Assessing NextGen Operational Improvements: A Case of Airspace Complexity and Aircraft Arrival Management System

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Lonnie H. Bowlin is the President and founder of Aerospace Engineering and Research Associates, Inc., as well as a Founding Partner of Atom Systems Inc. Mr. Bowlin led the development of several products in the ATC/ATM environment, including AERALIB®: the first COTS product used in operational air traffic control. AERALIB® formed the foundation for several commercially successful products deployed in 17 countries. As Director of Aviation Systems for Hughes STX, Mr. Bowlin served as technical advisor to both the ICAO ADS Panel, and the North Atlantic System Planning Group, and led the development and deployment of the Oceanic Systems.

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Abstract

The Next Generation Air Transportation System (NextGen) supports multiple operational and technological improvements that enable efficiencies for users and service providers. One of the potential components of the NextGen – the Aircraft Arrival Management System (AAMS) is a tool that jointly optimizes timing of arriving traffic to streamline flight arrivals at congested airports. This study utilizes experimental settings to examine the AAMS effect on the terminal area airspace complexity. During the experiment, the air traffic trajectory data before and after the AAMS implementation were collected at two terminal areas: Charlotte Douglas International Airport (CLT) and Minneapolis-St. Paul International Airport (MSP). Then, the trajectory data were used to estimate the Reciprocal Square Metrics (RSM) airspace complexity measures that were compared between the baseline and active AAMS periods. The results of the study suggest that potential implementation of AAMS concepts could reduce terminal area complexity at congested airports.

Notice

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the Federal Aviation Administration of the Department of Transportation.

Introduction

The Next Generation Air Transport Management System (NextGen) will transform the National Air Transportation System (NAS) and enable efficiencies for users and service providers. Multiple NextGen technological and operational improvements (OIs) will assist in solving existing and anticipated operational problems in the NAS. As part of the NextGen initiative, an Aircraft Arrival Management System (AAMS) is designed to increase arrival efficiency at congested airports. The AAMS optimizes timing of arriving traffic to streamline flight arrivals at the airport. The system preconditions the flow of traffic by supplying each arriving aircraft with the Requited Time of Arrival (RTA) at the airport corner post at a distance that allows pilots with minimal speed adjustment achieve the RTA to ensure smooth arrival sequence.

One of the challenges of assessing how the NextGen OIs would affect the NAS operations is the fact that typically no actual data is available before the OIs are implemented. Consequently, the assessments are done by modeling, simulation, and/or surveying the Subject Matter Experts (SMEs); these introduce subjectivity. Alternatively, an analysis of experimental data collected before and after the OI implementation would assist in an objective assessment of the effect of an OI. The FAA AAMS demonstration project at Charlotte Douglas International Airport (CLT) and at Minneapolis-St. Paul International Airport (MSP) provided a research opportunity in the NextGen OI assessment. The demonstration project used the ATH Group commercial available Airline Attila™ as the AAMS that managed the US Airways and Delta Air Lines arriving traffic flows at CLT and MSP respectively.

The objective of this paper is to evaluate the effect of the AAMS on the airspace complexity in the terminal areas of CLT and MSP. Specifically, the Aircraft Situation Display to Industry (ASDI) data is used to create aircraft trajectories before and after the AAMS implementation. Then, several raw and normalized airspace complexity measures are estimated and compared between the passive (no AAMS) and active (with AAMS) data collection periods. Several methods were used to control for the potentially diverse environments during the passive and active periods. First, to ensure similar weather conditions and airline schedules, the same calendar month (November) data were analyzed. Second, a subsample of days when there were no irregular events was used. Finally, multiple regression analyses were conducted to control for traffic load and separate the effect of the AAMS on raw airspace complexity measures.

This paper is organized as follows. The subsequent sections provide a brief overview of the airspace complexity literature and the airspace complexity measures used in this study. Next, the AAMS demonstration project is described. Finally, the analysis methodology is outlined and the key results of the study are provided, following by the main conclusions.

Airspace Complexity Literature

The Federal Aviation Administration (FAA) uses the Enhanced Traffic Management System (ETMS) at the Air Traffic Control System Command Center (ATCSCC), the Air Route Traffic Control Centers (ARTCCs), and major Terminal Radar Approach Control (TRACON) facilities to manage the flow of air traffic within the NAS. The airspace complexity is one of the variables considered by the ETMS. The currently employed method of complexity estimation under the ETMS documentation is the Monitor Alert Parameter (MAP) that is based upon peak aircraft counts in a one-minute period. This somewhat simplistic approach has resulted in a large body of work focusing on airspace complexity determination. The existing literature focuses around four major approaches: Dynamic Density; Conflict Prediction/Collision Risk estimation; Stochastic Modeling and Nonlinear Dynamics; and Trajectory Clustering/Flow Maps in addition to several other theoretical and computational methods. While primary efforts in the complexity research focus on the measures of controller workload, there is a consensus in the literature that emerging NextGen OIs would require new methods of assessing airspace complexity that would assist Air Traffic Management (ATM) systems safely and efficiently handle higher levels of traffic [Lee, Feron, and Pritchett, 2009; Salaun et al., 2009; Prandini et al., 2011].

Dynamic Density is an aggregate measure of complexity that usually centers on a linear weighted average of a number of numeric parameters. The parameters, such as heading changes, speed changes, altitude changes, and minimum spacing, are selected as individual measures of controller workload. Weights are then determined by linear regression against ATC participant evaluations of recorded sector events [Laudeman et al., 1998]. This method was originally calibrated against Oakland ARTCC but subsequent papers have been published with recalibrations and method adjustments, including recalibration for Cleveland Center due to metric underperformance [Kopardekar et al., 2009; Sridhar, Sheth, and Grabbe, 1998]. Furthermore, the method has been studied to determine the impact of aircraft trajectory uncertainties on predicted dynamic density [Sridhar and Kularni, 1998]. Interval Complexity is an adaptation of a metric similar to dynamic density featuring time smoothing. In particular, interval complexity uses a weighted linear combination of the number of flights, number of non-level trajectories, and number of aircraft near the border of the sector on average in a five to ten-minute period [Flener et al., 2007].

