



MIT
International Center for
Air Transportation

AIRCRAFT NOISE MODELING OF DISPERSED FLIGHT TRACKS AND METRICS FOR ASSESSING IMPACTS

Alison Y. Yu and R. John Hansman

This report is based on the Masters Thesis of Alison Y. Yu submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology.

The work presented in this report was also conducted in collaboration with:

Prof. R. John Hansman

Report No. ICAT-2019-07
May 2019

MIT International Center for Air Transportation (ICAT)
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

[Page Intentionally Left Blank]

AIRCRAFT NOISE MODELING OF DISPERSED FLIGHT TRACKS AND METRICS FOR ASSESSING IMPACTS

by

Alison Y. Yu and Prof. R. John Hansman

ABSTRACT

The implementation of Performance Based Navigation (PBN), such as Area Navigation (RNAV) and Required Navigation Performance (RNP), has led to aircraft being able to fly designed flight tracks very precisely. This has led to communities citing the concentration of aircraft along one flight track as a noise issue because of the frequent overflights above specific areas.

In order to assess the impact of frequent overflights, metrics for understanding the annoyance mechanism were necessary. The metric N_x , which is a count of the number of overflights above the A-weighted maximum sound level ($L_{A,max}$) of xdB during the day and (x-10)dB during the night, was investigated. The metric N_x required analysis of the $L_{A,max}$ noise level to count as an overflight, as well as the number of overflights that represented the annoyance threshold. N_{60} on a peak day with 50 overflights was shown to represent at least 80% of the complaint locations at BOS, MSP, LHR, and one runway at CLT. Alternatively peak day DNL is also shown to be a possible representative noise metric and will also be investigated.

A noise metric representative of the impacts of frequent overflights allowed for communication of analysis results for possibilities for dispersed flight tracks. Important ways to communicate analysis results to stakeholders included: overall increase or decrease in population exposure to N_{60} on a peak day with 50 overflights, the change in the number of N_{60} overflights for the areas of impact, and presentation of the data that allowed stakeholders to understand the impact within the boundaries of their specific representative area. These tools will allow communities to understand the noise impacts of the procedures considered and will support the stakeholder decision processes.

[Page Intentionally Left Blank]

ACKNOWLEDGEMENTS

This work was sponsored by the Federal Aviation Administration (FAA) under ASCENT Center of Excellence Project 23, Cooperative Agreement 13-C-AJFE-MIT-008 and by the Massachusetts Port Authority (Massport). Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government or by the Massachusetts Government.

Radar data and complaint data were provided by the airports in this study, BOS, MSP, LHR, and CLT.

The authors would like to acknowledge the management support of Chris Dorbian, Joseph DiPardo, and Bill He from FAA Office of Environment and Energy and of Flavio Leo from Massport. The author would also like to thank Luke Jensen, Jacqueline Thomas, M. Gregory O'Neill, Clement Li, and Pedro Manuel Maddens Toscano, who contributed to work used or referenced in this report.

[Page Intentionally Left Blank]

Table of Contents

Chapter 1 Introduction and Motivation	15
Chapter 2 Background	20
2.1 Noise Metrics	20
2.1.1 Sound Pressure Level.....	20
2.1.2 Frequency Weighting.....	20
2.1.3 Single Event Metrics: $L_{A,max}$ and Sound Exposure Level.....	21
2.1.4 Integrated Exposure Metrics: Day-Night Average Sound Level and Number Above.....	22
2.2 Literature Review	23
2.2.1 Annual Average DNL	23
2.2.2 Number Above.....	24
2.2.3 Alternative Representative Days.....	24
Chapter 3 Noise Modeling Methodology	25
Chapter 4 Representative Averaging Day of Peak Day	28
4.1 Peak Day Identification	28
Chapter 5 Correlation of Complaint Locations with Runway Use.....	30
5.1 BOS Clusters	31
5.2 MSP Clusters.....	32
5.3 LHR Clusters.....	33
5.4 CLT Clusters	34
Chapter 6 Annoyance Noise Threshold Determination: Peak Day N_x..	35
6.1 Noise Level Threshold	36
6.2 Overflight Count Threshold.....	37
6.3 Peak Day N_{60} Overflight Contours.....	37
6.3.1 BOS.....	37
6.3.2 MSP.....	39
6.3.3 LHR.....	42
6.3.4 CLT	43
6.3.4.1 CLT Peak Day N_{50}	46
6.4 Discussion.....	48
Chapter 7 Annoyance Noise Threshold Determination: Peak Day DNL	49
7.1 Peak Day DNL Contours.....	52
7.1.1 BOS.....	52
7.1.2 MSP.....	54
7.1.3 LHR.....	56
7.1.4 CLT	58

