

A COMPLEXITY METRIC FOR AUTOMATED SEPARATION

Arwa Aweiss, NASA Ames Research Center, Moffett Field, California

Abstract

A metric is proposed to characterize airspace complexity with respect to an automated separation assurance function. The Maneuver Option metric is a function of the number of conflict-free trajectory change options the automated separation assurance function is able to identify for each aircraft in the airspace at a given time. By aggregating the metric for all aircraft in a region of airspace, a measure of the instantaneous complexity of the airspace is produced. A six-hour simulation of Fort Worth Center air traffic was conducted to assess the metric. Results showed aircraft were twice as likely to be constrained in the vertical dimension than the horizontal one. By application of this metric, situations found to be most complex were those where level overflights and descending arrivals passed through or merged into an arrival stream. The metric identified high complexity regions that correlate well with current air traffic control operations. The Maneuver Option metric did not correlate with traffic count alone, a result consistent with complexity metrics for human-controlled airspace.

Introduction

Airspace complexity research to date has focused on controller workload associated with the separation assurance tasks. While such approaches show promise for human-controlled airspace operations, they may not be adequate for future concepts of more automated airspace operations. The work of Kopardekar et al. begins to bridge this gap by studying complexity factors under higher levels of automation [1]. Two of the factors considered as potential indicators of airspace complexity are the degrees-of-freedom indices. The first applies to pairs of aircraft in conflict and the second to individual aircraft.

The present work develops a Maneuver Option (MO) metric inspired by the degree-of-freedom concept proposed by Kopardekar et al. However, the focus here is on developing a metric for a specific automated separation assurance system: the Automated Airspace Concept (AAC) that forms the basis of NASA's ground-based separation assurance [2-4]. The

approach could be applied to other conflict detection algorithms. Since no algorithm is perfect in detecting and resolving conflicts, there is a need for a metric that is an indicator of when automation is reaching its limit and can no longer assure safe separation. The objective of this research is to develop a complexity metric for an automated separation assurance system and to investigate characteristics of the metric through a real-world traffic simulation.

A brief overview of airspace complexity work is presented in the next section. Then the Maneuver Option metric is introduced, and the details of the data set are presented in the methodology section. The results are presented along with some discussion of their implications. The paper concludes with a summary of the study and its findings.

Background

In human-controlled airspace, complexity is typically equated to controller workload. At present, controller workload is based on aircraft count, as expressed by Monitor Alert Parameter (MAP) values [5]. The MAP "establishes a numerical trigger to provide notification to facility personnel [traffic management team]" that the sector/airport efficiency might be degraded during specific periods of time [6]. This is an effective upper bound on the number of aircraft that can be permitted within a sector at a given time. If sector count is predicted to go over that sector's MAP value, then traffic management initiatives are implemented, which typically reduce the overall efficiency of the traffic flow. It is generally agreed that aircraft count is not always correlated with airspace complexity. Therefore, the use of MAP may lead to insufficient or excess traffic management initiatives, causing efficiency to suffer.

Air traffic demand is expected to increase dramatically in the next 20 years [7]. At this higher level of traffic, human controllers may not be able to safely separate aircraft. Automated separation assurance systems are envisioned that will safely and efficiently separate aircraft in this highly dense system [4]. Human controllers are limited by the cognitive workload associated with separating the aircraft for

which they are responsible, and MAP thresholds are the means by which that workload is kept manageable. Automated separation assurance systems are not limited by cognitive workload, so a more appropriate complexity metric for such automation is needed.

Numerous studies have proposed definitions for airspace complexity. Mogford et al. define Air Traffic Complexity as a “multidimensional construct that includes static sector characteristics (sector complexity) and dynamic traffic patterns (traffic complexity)” [8]. In a 2007 paper, Keumjin et al. define Air Traffic Complexity as “how difficult a given traffic situation is, in terms of the control activity required to resolve it, in response to an additional aircraft entering the airspace” [9]. As an improvement to MAP values, researchers proposed the Dynamic Density metric, which is a measure of airspace’s complexity at a given time. It is a combination of traffic density and traffic complexity [10]. A collaborative effort between NASA and three other organizations led to the development of a Dynamic Density metric composed of seventeen significant variables that contribute to airspace complexity. These include variables such as number of aircraft, aircraft density, horizontal and vertical proximity, and number of descending aircraft [11].