Conflict Prediction and Collision Risk estimation focus on taking known initial position and expected trajectory data to examine conflict propagation. Being a subject of extensive research, there are several tools for evaluating conflict probability, factoring and not factoring track uncertainty for airspace geometries [Paielli and Erzberger, 1997]. A parallel airspace complexity measure has been developed using airspace response to disturbance, also known as an input-output approach. The response to disturbances—including entering traffic, non-conforming traffic, and convective weather—are tabulated from the results of a mixed integer-linear program or a sequential conflict resolution algorithm by disturbance bearing and position as well as number of required heading changes as a “complexity map” [Lee, Feron, and Pritchett, 2009; Salaun et al., 2009]. These maps can be collapsed into scalar measures of complexity such as average heading change or maximum heading change [Lee, Feron, and Pritchett, 2009]. It should be noted that results from approaches such as these are greatly subject to the Traffic Flow Management algorithms in use [Prandini et al., 2011].

The Stochastic Modeling approach is generally seen as an extension of efforts to estimate airspace complexity using dynamical systems and Lyapunov exponent and vector fields predicated on exact position of the aircraft. Because of the sensitivity of the Lyapunov exponent map to errors, the stochastic extension developed a linear dynamical model that incorporates position and speed uncertainties [Lee, Delahaye, and Puechmorel, 2009; Puechmorel and Delahaye, 2009; Delahaye and Puechmorel, 2010].

Trajectory Clustering and Flow Maps provide a spacial representation of the complexity in the sector and attempts to sort flights into clustered flows or into a “white noise” outlier category [Gariel, Srivastava, and Feron, 2011]. The approach provides rich graphical information concerning the complexity of the sector, but the complexity plots must be integrated over the volume of the plot in order to arrive at a comparable, scalar value [Salaün et al., 2010].

In addition to the previously outlined methods, fractal dimensions have been applied to the airspaces at several ARTCCs. The concept set forth suggested higher fractal dimensions to more degrees-of-freedom employed and greater traffic complexity [Mondoloni and Liang, 2001]. Clustering has also been applied to the complexity problem by developing three-dimensional clusters on individual flights in the studied sector [Granger and Durand, 2003]. The method has been applied to 24-hour traffic records with the metric being ultimately computed using cluster complexity, separation, and temporal stability [Bilimoria and Jastrzebski, 2007].

Among the most recent work has been the application of interacting particle modeling to the airspace targets and complexity derived from a measure of the collision probability of the particles in the model. This approach is suggested to be targeted at inflight systems applications as opposed to ground observation, much like other studies on this topic with involvement of automated conflict resolution, automated traffic flow management, and free flight [Prandini, Blom, and Bakker, 2011].

Reciprocal Square Metrics

In this study the Reciprocal Square Metrics (RSM) is used as a measure of airspace complexity. The RSM is a new method developed by Aerospace Engineering and Research Associates, Inc. The metrics, which are scalar, can be computed as raw or normalized values. The RSM captures the core complexities of airspace using simple mathematics and, as opposed to many above mentioned metrics, can readily be estimated for diverse airspace sectors to facilitate comparison. In addition to the number of flights handled over time (traffic load), and number of flights over airspace volume (traffic density), the RSM provides measures of lateral, vertical, and angular complexities. The raw metrics, as defined below, reflect both the complexity of the traffic and the volume, thus could be useful in measuring potential controller workload, total conflict risk, and other parameters of a particular sector. The RSM includes four core metrics: RS2 that measures lateral spacing complexity, RS3 that combines lateral and vertical complexity, and RS2+ and RS3+ which add angular complexity to RS2 and RS3.

$$Raw\ RS2 = \sum_{ij} \left({1}/{R_{ij}} \right)^2 \qquad (1)$$

$$Raw\ RS2{+} = \sum_{ij} \left({1}/{R_{ij}} \times {1}/{A_{ij}} \right)^2 \qquad (2)$$

$$Raw\ RS3 = \sum_{ij} \left({1}/{R_{ij}} \times {1}/{H_{ij}} \right)^2 \qquad (3)$$

$$Raw\ RS3{+} = \sum_{ij} \left({1}/{R_{ij}} \times {1}/{H_{ij}} \times {1}/{A_{ij}} \right)^2 \qquad (4)$$

Where:

$$R_{ij} = \max\left(\frac{r_{ij}}{r_0}, 1\right) \quad (5)$$

$$H_{ij} = \max\left(\frac{h_{ij}}{h_0}, 1\right) \quad (6)$$

$$A_{ij} = 1 + \frac{a_{ij}}{\pi} \quad (7)$$

r_{ij} is the horizontal distance between ith and jth targets; h_{ij} is the absolute vertical distance between ith and jth targets; and a_{ij} is the absolute difference between ith and jth target headings. Additionally, r_0 is the lateral scaling constant (r_{ij} values below this constant result in maximum horizontal distance penalty) and h_0 is the vertical scaling constant (h_{ij} values below this constant result in maximum vertical distance penalty).

It should be noted that each target pair is used twice, once for (i, j) and once again for (j, i). If multiple airspaces are in use, any paring with aircraft between airspaces will result in the pairing being counted once in both airspaces.