Chapter 8 Dispersion Analysis	61
8.1 Dispersion Analysis Communication Tools	61
8.1.1 Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	61
8.1.2 Change in Peak Day N ₆₀ Maps	62
8.1.3 Town by Town Analysis	64
8.2 Peak Day Analysis for Dispersion Modeling	65
8.3 Arrivals Dispersion	67
8.4 Altitude-Based Dispersion.....	67
8.5 Controller-Based Dispersion.....	72
8.6 Divergent Heading Dispersion	75
8.7 RNAV Turning Waypoint Relocation.....	78
Chapter 9 Conclusion	85
References.....	86
Appendix A Aircraft Types Table [19]	90
Appendix B Peak Day Analysis for Dispersion Modeling	93
Appendix C Arrivals Dispersion	95
Appendix D BOS 27 Departures Dispersion Analysis and Record of Decision	98
Appendix E Dispersion Histograms	111

List of Figures

Figure 1. Performance-Based Navigation [1]	15
Figure 2. Airport Operator Equipage at BOS in December 2018 [2]	16
Figure 3. RNAV Track Concentration and Increase in Complaint Locations	17
Figure 4. Need for Noise Metrics to Communicate Analysis Results to Allow for Community Decision Process [7]	18
Figure 5. A-weighting and C-weighting Adjustment Curves [10]	21
Figure 6. $L_{A,max}$ and Sound Exposure Level [11].....	22
Figure 7. N_{60} Calculation	23
Figure 8. Noise Modeling Framework.....	25
Figure 9. BOS Complaint Locations and Radar Data 2017	31
Figure 10. MSP Complaint Locations and Radar Data 2017.....	32
Figure 11. LHR Complaint Locations and Radar Data 2017.....	33
Figure 12. CLT Complaint Locations and Radar Data 2017	34
Figure 13. BOS 33L Departures Peak Day N_{60} at 25, 50, and 100 Overflights	38
Figure 14. BOS 27 Departures Peak Day N_{60} at 25, 50, and 100 Overflights.....	38
Figure 15. BOS 4L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights	39
Figure 16. MSP 17 Departures Peak Day N_{60} at 25, 50, and 100 Overflights.....	40
Figure 17. MSP 30L Departures Peak Day N_{60} at 25, 50, and 100 Overflights	40
Figure 18. MSP 12L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights.....	41
Figure 19. MSP 30R Departures Peak Day N_{60} at 25, 50, and 100 Overflights.....	41
Figure 20. LHR 9R Departures Peak Day N_{60} at 25, 50, and 100 Overflights.....	42
Figure 21. LHR 27L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights.....	43
Figure 22. CLT 18L/C/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights.....	44
Figure 23. CLT 18C Departures Peak Day N_{60} at 25, 50, and 100 Overflights	44
Figure 24. CLT 18L Departures Peak Day N_{60} at 25, 50, and 100 Overflights.....	45
Figure 25. CLT 36R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights.....	45
Figure 26. CLT 18C Departures Peak Day N_{50} at 25, 50, and 100 Overflights	47
Figure 27. CLT 18L Departures Peak Day N_{50} at 25, 50, and 100 Overflights.....	47
Figure 28. CLT 36R Arrivals Peak Day N_{50} at 25, 50, and 100 Overflights	48
Figure 29. BOS 33L Departures Peak Day DNL Contours	52
Figure 30. BOS 27 Departures Peak Day DNL Contours	53
Figure 31. BOS 4L/R Arrivals Peak Day DNL Contours.....	53
Figure 32. MSP 17 Departures Peak Day DNL Contours	54
Figure 33. MSP 30L Departures Peak Day DNL Contours.....	55
Figure 34. MSP 12L/R Arrivals Peak Day DNL Contours	55
Figure 35. MSP 30R Departures Peak Day DNL Contours.....	56
Figure 36. LHR 9R Departures Peak Day DNL Contours.....	57
Figure 37. LHR 27 Arrivals Peak Day DNL Contours.....	57
Figure 38. CLT 18L/C/R Arrivals Peak Day DNL Contours	58
Figure 39. CLT 18C Departures Peak Day DNL Contours	59
Figure 40. CLT 18L Departures Peak Day DNL Contours	59
Figure 41. CLT 36R Arrivals Peak Day DNL Contours	60