Others have studied complexity from a different perspective. Flener et al. used constraint programming to resolve complexity through “dynamic modification of flight profiles to reduce the predicted complexities over a given time interval of some sectors, thereby avoiding intolerable peaks of ATC workload” [12]. Ishutkina et al. investigated the “role of traffic flow organization in defining airspace complexity” through an interpolating velocity vector field. This was to provide a visual representation that would help air traffic controllers in resolving conflicts [13]. Idris et al. presented an approach to “manage traffic complexity in a distributed control environment, based on preserving trajectory flexibility and minimizing constraints” [14]. Bilimoria et al. looked at aircraft clustering as a way of quantifying airspace congestion independent of sector boundaries [15-17].

Maneuver Option Metric

The Maneuver Option (MO) is proposed here as a practicable complexity metric for an automated separation assurance system.

By definition, a Maneuver Option is available in a specific direction if a predetermined set of maneuvers in that direction does not cause a conflict within the next five minutes. Five Maneuver Options (straight, left turn, right turn, climb, and descent) are considered for an aircraft. A Maneuver Option encompasses several simple trajectory changes in that direction. For example, in determining the availability of a Right Turn Maneuver Option, both 15- and 30-degree heading changes are checked for conflicts over a five-minute time horizon, and an all-or-nothing condition is applied. If either heading change is not conflict-free, the Right Turn Maneuver Option is considered unavailable. As another example, in determining the availability of a Climb Maneuver Option, five altitude changes in 1000-ft increments are checked for conflicts over the same five-minute time horizon. All five altitude changes must be conflict-free in order for the Climb Maneuver Option to be considered available. This all-or-nothing criterion was applied to be conservative. A total of sixteen five-minute simple trajectory maneuvers are tested; five heading changes that include straight, 15 and 30 degrees to the right and to the left, and 11 altitude changes which include level, 5 climb, and 5 descent in 1,000-ft increments (Fig. 1). For altitude changes, the current climb/descent speed is used for aircraft already in climb or descent, and default climb (+500 ft/min) and descent (-1,500 ft/min) speeds are used for level aircraft.

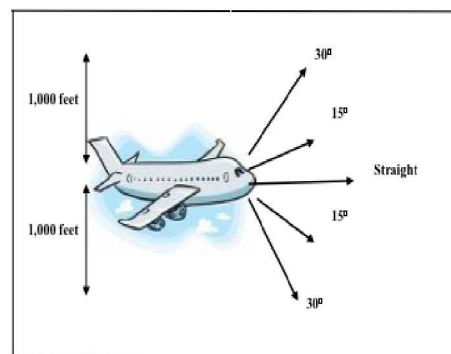


Figure 1. Maneuver Changes

Two variations of the MO metric are proposed and evaluated as measures of complexity. The first metric is the number of Zero Maneuver Options

aircraft in a region; a higher number indicates higher complexity. A Zero Maneuver Options aircraft is one for which all five of its Maneuver Options (straight, left, right, climb, and descent) are unavailable based on the logic described above. It is effectively “boxed-in.” The second MO metric is the Average MO value, which is the average number of Maneuver Options available for an aircraft in a region. The lower the Average MO value is, the higher the complexity. By checking for conflict-free maneuvers for each aircraft in any region, the algorithm inherently accounts for the geometry and existing traffic situation in the region.

Methodology

The Maneuver Options metrics were evaluated in a series of real-time, closed-loop simulations. The algorithms described in the prior section were implemented into the Center-TRACON Automation System (CTAS) airspace simulation environment. CTAS uses host track data and aircraft model data to calculate trajectories. The new capability generated simple five-minute look-ahead trajectories for each aircraft based on the five types of Maneuver Options using current position and speed for each aircraft. The predetermined set of maneuver trajectories for each aircraft was probed against the existing trajectories of all other aircraft. A one-minute execution rate was used; however, it is possible to increase the rate to 12 seconds. Every minute, as the Maneuver Options were calculated for all aircraft, the location, altitude, type (overflight, departure, arrival) and flight phase (level, descent, climb) of each aircraft were recorded. Also recorded were the type of conflict (heading or altitude), the heading or altitude step, time to conflict, location of predicted conflict, and minimum separation. Data extracted from this output included a list of aircraft at specific time steps that were detected to have a conflict and if a Maneuver Option existed in each of the five directions for each of those aircraft.

The region/volume, aircraft, and look-ahead time are inputs of the CTAS Maneuver Options capability. The horizontal separation criterion used was 5 nmi, and the vertical separation standard was 1,000 feet for level aircraft and 1,500 feet for transitioning aircraft (i.e., a mixture of level, climb, and descent). This method is sector independent, which means that it can be used to analyze any volume of airspace.