The RSM values can also be normalized using a normalization factor. Normalized RSM values, using the normalization factor C below, remove the effect of traffic load and density to provide a more specific study of the complexity of the traffic flows and can be easily compared between sectors.

$$C = N \times N / S \quad (8)$$

With the normalization factor, the RSM definitions can be expressed as:

$$RS2 = \sum_{ij} \frac{\left({}^{1}/_{R_{ij}}\right)^2}{C} \quad (9)$$

$$RS2+ = \sum_{ij} \frac{\left({}^{1}/_{R_{ij}} \times {}^{1}/_{A_{ij}}\right)^2}{C} \quad (10)$$

$$RS3 = \sum_{ij} \frac{\left({}^{1}/_{R_{ij}} \times {}^{1}/_{H_{ij}}\right)^2}{C} \quad (11)$$

$$RS3+ = \sum_{ij} \frac{\left({}^{1}/_{R_{ij}} \times {}^{1}/_{H_{ij}} \times {}^{1}/_{A_{ij}}\right)^2}{C} \quad (12)$$

The scale factors r_0 and h_0, which are constants selected outside the model, can have considerable impact on the sensitivity of the metrics. A primary consideration in assigning these values is ensuring that the factor values are greater than the error or noise in the position data used in the trajectories. Generally acceptable values for enroute applications of r_0 are between 10 and 30 nmi while enroute values of h_0 can range from 1,000 to 4,000 ft computed as Flight Level.

As a brief conceptual example, the RS2 metric for the situation depicted in Figure 1 is estimated to demonstrate the mechanics and efficiency of the metric calculation using an r_0 of 35 nmi.

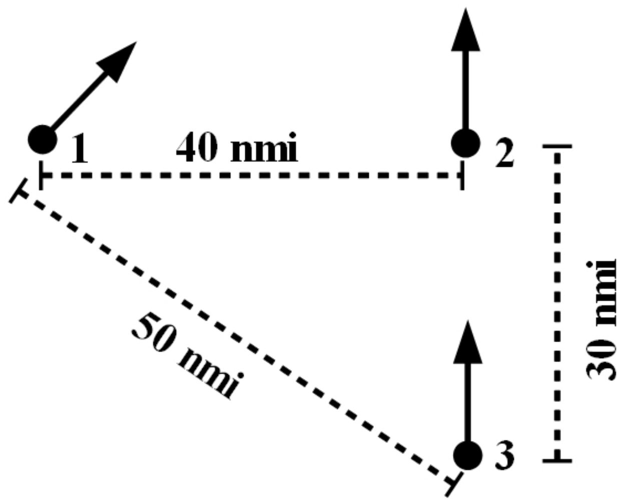

Figure 1. Illustration of RS2 Calculation.

First, R_{ij} for the three targets (six interactions) must be calculated:

$$R_{12} = R_{21} = \max\left(1, {}^{40}/_{35}\right)$$
$$R_{13} = R_{31} = \max\left(1, {}^{50}/_{35}\right)$$
$$R_{23} = R_{32} = \max\left(1, {}^{30}/_{35}\right)$$

Then, the values applied to the Raw RS2 formula:

$$Raw\ RS2 = 2 \times \left({}^{1}/_{1.14}\right)^2 + 2 \times \left({}^{1}/_{1.43}\right)^2 + 2 \times (1)^2$$

$$Raw\ RS2 = 4.51$$

This example demonstrates how computationally light the RSM is in comparison to the other complexity measures discussed in the previous section. Also, the RSM can be easily understood by daily users and provide airspace complexity measures comparable among different sectors.

Aircraft Arrival Management System

As part of the FAA NextGen initiative, a number of operational improvements have been brought into consideration. One initiative, the AAMS was demonstrated on commercial operations at CLT and MSP. The AAMS demonstration used commercially available software to precondition inbound aircraft according to goal functions written to suit the commercial needs of the participating airlines: US Airways at CLT and Delta Air Lines at MSP. To accomplish this, the software calculates a Required Time of Arrival (RTA) that is uplinked to the aircraft over Aircraft Communications Addressing and Reporting System (ACARS). The RTAs may require the aircraft to increase, decrease, or make no change in speed based on the airline business needs, airport capacity, and other factors with the objective of improving the efficiency of the system-wide arrival flow at the airport as conceptually outlined in Figure 2.

Figure 2. Conceptual Overview of AAMS

As illustrated in Figure 3, the AAMS action area is outside of the FAA Traffic Management Advisor (TMA) freeze horizon (250 nm) and, thus, the AAMS does not interfere with TMA.

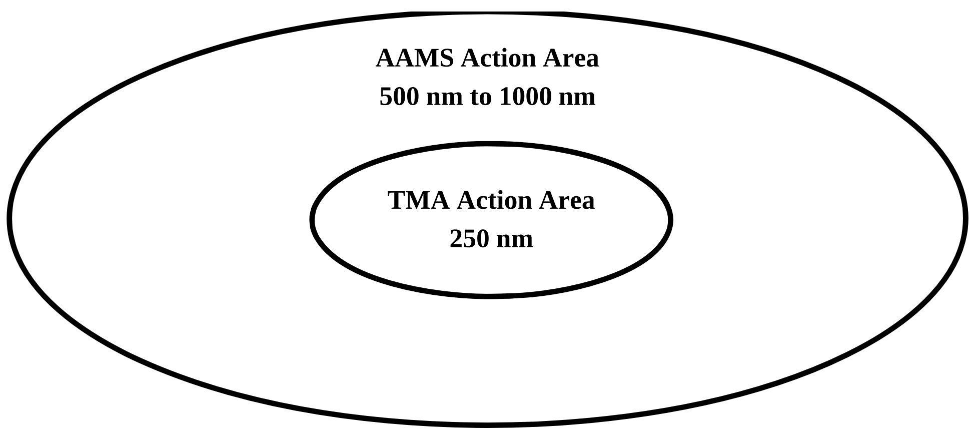

Figure 3. AAMS Action Area.

The commercial software used in the AAMS demonstration, has been used by Delta Air Lines at Hartsfield-Jackson Atlanta International Airport (ATL) since 2006 as well as at Detroit Metropolitan Wayne County Airport (DTW) and MSP since 2011. The primary objectives of the AAMS demonstration Project at CLT and MSP were to investigate how airline operations center-based metering tools may support NextGen time-based metering concepts and quantify operational benefits to the NAS and participating airlines.

The demonstration at CLT ran in three major phases: a passive phase (09/16/2010 to 12/12/2010), where a baseline was recorded to benchmark improvements; a first active phase where US Airways mainline flights were issued RTAs (02/17/2011 to 06/09/2011); and a second active phase where RTAs were issued to US Airways and PSA Airlines flights (06/13/2011 to 12/13/2011). The active phase AAMS configuration is presented in Figures 4.