Figure 42. BOS 33L Departures Pre-RNAV to RNAV Comparison Change in Peak Day N ₆₀	63
Figure 43. BOS 33L Departures Pre-RNAV to RNAV Comparison Change in N ₆₀ Town Histograms	64
Figure 44. BOS 33L Departures Peak Day Flight Tracks Clustered by Transition Waypoint.....	66
Figure 45. Natural Variability in Aircraft Climb Rates [27]	68
Figure 46. BOS 33L Departures Altitude-Based Dispersion at 3000ft Flight Tracks	69
Figure 47. BOS 33L Departures Altitude-Based Dispersion at 4000ft Flight Tracks	69
Figure 48. BOS 33L Departures Altitude-Based Dispersion at 3000ft Change in N ₆₀ Overflights on a Peak Day	70
Figure 49. BOS 33L Departures Altitude-Based Dispersion at 4000ft Change in N ₆₀ Overflights on a Peak Day	72
Figure 50. BOS 33L Departures Controller-Based Dispersion Flight Tracks	74
Figure 51. BOS 33L Departures Controller-Based Dispersion Change in N ₆₀ Overflights on a Peak Day	75
Figure 52. BOS 33L Departures Divergent Heading Dispersion Flight Tracks	76
Figure 53. BOS 33L Departures Divergent Heading Dispersion Change in N ₆₀ Overflights on a Peak Day	77
Figure 54. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks -1nmi ...	78
Figure 55. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks -0.5nmi	79
Figure 56. BOS 33L Dep. RNAV Turning Waypoint Reloc. Flight Tracks +0.5nmi	79
Figure 57. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks +1nmi ..	80
Figure 58. BOS 33L Departures RNAV Turning Waypoint Relocation -1nmi Change in N ₆₀ Overflights on a Peak Day.....	81
Figure 59. BOS 33L Departures RNAV Turning Waypoint Relocation -0.5nmi Change in N ₆₀ Overflights on a Peak Day.....	82
Figure 60. BOS 33L Departures RNAV Turning Waypoint Relocation +0.5nmi Change in N ₆₀ Overflights on a Peak Day	83
Figure 61. BOS 33L Departures RNAV Turning Waypoint Relocation +1nmi Change in N ₆₀ Overflights on a Peak Day.....	84

List of Tables

Table 1. Representative Aircraft Vertical Flight Profiles [19]	26
Table 2. Annual Average Day Operations vs Peak Day Operations*	29
Table 3. Peak Day N ₅₅	35
Table 4. Peak Day N ₆₀	36
Table 5. Peak Day N ₆₅	36
Table 6. CLT Peak Day N ₅₀	46
Table 7. BOS Peak Day DNL.....	50
Table 8. MSP Peak Day DNL.....	50
Table 9. LHR Peak Day DNL.....	51
Table 10. CLT Peak Day DNL	51
Table 11. Population Exposure to N ₆₀ on a Peak Day with 50 Overflights for BOS 33L Departures Pre-RNAV to RNAV Conditions	62
Table 12. BOS 33L Departures Peak Day Sorted by Transition Waypoint Clusters	66
Table 13. BOS 33L Departures Peak Days Comparison	66
Table 14. BOS 33L Departures Altitude-Based Dispersion at 3000ft Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	70
Table 15. BOS 33L Departures Altitude-Based Dispersion at 4000ft Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	71
Table 16. BOS 33L Departures 2010 Peak Day Normalized Against 2017 Peak Day	73
Table 17. BOS 33L Departures Controller-Based Dispersion Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	74
Table 18. BOS 33L Departures Divergent Heading Dispersion Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	77
Table 19. BOS 33L Departures RNAV Turning Waypoint Relocation -1nmi Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	81
Table 20. BOS 33L Departures RNAV Turning Waypoint Relocation -0.5nmi Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	82
Table 21. BOS 33L Departures RNAV Turning Waypoint Relocation +0.5nmi Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	83
Table 22. BOS 33L Departures RNAV Turning Waypoint Relocation +1nmi Population Exposure to N ₆₀ with 50 Overflights on a Peak Day	84