While the MO metric is primarily intended as a measure of complexity for automated systems at higher levels of traffic, current traffic levels were used for this initial study. Traffic data used for this analysis were actual recordings of Fort Worth Center (ZFW) traffic from 22:00 to 24:00 UTC time for three nominal days (05/09/2008, 03/04/2009, 03/06/2009). This two-hour interval was chosen because it is a period of high traffic congestion. At any given minute in the time period for each of the three days, the number of aircraft above 10,000 ft. in the ZFW Center ranged from 167 to 251.

Results

There are three types of analysis presented in the results section. The first is a description of MO metric results for the six-hour period. The second type is categorization of Zero Maneuver Options aircraft, and the third involves identification of complex regions as determined by the MO metric.

MO Metric Results

In this first section of the results, the categorization of aircraft based on the number of Maneuver Options available is presented. Then, the two variations of the MO metric are presented for each of the two hours of the three days. Finally, results of the correlation study of aircraft count with the MO metric are discussed.

Figure 2 shows a histogram for the number of Maneuver Options available to all aircraft above 10,000 ft. in ZFW airspace over the six-hour period. A total of 113 cases (0.12%) occurred where an aircraft had Zero Maneuver Options, meaning that Maneuver Options in both the vertical and horizontal dimensions were unavailable. These cases are not unique, in that the same aircraft could be a Zero Maneuver Options case at different points in time. It is important to note that this does not imply that there were 113 losses of separation. This high number is a byproduct of the conservative (all-or-nothing) definition of an available Maneuver Option in a specific dimension. Omitted from the figure are the 90.36% of cases of aircraft that have all their Maneuver Options available. This suggests that the ZFW airspace in this six-hour period, according to this automated separation assurance metric, is of low complexity.

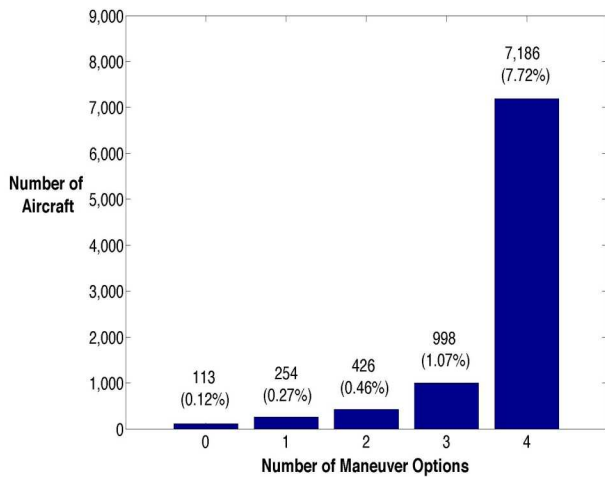


Figure 2. Histogram of Available Maneuver Options

The following is the analysis of the MO metric based on the number of Zero Maneuver Options aircraft. For this metric, a higher value implies higher complexity. In Figure 3, aircraft count on May 9, 2008, along with the number of Zero Maneuver Options aircraft is plotted over the two-hour period. The 15 minutes with the highest average aircraft count was chosen for further analysis. Notably, during the time period of 38 to 53 minutes (Period 1), which has the highest volume of traffic (average of 243), there are only six cases of Zero Maneuver Options aircraft. A second 15-minute period from 81 to 96 elapsed minutes (Period 2) has a lower overall aircraft count (average of 216) but a much higher number of cases (16) of Zero Maneuver Options aircraft. According to the MO metric, this second period would be considered more complex than the first period. However, according to the aircraft-count metric used for the MAP, Period 1 is considered more complex than Period 2. In this case, periods of complexity in terms of the MO metric based on the number of Zero Maneuver Options aircraft did not coincide with periods of highest traffic volume.

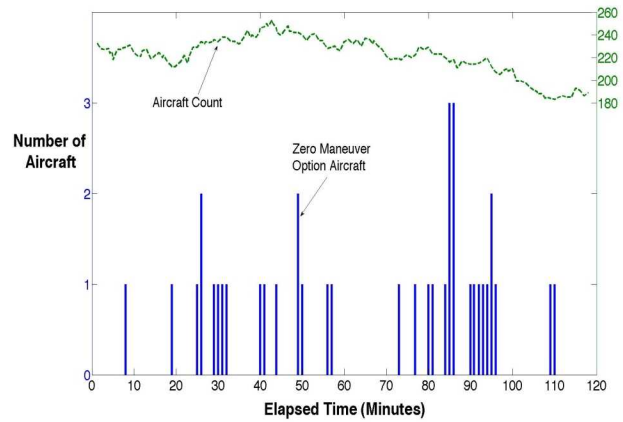


Figure 3. Zero Maneuver Options Aircraft 05-09-08

Similar results were observed for the other two days as seen in Figures 4 and 5.