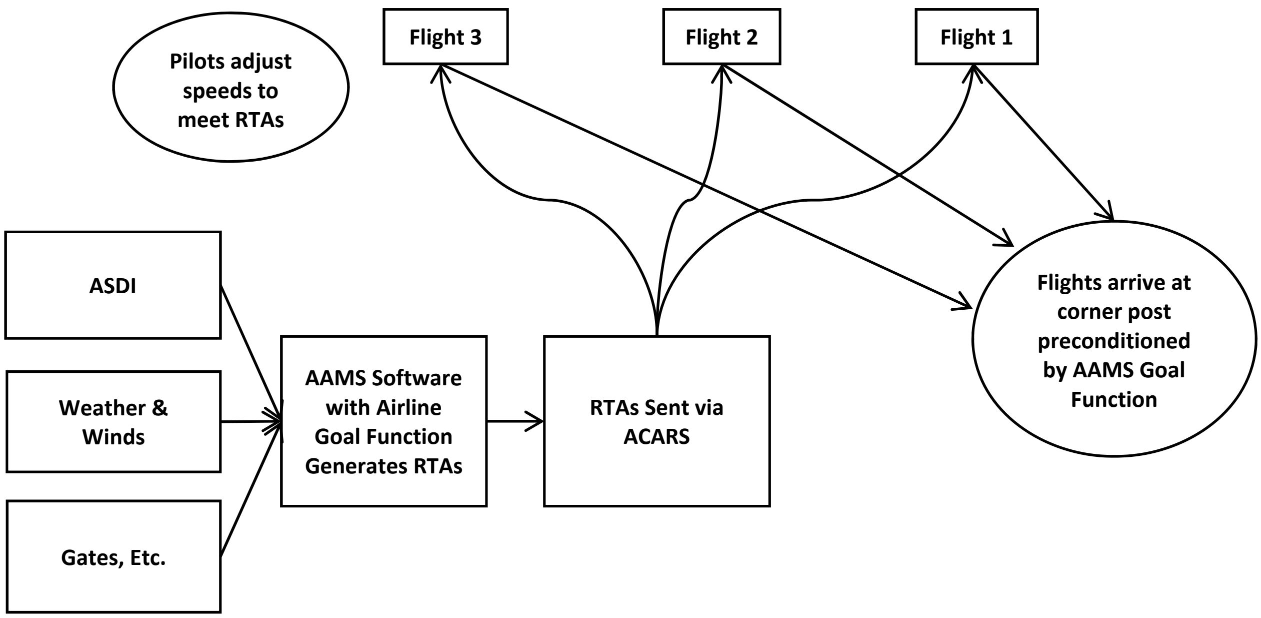

Figure 4. Single-Airline AAMS Configuration

The MSP demonstration featured a passive period and a single active period where RTAs were issued to Delta Air Lines mainline flights. The passive period ran from November 1, 2010 to April 30, 2011 while the active period ran one year later from November 1 2011 to April 30, 2012. The MSP AAMS was configured as presented in Figure 4.

AAMS effect on Airspace Complexity

For the purpose of the study the airspaces around the AAMS demonstration airports were divided into five equal-area polygons that were arranged with a central circular zone around the terminal and four arcs around each approach quadrant composing an outer ring. The inner and outer radii are 32 and 72 nmi respectively, and the area of each polygon is approximately 3,217 sq nmi. Figure 6 illustrates the airspace partitions used in the complexity study. For each zone four types of RSM measures are calculated: raw overall, raw cruise, normalized overall and normalized cruise. Cruise RMS measures are estimated only for the cruise segments of flights. The primary reason for the airspace complexity investigation in the outer and inner sectors separately, is to ensure that the "dwell" time optimization does not lead to increased airspace complexity in the outer area. The "dwell" time is defined as the time that takes arriving aircraft to fly from the corner post to the runway threshold. In addition, separate cruise RSM measures are calculated to examine if the "dwell" time optimization pushes the complexity from the approach phase to the cruise phase of the flights.

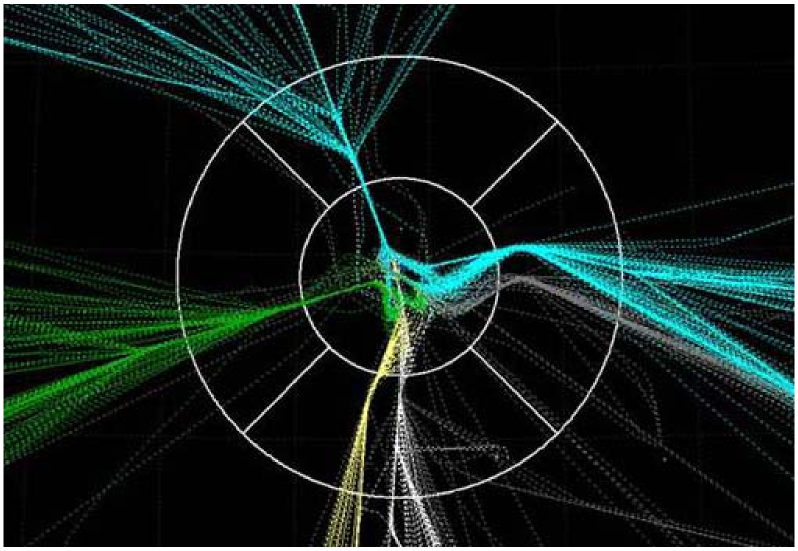

Figure 5. Sectors for Complexity Assessment.

For both AAMS airports daily RSM measures are estimated for November 2010 (baseline) and November 2011 (active AAMS period). Since airline schedules and weather were similar in November 2010 and November 2011, comparing the same months of the year reduces the variability and provides more stables test environment. In addition, a subsample of "representative" days in both months was used to lessen the impact of any traffic flow disruptions. A "representative" day is defined as a day when at least 70% of US Airways flights at CLT and Delta Air Lines flights at MSP arrived within 15 minutes of scheduled arrival time (an airline statistic known as A14). This level of A14 performance indicates that there were no irregular operations at the airport (no major weather or other events that disrupted the arrival flow).