List of Equations

Equation 1. Sound Pressure Level	20
Equation 2. Day Night Average Sound Level [12].....	22

List of Acronyms and Abbreviations

Term	Definition
AEDT	Aviation Environmental Design Tool
BOS	Boston Logan International Airport
CLT	Charlotte Douglas International Airport
dB	Decibel
DNL	Day-night average sound level
FAA	Federal Aviation Administration
Frequency of overflight	The rate at which aircraft are flying overhead, ex. a flight every five minutes
GPS	Global Positioning System
$L_{A,max}$	A-weighted maximum sound pressure level
LHR	London Heathrow International Airport
LRJ	Large regional jet
MSP	Minneapolis-St. Paul International Airport
NAVAID	Navigational Aid
NEPA	National Environmental Policy Act
nmi	Nautical mile
N_x	Number of overflights above $L_{A,max}$ xdB during the day and $L_{A,max}$ (x-10)dB during the night
OJ	Older jet
PBN	Performance Based Navigation
PVD	T. F. Green Airport (Providence)
RNAV	Area Navigation
RNP	Required Navigation Performance
RNP-AR	Required Navigation Performance - Authorization Required
ROD	Record of Decision
SEL	Sound Exposure Level
SPL	Sound Pressure Level
SRJ	Small regional jet
TA	Twin-aisle jet

[Page Intentionally Left Blank]

Chapter 1 Introduction and Motivation

Aircraft navigation has modernized from conventional routes towards PBN which includes RNAV and RNP. Figure 1 illustrates the differences between conventional routes, RNAV, and RNP. Conventional routes require moving between navigational aids (NAVAIDs), which are pieces of hardware equipment on the ground. The novelty of RNAV is that aircraft can navigate between waypoints, which can be defined by any latitude and longitude coordinates using Global Positioning System (GPS) technology. RNP-Authorization Required (RNP-AR) is even more technologically advanced in that RNP-AR allows defining the path between waypoints. Almost all general aviation aircraft are currently equipped with RNAV, and airlines are working towards equipping all the general aviation aircraft with RNP-AR technology. Figure 2 shows the equipage levels at BOS as of December 2018 where almost 100% of general aviation aircraft are RNAV equipped and greater than 50% of general aviation aircraft are RNP-AR equipped [2].