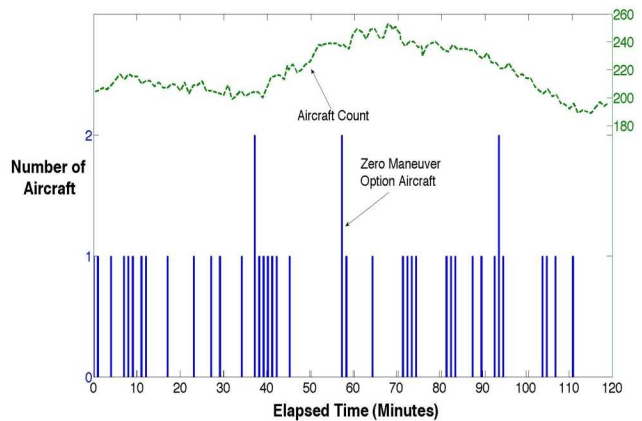


Figure 4. Zero Maneuver Options Aircraft 03-04-09

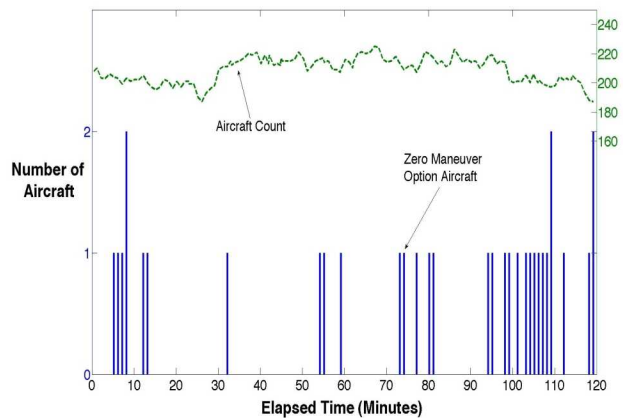


Figure 5. Zero Maneuver Options Aircraft 03-06-09

Another way to look at complexity is by defining the Average MO value as the average number of Maneuver Options available for an aircraft in a region. The value ranges from zero to five. The lower the Average MO value, the higher the complexity. Figures 6 through 8 depict the Average MO metric as compared to aircraft count for the three two-hour periods, respectively. For March 4, 2009 (Figure 7) for example, the Average MO value during the period of 60 to 75 minutes, in which there are on average 246 aircraft, is 4.86. That number is higher than that of 4.81 for the period from 27 to 42 minutes where there are on average 205 aircraft. Note that the values are still very close to 5, indicating that aircraft have most Maneuver Options available in current traffic conditions. The same is true for the other two days: periods of higher complexity as indicated by the Average MO metric do not correlate with periods of highest traffic (Figures 6 and 8).