Aggregate RSM Estimates

Tables 1 to 4 present mean values and standard deviations of estimated daily RSM measures for both data collection periods, as well as the differences between active and passive periods and the statistical significance of the differences. It should be noted that with only 30 or fewer days in each sample the difference between means should be rather substantial to yield statistical significance. Nonetheless, as presented in Table 1, it seems that the airspace in the inner sector of CLT was significantly less complex during the active AAMS period than in the passive period. All raw RSM measures demonstrate statistically significant improvement in the active period. Normalized measures of the same sector are also lower in the active period, but the differences are not statistically significant. The absence of the statistically significant differences for the cruise portion of the inner sector suggests that the AAMS did not affect the complexity of this area in any meaningful way. The raw RSM measures of the outer sector of CLT were also significantly lower in the active period. However, normalized RS2, RS2+, and RS3 measures went up in the active period and the differences were statistically significant. This counterintuitive result can be explained by a significantly lower traffic load in the CLT outer sector during the AAMS active period that made the normalized values relatively higher. As indicated by negative and statistically significant differences in mean raw RSM values for the cruise portion of the CLT outer sector, the airspace there was less complex in the active period. In addition, normalized lateral spacing complexity measures (RS2 and RS2+) are also significantly lower in the active data collection period.

Table 2 presents the estimates of CLT RSM measures for a subsample of "representative" days. The subsample of "representative" days reduces the "noise" in the data and helps in isolating the effect of the AAMS on the airspace complexity. Three days from the passive period (November 11, 12, and 25, 2010) and one day from the active period (November 24, 2011) with A14 less than 70% were not included in the subsample. The RSM estimates presented in Table 2 are very similar to the overall sample estimates suggesting that even with the more homogenous subsample of "representative" days the airspace complexity was lower in the AAMS active period than in the passive period of data collection.

The RSM estimates for MSP are presented in Tables 3 and 4 for the overall sample and subsample of "representative" days, respectively. Six days in the passive period with A14 less than 70% were not included in the "representative" day subsample at MSP (November13, 18, 21, 22, 24, and 30, 2010). All days in the active period had A14 70% or above and, thus, were considered to be "representative" days. The differences in means of airspace complexity measures are not statistically significant for all sectors for both: the overall sample and subsample of "representative" days. These results indicate that the airspace complexity was not affected by the AAMS actions at MSP.

The aggregate analysis of the RSM measures seems to suggest that the AAMS reduced the arrival airspace complexity at CLT and did not have any effect on the complexity of the airspace at MSP. However, this somewhat simplistic analysis of statistical significance of difference in means could be affected by an aggregation bias. To further investigate the airspace complexity in the active and passive data collection periods, we conduct a series of regression analyses that are described in the following section.

Table 1. CLT RSM Measures (All Days)

(*) indicates statistical significance at the 5% level. (**) indicates statistical significance at the 10% level.

CLT Inner Sector Measures All Days Overall

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	15.25	178.95	413.71	63.39	133.89	7.75	17.91	2.70	5.71	21.03
	St Dev	1.90	24.69	58.15	10.32	22.50	0.78	1.83	0.35	0.78	3.86
Active	Mean	14.56	160.09	369.90	55.94	118.62	7.75	17.91	2.70	5.71	22.58
	St Dev	1.90	31.76	75.20	13.71	30.71	0.78	1.83	0.35	0.78	5.17
Active - Passive	Means	-0.70	-18.86*	-43.81*	-7.45*	-15.27*	-0.12	-0.28	-0.08	-0.16	N/A

CLT Inner Sector Measures All Days Cruise Only

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	3.34	30.47	70.69	4.65	10.09	27.94	64.79	4.26	9.24	1.10
	St Dev	0.39	5.77	13.49	0.90	2.01	2.09	4.75	0.37	0.76	0.26
Active	Mean	3.25	28.26	65.79	4.38	9.54	27.38	63.70	4.27	9.29	1.05
	St Dev	0.40	5.37	12.66	0.76	1.72	2.28	5.29	0.51	1.04	0.24
Active - Passive	Means	-0.09	-2.21	-4.90	-0.27	-0.55	-0.56	-1.09	0.01	0.05	N/A

CLT Outer Sectors Measures All Days Overall

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	25.75	151.35	343.28	31.67	67.47	11.60	26.30	2.43	5.16	13.07
	St Dev	2.54	29.60	68.56	6.37	14.52	0.37	0.85	0.13	0.30	2.63
Active	Mean	23.13	126.54	286.35	26.44	55.70	12.06	27.28	2.54	5.34	10.59
	St Dev	2.71	24.17	55.12	4.54	9.87	0.69	1.52	0.23	0.46	2.29
Active - Passive	Means	-2.62*	-24.81*	-56.92*	-5.23*	-11.77*	0.46*	0.98*	0.11*	0.17	N/A

CLT Outer Sectors Measures All Days Cruise Only

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	12.90	75.18	170.51	15.97	33.89	22.99	52.13	4.91	10.40	3.27
	St Dev	1.06	13.29	30.50	2.48	5.46	0.93	2.30	0.33	0.73	0.55
Active	Mean	12.32	66.41	150.46	14.68	31.11	22.24	50.38	4.95	10.48	3.01
	St Dev	1.44	13.28	30.23	2.60	5.66	1.10	2.49	0.39	0.79	0.65
Active - Passive	Means	-0.57	-8.77*	-20.05*	-1.30**	-2.78**	-0.75*	-1.75*	0.04	0.08	N/A

Table 2. CLT RSM Measures (Representative Days)

(*) indicates statistical significance at the 5% level. (**) indicates statistical significance at the 10% level.

