cooperative maneuver would have used. This is an operational issue where the pilots, air traffic controllers, implementation choices, and other factors may all play roles in choosing the maneuver.

There is a possibility aircraft will, in a distributed manner, come to different conclusions about which of the eight maneuvers to perform. This may result in a LOS because of a failure to agree on the same maneuver. However, the occurrence of these failures is relatively small when compared to the number of conflicts resolved. All aircraft can be synchronized on the same maneuver through a communication step as discussed in Chapter 3. Figure 33 shows most failures would have resulted in a LOS, thus communication for the sake of agreement must be taken into consideration during any future work.

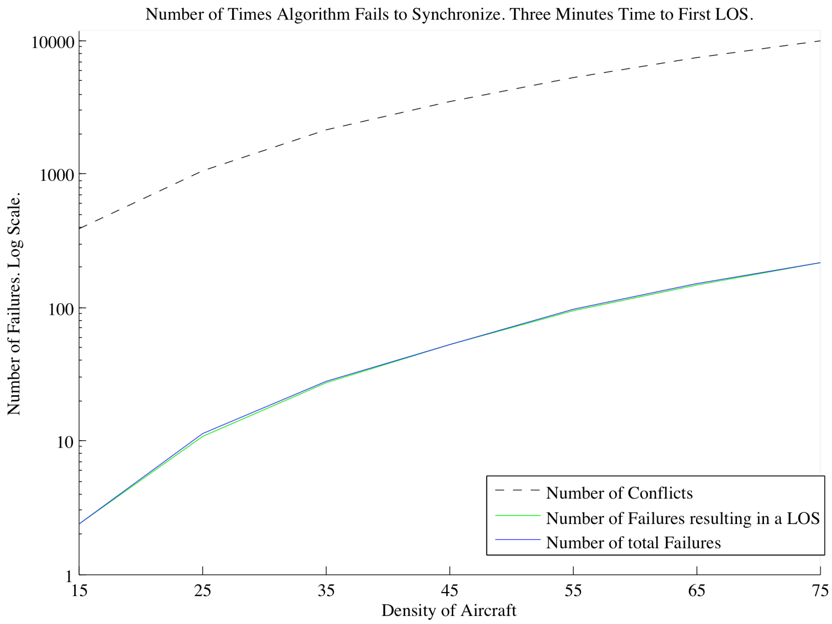

Figure 33: The number of times two aircraft fail to choose the same maneuver is relatively small compared to the number of total conflicts as aircraft density increases. All failures here are due to discrete calculation differences.

V. Summary, Conclusions, and Future Work

A simulation to test this algorithm's dynamics was developed. The simulation is built upon the turn dynamics used in the separation assurance algorithm. Important performance thresholds of the algorithm have been found by varying key parameters to the simulation and measuring their effects upon the algorithms performance. These thresholds include the time when one aircraft maneuvering is no longer sufficient for maintaining separation, and the time when primary conflicts may result in a LOS even with both aircraft maneuvering. Types of conflicts and LOS that can occur when two maneuvering aircraft ignore all other aircraft have also been observed and categorized. Counting and classifying these types of LOS are the basis for continued development of this algorithm.

Horizontal secondary conflict detection and resolution is the primary next step in developing a distributed separation assurance algorithm. By first looking ahead at the other aircraft in the local area, it is possible to choose from the available maneuvers that either avoid secondary conflicts entirely, or maximizes the time at which a secondary conflict is detected if one is unavoidable. Once a maneuver has been decided upon, each aircraft could broadcast its intentions to every other aircraft. Given known intent, it is likely possible to avoid many of the observed secondary conflicts.

Another future step is to evaluate the algorithm's robustness to a delay before the maneuver begins. If one aircraft decides to start the maneuver later than expected, the amount of delay allowed until a LOS would occur on the expected maneuver must be determined.

Given the structure of the algorithm and the option of broadcasting intent, it may be possible to predict conflict detections for other aircraft. This is important if two pair-wise conflicts occur in a local area at the same time, such as in Figure 11. If they can predict each other's conflict, they could communicate intent to help resolve any secondary conflicts or LOS that may otherwise occur without coordination. The method of a timely, accurate, and secure communication is future work.

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