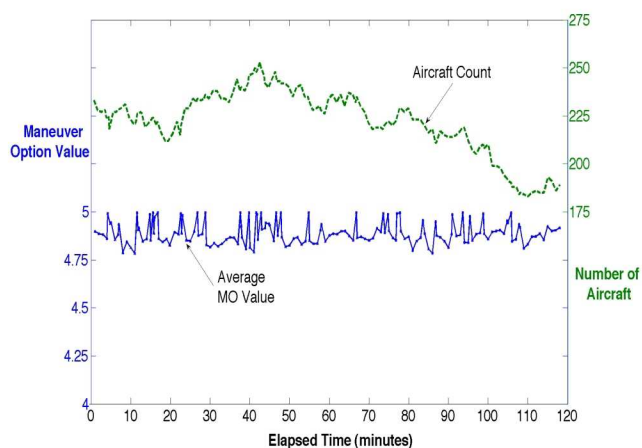


Figure 6. Average MO Value 05-09-08

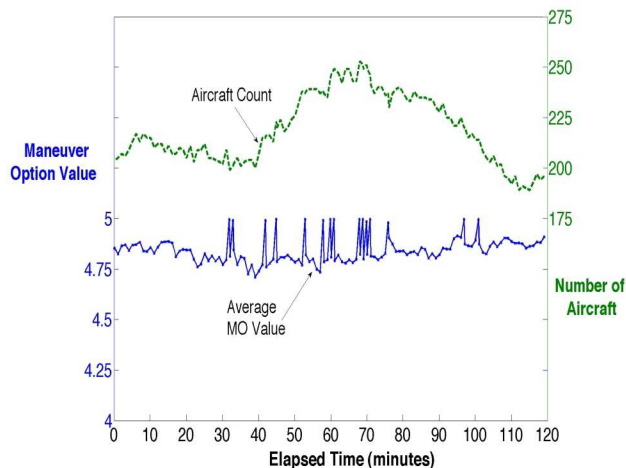


Figure 7. Average MO Value 03-04-09

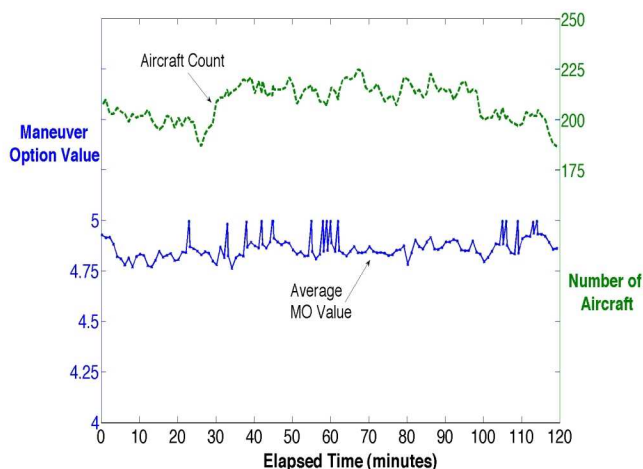


Figure 8. Average MO Value 03-06-09

To verify the results of Figures 2 through 8, the statistical correlations between total aircraft count with the number of aircraft with Zero Maneuver Options and with the Average MO value were calculated. The very low values of the correlation coefficients, ranging from 0.01 to 0.24 indicate that aircraft count and the MO metrics for this study region are uncorrelated. This finding agrees with researchers' assertion that aircraft count alone is not a good indicator of airspace complexity and therefore not a sufficient measure. In a later section of the results, the correlation for a smaller region is reported.

Categorization of Maneuver Options

As presented in the prior section, 113 cases were identified where an aircraft had no Maneuver Options. Figure 9 shows that most of these cases involve level overflight aircraft, accounting for 38.9% of the cases. Another 40.7% were aircraft in descent (overflights or arrivals). These categories of aircraft will be addressed further in the next section. As seen in Figure 10, aircraft are twice as likely to be constrained in the vertical dimension as the horizontal one.

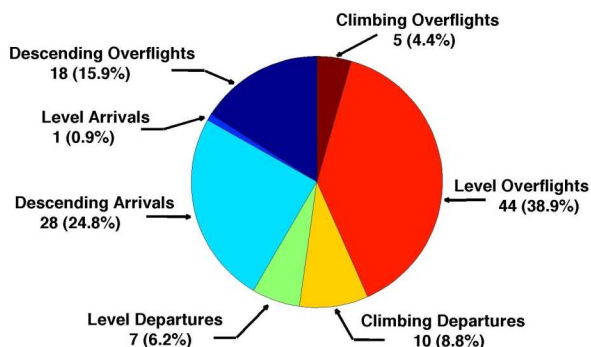


Figure 9. Aircraft with Zero Maneuver Options

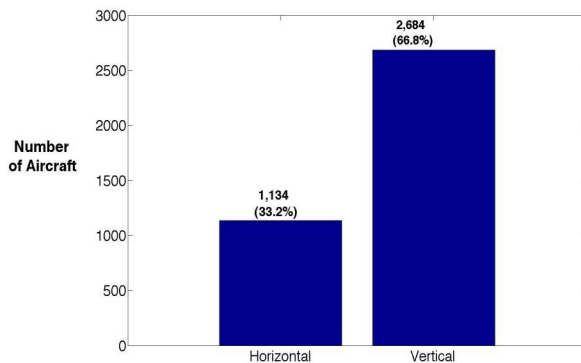


Figure 10. Unavailable Maneuver Options

Identifying Regions of Complexity

The Zero Maneuver Options metric was applied to the ZFW airspace. The breakdown of the location, by sectors, of the Zero Maneuver Options cases can be seen in Table 2. The table lists the nine sectors rated the most complex by the MO metric as defined by the number of Zero Maneuver Options aircraft. The table indicates that Sector 37 has the highest percentage (22.2%) of detected cases of Zero Maneuver Options aircraft followed by 17.6% in Sector 46. Sector 37 is the ZFW low-altitude Northeast arrival sector; Sector 46 is a ZFW high-altitude sector responsible for southbound departures. Most aircraft in these two sectors are transitioning or merging, so it is no surprise that the MO metric would identify them as being complex.