CLT Inner Sector Measures Representative Days Overall

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	15.15	177.31	409.65	62.55	131.84	7.90	18.25	2.78	5.87	22.56
	St Dev	1.21	23.63	55.26	9.52	20.23	0.40	0.97	0.20	0.44	3.56
Active	Mean	14.56	160.09	369.90	55.94	118.62	7.75	17.91	2.70	5.71	21.03
	St Dev	1.90	31.76	75.20	13.71	30.71	0.78	1.83	0.35	0.78	5.17
Active - Passive	Means	-0.60	-17.21*	-39.75*	-6.61*	-13.23*	-0.14	-0.34	-0.08	-0.15	N/A

CLT Inner Sector Measures Representative Days Cruise Only

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	3.32	30.26	70.24	4.62	10.05	28.01	64.97	4.27	9.28	1.09
	St Dev	0.39	5.78	13.55	0.91	2.03	2.10	4.76	0.37	0.75	0.26
Active	Mean	3.25	28.26	65.79	4.38	9.54	27.38	63.70	4.27	9.29	1.05
	St Dev	0.40	5.37	12.66	0.76	1.72	2.28	5.29	0.51	1.04	0.24
Active - Passive	Means	-0.07	-2.00	-4.45	-0.25	-0.50	-0.63	-1.27	0.00	0.02	N/A

CLT Outer Sectors Measures Representative Days Overall

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	25.73	151.24	343.13	31.71	67.62	11.61	26.33	2.44	5.18	13.06
	St Dev	2.59	30.18	69.92	6.50	14.79	0.38	0.85	0.13	0.29	2.68
Active	Mean	23.13	126.54	286.35	26.44	55.70	12.06	27.28	2.54	5.34	10.59
	St Dev	2.71	24.17	55.12	4.54	9.87	0.69	1.52	0.23	0.46	2.29
Active - Passive	Means	-2.60*	-24.69*	-56.78*	-5.28*	-11.91*	0.45*	0.95*	0.10*	0.16	N/A

CLT Outer Sectors Measures Representative Days Cruise Only

		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	12.86	74.92	170.00	15.97	33.92	23.03	52.25	4.93	10.46	3.25
	St Dev	1.06	13.48	30.99	2.53	5.57	0.92	2.26	0.31	0.67	0.55
Active	Mean	12.32	66.41	150.46	14.68	31.11	22.24	50.38	4.95	10.48	3.01
	St Dev	1.44	13.28	30.23	2.60	5.66	1.10	2.49	0.39	0.79	0.65
Active - Passive	Means	-0.54	-8.52*	-19.54*	-1.29**	-2.80**	-0.79*	-1.88*	0.02	0.02	N/A

Table3. MSP RSM Measures (All Days)

MSP Inner Sector Measures All Days Overall											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	9.26	69.17	157.41	30.92	62.98	8.67	19.70	3.82	7.77	8.80
	St Dev	2.14	21.08	48.19	9.99	20.86	3.06	6.91	1.24	2.50	3.29
Active	Mean	9.22	68.37	155.87	29.31	59.72	8.18	18.68	3.52	7.18	8.51
	St Dev	1.47	16.98	38.25	7.22	14.91	0.72	1.74	0.38	0.87	2.42
Active - Passive	Means	-0.04	-0.80	-1.54	-1.61	-3.26	-0.48	-1.02	-0.30	-0.58	N/A
MSP Inner Sector Measures All Days Cruise Only											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	0.70	3.45	8.05	0.43	0.94	75.55	176.74	9.50	20.53	0.05
	St Dev	0.15	1.02	2.39	0.15	0.32	20.09	48.76	3.18	6.59	0.02
Active	Mean	0.68	3.32	7.83	0.41	0.90	74.37	175.22	9.21	19.96	0.05
	St Dev	0.15	1.02	2.37	0.15	0.32	15.37	35.11	2.68	5.14	0.02
Active - Passive	Means	-0.01	-0.12	-0.22	-0.02	-0.04	-1.19	-1.52	-0.28	-0.57	N/A
MSP Outer Sectors Measures All Days Overall											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	7.86	19.64	42.57	4.71	8.98	17.01	36.95	4.08	7.78	1.27
	St Dev	1.81	6.23	13.56	1.51	2.89	6.09	13.60	1.48	2.85	0.48
Active	Mean	8.19	21.03	45.50	5.11	9.65	15.91	34.31	3.91	7.32	1.35
	St Dev	1.48	5.94	13.10	1.40	2.76	1.57	2.94	0.58	0.92	0.44
Active - Passive	Means	0.33	1.39	2.93	0.40	0.67	-1.10	-2.64	-0.17	-0.46	N/A
MSP Outer Sectors Measures All Days Cruise Only											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	2.29	7.08	16.33	1.23	2.71	51.51	118.43	9.13	19.93	0.16
	St Dev	0.55	12.67	29.99	2.08	4.84	24.46	59.04	4.15	9.77	0.33
Active	Mean	2.16	4.57	10.45	0.77	1.66	49.57	113.28	8.34	17.88	0.10
	St Dev	0.49	1.61	3.65	0.29	0.62	5.90	13.69	1.10	2.01	0.04
Active - Passive	Means	-0.12	-2.50	-5.89	-0.46	-1.06	-1.94	-5.16	-0.78	-2.05	N/A

Table 4. MSP RSM Measures (Representative Days)