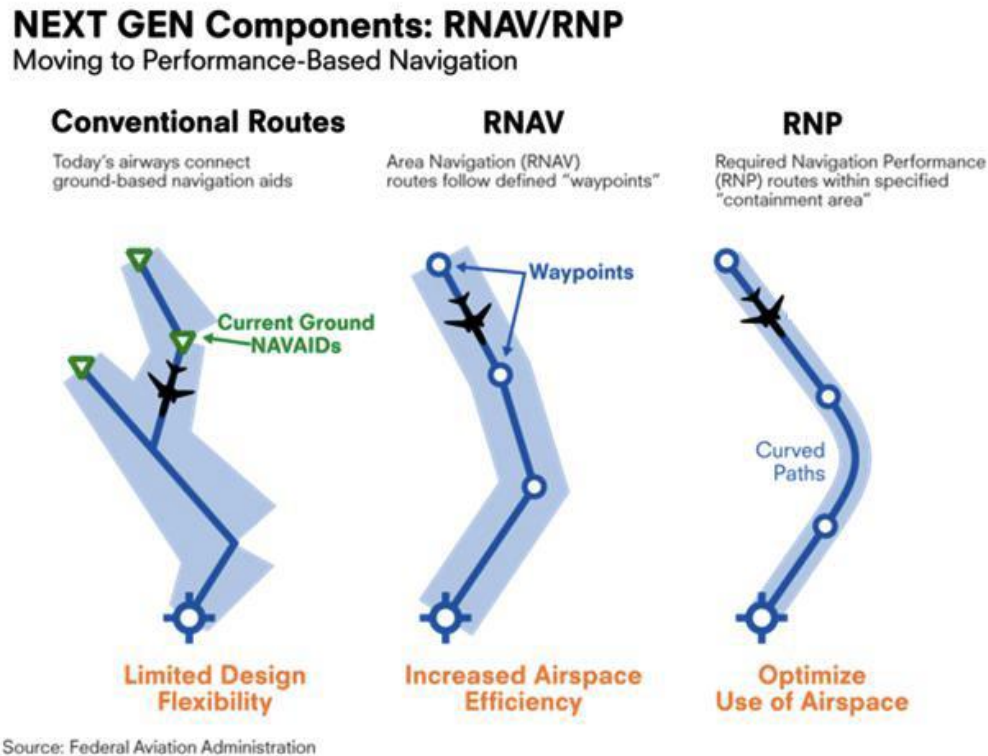


Figure 1. Performance-Based Navigation [1]