Table 2. Sector Distribution of Zero Maneuver Option Cases

Sector	# Level Arrival	# Level Departure	# Level Overflight	# Climb Departure	# Climb Overflight	# Descending Arrival	# Descending Overflight	Sector %
Sector 37	0	0	5	0	0	16	3	22.2
Sector 46	0	7	0	7	0	0	5	17.6
Sector 75	0	0	2	0	0	0	3	5.6
Sector 52	0	0	4	0	1	0	1	5.6
Sector 83	0	0	5	1	0	1	0	5.6
Sector 28	0	0	6	0	0	0	0	5.6
Sector 42	0	0	0	0	0	5	0	4.6
Sector 29	0	0	0	0	0	3	1	3.7
Sector 32	0	0	4	0	0	0	0	3.7
Seventeen other sectors	1	0	15	1	2	3	5	25.8

The geometry of the low-altitude and high-altitude ZFW sectors, as well as traffic flow patterns of the arrival and departure streams is shown in Figures 11 and 12. The white, green, and blue dots represent overflights, arrivals, and departures, respectively.

Sectors 37 and 46, which were found to be the most complex according to the Zero Maneuver Options MO metric, are highlighted in Figures 11 and 12, respectively.

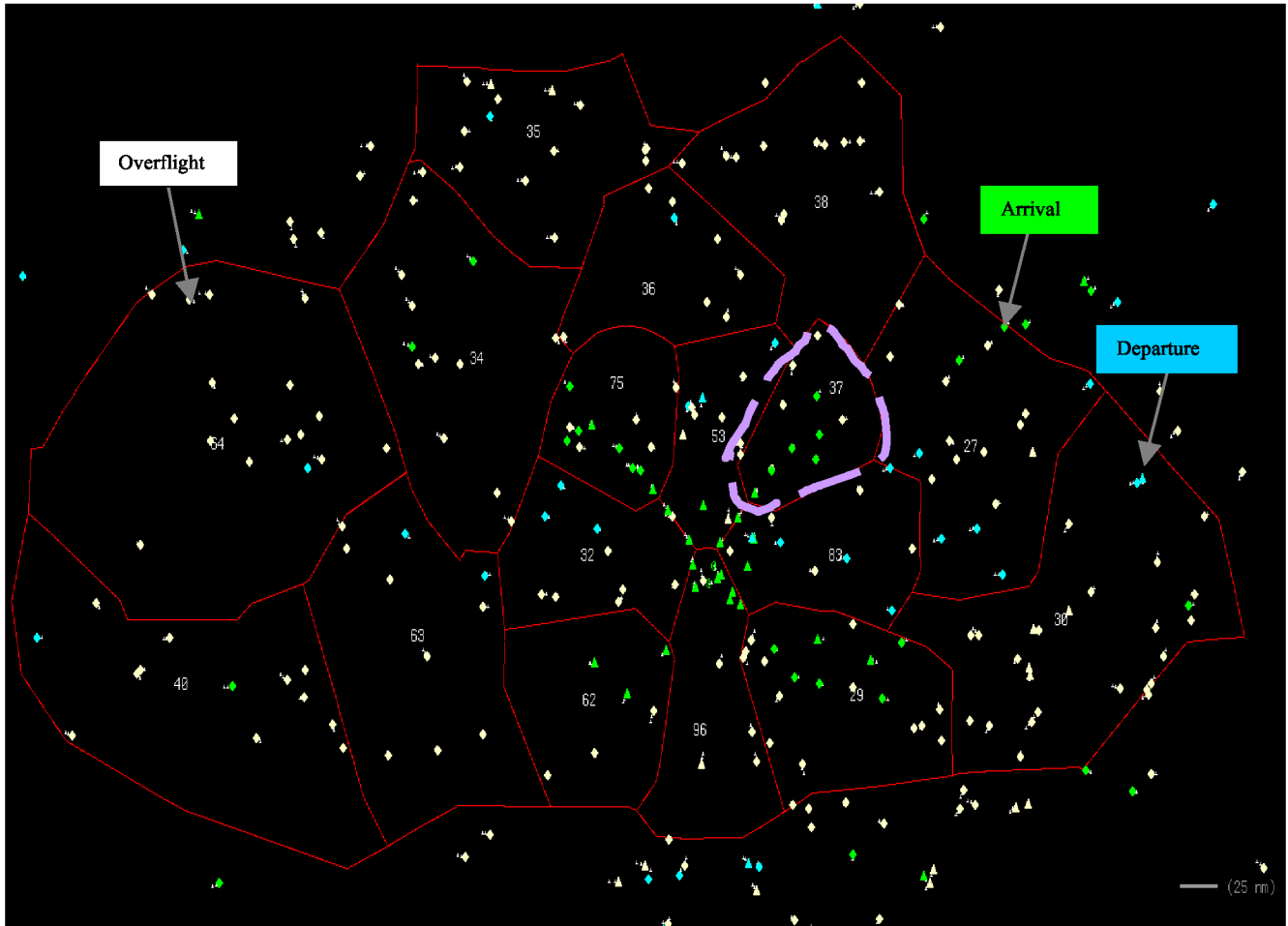


Figure 11.ZFW Low-Altitude Center

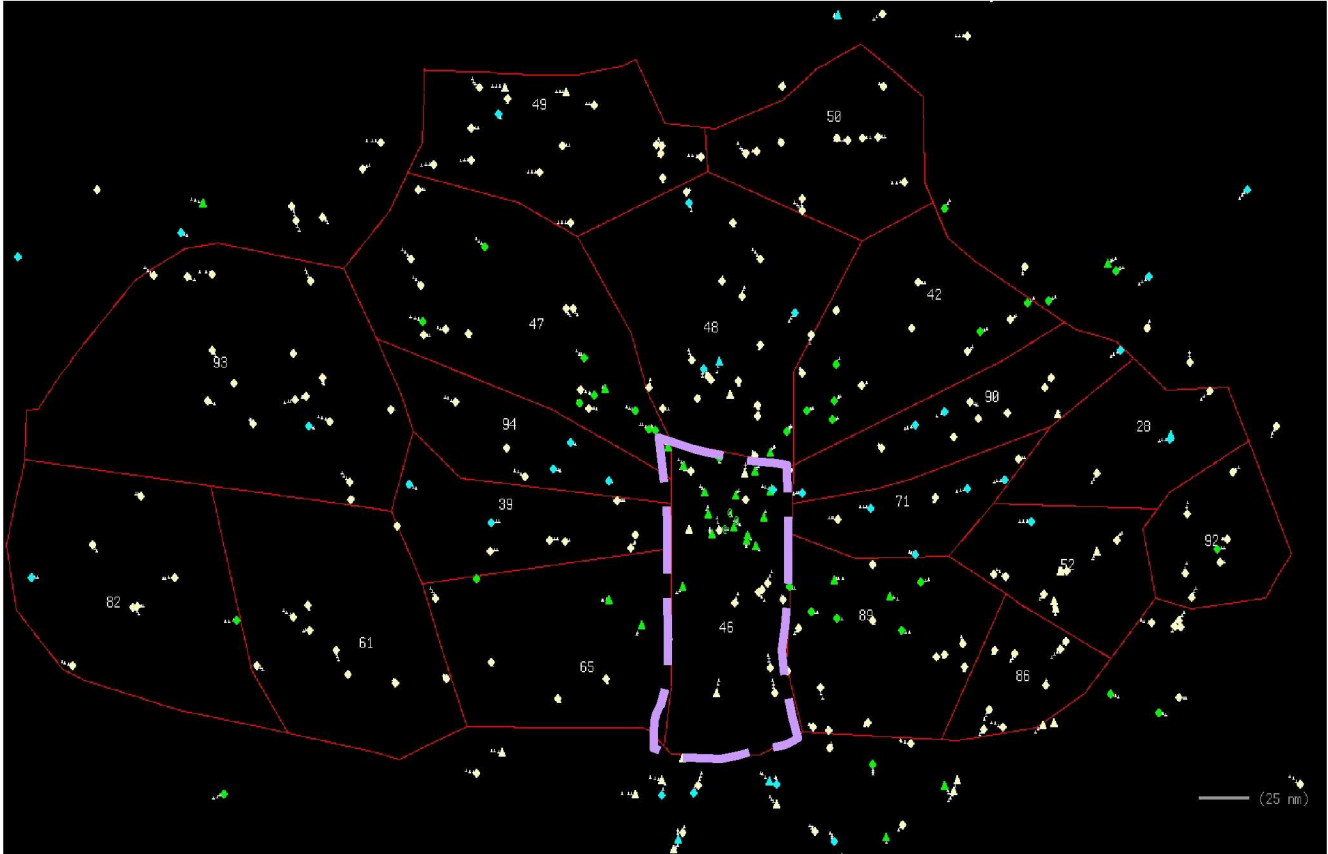


Figure 12. ZFW High-Altitude Sectors

Since Sector 37 had the most cases of Zero Maneuver Options aircraft, it was investigated in more detail. Figure 13 is an example that shows the total number of Zero Maneuver Options aircraft in Sector 37 for the two-hour period on May 9, 2008 as compared to total aircraft count in that sector. Note that during the time period of 24 to 39 minutes in which there is the highest average number of aircraft, eight, there are no Zero Maneuver Options aircraft. All eight cases of Zero Maneuver Options aircraft occur in the period of 85 to 100 minutes, where there are on average only five aircraft. As seen in this example, even when looking at this smaller volume of airspace, periods of high complexity in terms of the number of Zero Maneuver Options aircraft do not necessarily coincide with periods of high traffic volume.