MSP Inner Sector Measures Representative Days Overall											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	9.04	67.77	153.93	30.20	61.34	9.01	20.44	3.96	8.03	8.44
	St Dev	2.21	21.13	48.39	9.82	20.53	3.35	7.57	1.36	2.74	3.31
Active	Mean	9.22	68.37	155.87	29.31	59.72	8.18	18.68	3.52	7.18	8.51
	St Dev	1.47	16.98	38.25	7.22	14.91	0.72	1.74	0.38	0.87	2.42
Active - Passive	Means	0.18	0.60	1.94	-0.89	-1.62	-0.83	-1.76	-0.44	-0.84	N/A
MSP Inner Sector Measures Representative Days Cruise Only											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	0.67	3.28	7.66	0.42	0.90	78.05	182.46	9.91	21.32	0.05
	St Dev	0.15	1.00	2.33	0.14	0.30	21.26	51.93	3.34	6.86	0.02
Active	Mean	0.68	3.32	7.83	0.41	0.90	74.37	175.22	9.21	19.96	0.05
	St Dev	0.15	1.02	2.37	0.15	0.32	15.37	35.11	2.68	5.14	0.02
Active - Passive	Means	0.01	0.04	0.18	-0.01	0.00	-3.68	-7.24	-0.70	-1.36	N/A
MSP Outer Sectors Measures Representative Days Overall											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	7.79	19.58	42.44	4.74	9.03	17.50	38.00	4.24	8.07	1.25
	St Dev	1.92	6.46	14.08	1.54	2.98	6.74	15.06	1.62	3.13	0.50
Active	Mean	8.19	21.03	45.50	5.11	9.65	15.91	34.31	3.91	7.32	1.35
	St Dev	1.48	5.94	13.10	1.40	2.76	1.57	2.94	0.58	0.92	0.44
Active - Passive	Means	0.40	1.45	3.05	0.38	0.62	-1.58	-3.69	-0.33	-0.75	N/A
MSP Outer Sectors Measures Representative Days Cruise Only											
		Raw					*Normalized*				
		Load	**RS2**	**RS2+**	**RS3**	**RS3+**	**RS2**	**RS2+**	**RS3**	**RS3+**	**Norm Constant**
Passive	Mean	2.22	19.58	42.44	4.74	9.03	53.67	124.01	9.45	20.76	0.17
	St Dev	0.59	6.46	14.08	1.54	2.98	26.81	64.54	4.57	10.75	0.37
Active	Mean	2.16	21.03	45.50	5.11	9.65	49.57	113.28	8.34	17.88	0.10
	St Dev	0.49	5.94	13.10	1.40	2.76	5.90	13.69	1.10	2.01	0.04
Active - Passive	Means	-0.06	1.45	3.05	0.38	0.62	-4.10	-10.73	-1.11	-2.88	N/A

Regression Analyses of RSM Measures

To examine RSM measures in the active and passive data collection periods, we conduct a series of regression analyses with the RSM measures as dependent variables and the traffic load and data collection period dummy as independent variables. The regression model can be presented as follows.

$$RSM_i = a + b_1 Load_i + b_2 ACT_i + e_i \qquad (13)$$

where: *RSM* is one of the complexity measures (RS2, RS2+, RS3, or RS3+); *a* is constant; *Load* is the traffic load, *ACT* is a dummy variable indicating the AAMS active period; and *e* in the error term.

The coefficient of interest is the coefficient of *ACT*. Negative and statistically significant coefficient of *ACT* would indicate a reduction in the airspace complexity measures in the AAMS active period. *Load* variable is included to control for daily traffic load. The same regressions were performed for all RSM measures; inner and outer sectors of CLT and MSP; for overall measures and cruise only measures; for overall samples and "representative" days subsamples. Parameter estimates for all regression analyses are presented in Table 5.

As indicated in Panel A of Table 5, the coefficient of *ACT* is negative and statistically significant in RS2, RS2+, and RS3 regressions performed for the overall traffic in both the all days sample and the subsample of "representative" days. The RS3+ regression resulted in negative, but marginally statistically significant (at the 10% level) coefficient of *ACT*. The cruise lateral complexity measures (RS2 and RS2+) also produced negative and significant coefficients of *ACT*, indicating that the reduced complexity in the CLT inner sector was not achieved at the expense of the cruise portions of the arriving trajectories.

Panel B of Table 5 presents the parameter estimates for the CLT outer sector regressions. The coefficients of *ACT* are not statistically significant for all regressions with overall trajectory data. However, similar to the inner sector the analysis of only cruise portion of trajectories produced negative and significant coefficients for lateral complexity measures, indicating reduced lateral complexity for the cruise portion of the airspace.

Panels C and D of Table 5 present the estimates for the MSP inner and outer sector regressions. The coefficients of *ACT* in the outer sector regressions confirm the outcome of the aggregate analysis that does not show any complexity changes between the passive and active data collection periods. However, the inner sector regressions suggest reduced complexity in the AAMS active period as indicated by negative and statistically significant coefficients of RS3 and RS3+ regressions. The MSP cruise complexity measure regressions do not produce any statistically significant coefficients implying that the airspace complexity of the cruise portion of arriving trajectories was the same in both data collection periods.

Table 5. RSM Measures Regression Estimates

For each regression the unstandardized coefficients are presented with t-statistics in parentheses. (*) indicates statistical significance at the 5% level. (**) indicates statistical significance at the 10% level.

Panel A: CLT Inner Sector

	All Days						Representative Days					
	Overall			Cruise			Overall			Cruise		
	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT
RS2	-98.1*	18.2*	-7.2*	-15.2*	13.7*	-1.1*	-99.9*	18.3*	-7.4*	-15.3*	13.7*	-1.1*
	(-10.2)	(29.0)	(-4.1)	(-7.2)	(21.9)	(-2.4)	(-10.0)	(28.1)	(-4.1)	(-7.1)	(21.5)	(-2.4)
RS2+	-241.1*	42.9*	-16.6*	-36.7*	32.1*	-2.2*	-243.6*	43.1*	-16.7*	-36.8*	32.2*	-2.3*
	(-9.7)	(26.7)	(-3.6)	(-7.3)	(21.7)	(-2.1)	(-9.5)	(25.7)	(-3.6)	(-7.3)	(21.3)	(-2.1)
RS3	-54.1*	7.7*	-2.8*	-2.3*	2.1*	-0.1	-53.4*	7.7*	-2.8*	-2.3*	2.1*	-0.1
	(-8.1)	(17.8)	(-2.3)	(-6.3)	(19.6)	(-1.4)	(-7.8)	(17.0)	(-2.2)	(-6.4)	(19.4)	(-1.5)
RS3+	-126.2*	17.1*	-5.1**	-5.3*	4.6*	-0.2	-123.0*	16.8*	-4.9**	-5.4*	4.6*	-0.2
	(-8.1)	(16.9)	(-1.8)	(-6.5)	(19.2)	(-1.1)	(-7.7)	(16.1)	(-1.7)	(-6.6)	(19.2)	(-1.2)