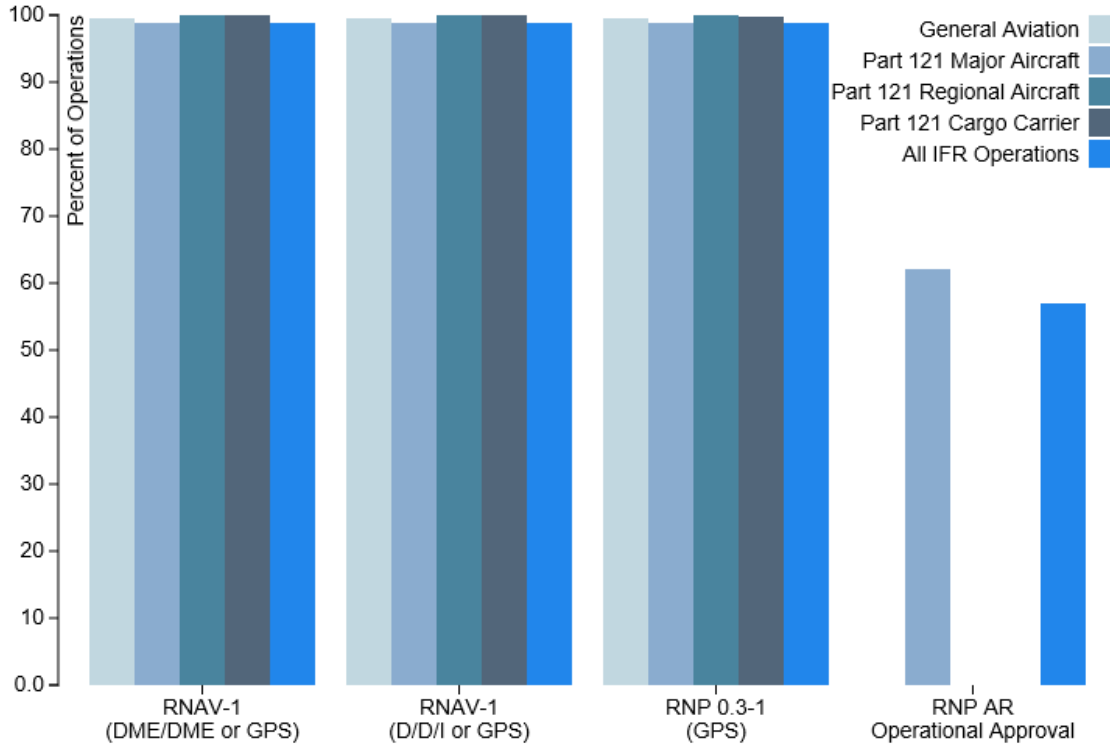
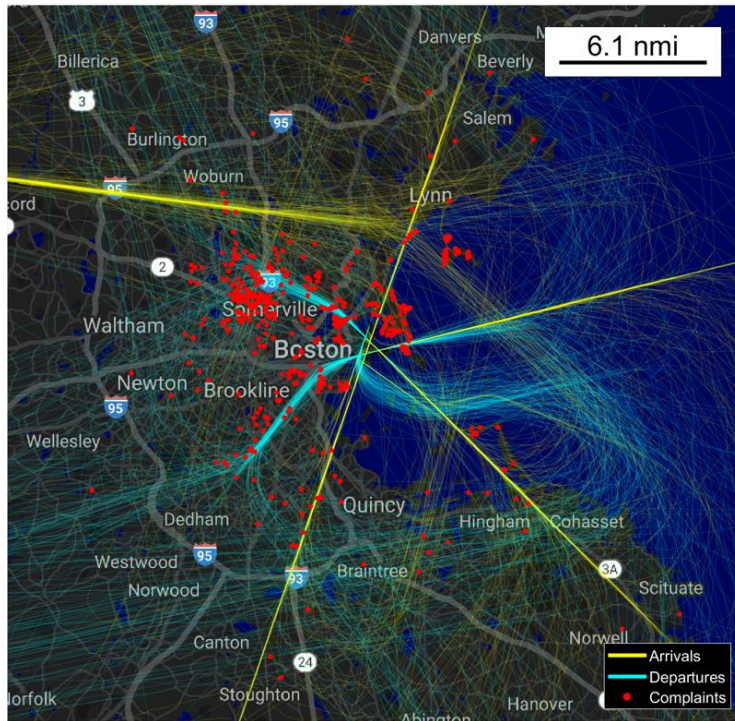
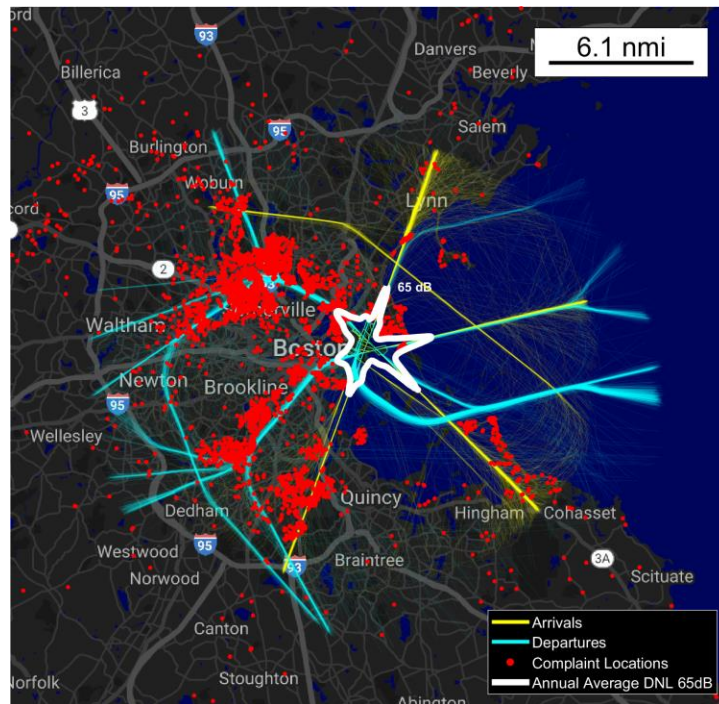


Figure 2. Airport Operator Equiptage at BOS in December 2018 [2]

The modernization of aircraft navigation has meant that aircraft are able to fly designed flight tracks more precisely. This has led to a concentration of flights over the communities along the flight tracks. Communities at airports in many countries have cited the concentration in flight tracks as an increasing noise issue because of the frequent overflights above specific areas [3][4][5]. Figure 3 shows the flight track concentration and the increase in complaint locations following the implementation of RNAV, where the blue lines represent the departure tracks, the yellow lines represent the arrival tracks, and the red dots represent the complaint locations. Figure 3(a) shows the data from 2010, which was prior to the implementation of RNAV, and the flight tracks are dispersed. Figure 3(b) shows the data from 2017, which was after the implementation of RNAV, and the flight tracks are concentrated and there appear to be geographic areas of complaint locations associated with the RNAV procedures.