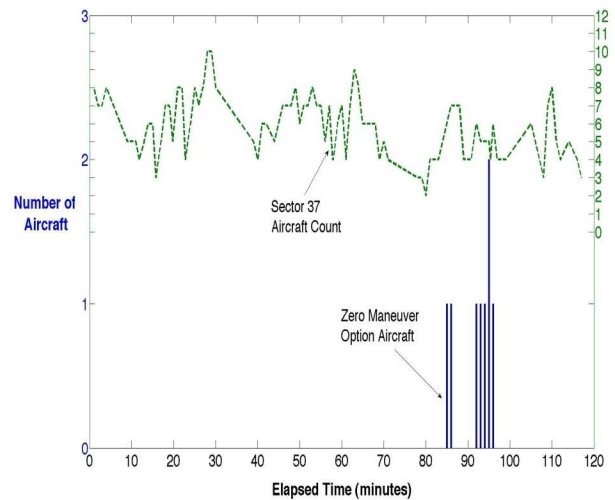


Figure 13. Sector 37 Zero MO (05-09-08)

To gain a better understanding of the traffic characteristics that contribute to occurrences of Zero Maneuver Options, those cases were investigated in more detail. A description of the types of situations found is presented in Table 3. As seen in the table, most of the cases involve aircraft merging or passing through an arrival stream.

Table 3. Distribution by Conflict Situation Type

Conflict Situation Type	# of Cases
Descending arrival, descending overflight, and level overflight merging into arrival stream	29
Level Overflight in conflict while passing through an arrival stream	19
Descending overflight in conflict with descending and/or level overflight	13
Level overflight in conflict with climbing overflight	11
Departure in conflict with climbing overflight and/or level overflight	8
Climbing/level departure in conflict with descending overflight	6
Level overflight in conflict with level overflight	5
Descending overflight in conflict with level departure/overflight	4
Descending arrival in conflict with descending overflight	4
Level arrival in conflict with level overflight	4
Climbing departure in conflict with climbing overflight	4
Climbing departure in conflict with level departure	3
Climbing departure in conflict with climbing departure	2
Level arrival in conflict with descending arrival	1

Summary

The Maneuver Option (MO) was presented as a metric to characterize the instantaneous complexity of an airspace with respect to an automated separation assurance function. Two variants of the metric were proposed: number of aircraft having zero Maneuver Options and average number of Maneuver Options per aircraft in a region (Average MO value). An analysis