Panel B: CLT Outer Sector

	All Days						Representative Days					
	Overall			Cruise			Overall			Cruise		
	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT
RS2	-121.1*	10.6*	2.0	-61.8*	10.6*	-3.1*	-121.1*	10.6*	1.9	-62.3*	10.7*	-3.2*
	(-15.7)	(35.5)	(1.3)	(-11.5)	(25.8)	(-3.3)	(-15.6)	(35.3)	(1.2)	(-11.6)	(25.7)	(-3.4)
RS2+	-283.2*	24.3*	4.6	-140.8*	24.1*	-7.1*	-283.3*	24.3*	4.3	-142.3*	24.3*	-7.4*
	(-15.2)	(33.9)	(1.2)	(-10.9)	(24.3)	(-3.2)	(-15.2)	(33.8)	(1.1)	(-11.0)	(24.4)	(-3.3)
RS3	-22.6*	2.1*	0.1	-9.0*	1.9*	-0.2	-22.6*	2.1*	0.0	-9.2*	2.0*	-0.3
	(-8.9)	(21.5)	(0.1)	(-6.4)	(17.8)	(-1.0)	(-9.0)	(21.7)	(0.0)	(-6.7)	(18.5)	(-1.2)
RS3+	-53.9*	4.7*	0.1	-20.4*	4.2*	-0.5	-54.0*	4.7*	-0.2	-21.1*	4.3*	-0.6
	(-8.9)	(20.1)	(0.0)	(-6.4)	(17.2)	(-0.8)	(-9.0)	(20.5)	(-0.1)	(-6.9)	(18.2)	(-1.2)

Panel C: MSP Inner Sector

	All Days						Representative Days					
	Overall			Cruise			Overall			Cruise		
	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT
RS2	-25.0*	10.2*	-0.4	-0.9*	6.2*	0.0	-23.3*	10.1*	-1.2	-0.8*	6.1*	0.0
	(-8.5)	(33.1)	(-0.4)	(-3.1)	(16.5)	(-0.4)	(-8.0)	(32.6)	(-1.1)	(-3.0)	(15.9)	(-0.4)
RS2+	-56.4*	23.1*	-0.7	-1.9*	14.4*	0.0	-52.8*	22.9*	-2.3	-1.9*	14.2*	0.0
	(-8.3)	(32.7)	(-0.3)	(-3.0)	(16.0)	(-0.1)	(-7.7)	(31.6)	(-0.9)	(-2.8)	(15.3)	(0.0)
RS3	-11.3*	4.6*	-1.4*	-0.1*	0.8*	0.0	-10.0*	4.4*	-1.7*	-0.1*	0.8*	0.0
	(-6.6)	(25.7)	(-2.3)	(-2.1)	(10.1)	(-0.5)	(-6.1)	(25.6)	(-2.7)	(-2.1)	(10.1)	(-0.7)
RS3+	-23.5*	9.3*	-2.9**	-0.3*	1.8*	0.0	-20.9*	9.1*	-3.3*	-0.3*	1.8*	0.0
	(-5.8)	(22.0)	(-1.9)	(-2.5)	(11.1)	(-0.3)	(-5.2)	(21.3)	(-2.1)	(-2.6)	(11.4)	(-0.5)

Panel D: MSP Outer Sector

	All Days						Representative Days					
	Overall			Cruise			Overall			Cruise		
	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT	Const.	Load	ACT
RS2	-8.5*	3.6*	0.2	-7.3	6.3*	-1.7	-8.1*	3.6*	0.0	-7.7	6.8*	-2.5
	(-9.4)	(32.3)	(0.6)	(-1.4)	(3.0)	(-0.8)	(-8.6)	(31.0)	(0.1)	(-1.4)	(3.0)	(-1.0)
RS2+	-19.0*	7.8*	0.4	-17.0	14.6*	-4.1	-18.2*	7.8*	-0.1	-17.9	15.9*	-6.0
	(-9.3)	(31.4)	(0.4)	(-1.4)	(2.9)	(-0.8)	(-8.6)	(30.1)	(-0.1)	(-1.4)	(2.9)	(-1.0)
RS3	-1.9*	0.8*	0.1	-1.2	1.1*	-0.3	-1.8*	0.8*	0.0	-1.3	1.2*	-0.5
	(-7.1)	(25.4)	(1.2)	(-1.5)	(3.1)	(-0.9)	(-6.6)	(25.4)	(0.4)	(-1.4)	(3.1)	(-1.1)
RS3+	-3.9*	1.6*	0.1	-2.7	2.4*	-0.8	-3.6*	1.6*	0.0	(-2.9	2.6*	-1.1
	(-7.2)	(25.0)	(0.6)	(-1.4)	(2.9)	(-0.9)	(-6.8)	(24.8)	(-0.1)	(-1.4)	(3.0)	(-1.1)

Conclusion

This study presents an assessment of the effect of the AAMS on the terminal area airspace complexity using the experimental data collected before and during the FAA AAMS demonstration project at CLT and MSP. The results indicate that the airspace complexity was significantly lower in the inner sectors of the terminal areas (32 nmi radius from the airport) when the AAMS was active. In addition, this reduction in the overall complexity was not driven by the increased complexity of the cruise portion of arrival trajectories, suggesting that the AAMS did not reduce the overall complexity at the expense of the cruise segment of the flights. Moreover, the CLT analysis implies that the lateral complexity of the cruise segment was also lower in the AAMS active period in both inner and outer sectors. While the analysis of the MSP data does not produce strong evidence of the reduction in the lateral complexity measures, the combined (lateral and vertical) measures in the MSP inner sector were significantly lower during the AAMS active period and the cruise segments of the trajectories were not affected.

The results of the study suggest that potential implementation of AAMS concepts as one of the NextGen components could reduce terminal area complexity at congested airports.

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