was conducted of the Fort Worth Center airspace above 10,000 ft in order to assess the proposed metric.

Nominally, an aircraft is expected to have five Maneuver Options available: left turn, right turn, climb, descent, and straight ahead. Ninety-eight percent of the time, at least four of these options were available, indicating low-complexity with respect to automated separation for this region at current traffic levels. When less than the full complement of options was available, vertical constraints were most frequently involved (69% of cases).

While instances of Zero Maneuver Options cases were found to be rare under current-day assumptions of airspace structure and traffic demand, they did occur (0.12% of cases). Sixty-one percent of these cases involved aircraft in transition, i.e. aircraft not in level overflight, which is in line with expectations. The ZFW sectors rated most complex based on this metric for automated separation assurance are the same arrival and departure sectors known to be among the most complex for today's manual separation assurance providers.

To be useful, the MO metric needs to be validated against loss-of-separation cases in automated airspace. If the metric can be shown to have predictive value in identifying airspace where separation losses subsequently occur, then the metric could have application as a real-time warning system to alert traffic managers of an urgent need to intervene. Average MO value calculations can be used to establish safety thresholds in simulations with higher traffic using an automated separation assurance system. Alternatively, the metric could be used for post-operations analysis of automated airspace sectors to monitor trends and measure the effectiveness of traffic flow management initiatives.

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