(a) 2010



(b) 2017, Annual Average DNL 65dB Contour

Figure 3. RNAV Track Concentration and Increase in Complaint Locations

In order to understand the impacts of frequent overflights, metrics for assessing the annoyance mechanism were necessary. The metric for defining significant noise level in United States policy is annual average day-night average sound level (DNL) at 65dB [6]. However, the annual average DNL at 65dB does not appear to be representative of the complaint locations. In Figure 3(b), the white contour is the annual average DNL contour at the 65dB level at BOS in 2017 and only 1.2% of the of the complaint locations are within the contour. Therefore alternate metrics for assessing the impacts of frequent overflights were investigated in this thesis.

Metrics for assessing the impacts of frequent overflights allow for analysis of concepts for dispersed flight tracks. In many cases, the idea of returning to an airspace environment similar to pre-RNAV conditions with dispersed flight tracks is a politically attractive idea. However, the community noise impacts of dispersion are complex due to redistribution issues, and the implementation of dispersion may also be difficult for technical reasons. Figure 4 illustrates the need to have communication tools and visualizations to present noise analysis to communities, in order to support the community decision processes.

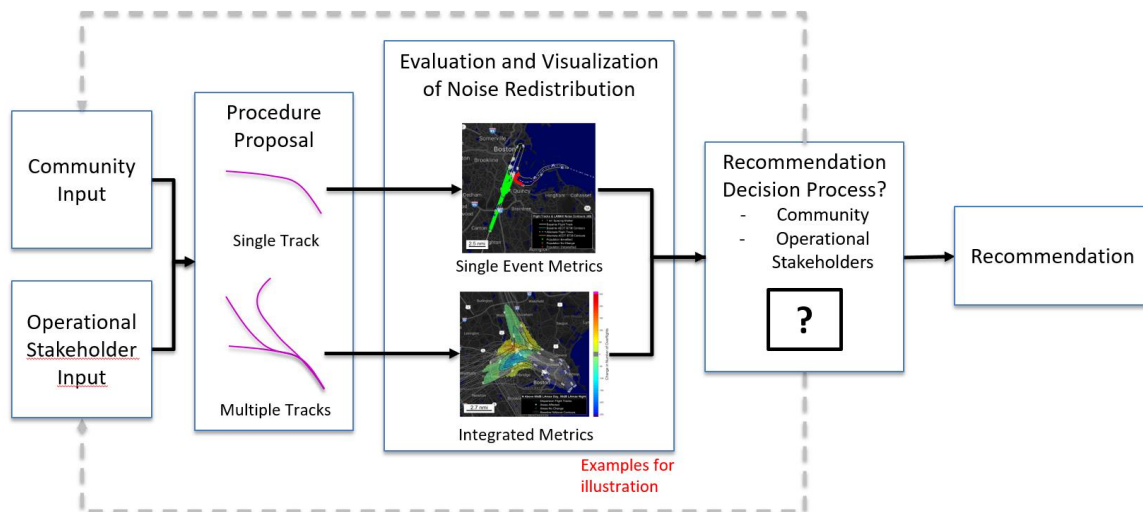


Figure 4. Need for Noise Metrics to Communicate Analysis Results to Allow for Community Decision Process [7]

The objectives of this thesis were, firstly, to determine a noise metric which is representative of the impacts of numerous overflights and, secondly, to analyze the potential impacts of dispersed flight tracks and various methods of communicating these results to stakeholders. Integrated exposure noise metrics of DNL and N_x were considered. The representative days of annual average day and peak day were also compared. Varying ways of communicating the analysis data to the communities have been presented in stakeholder meetings and will be discussed in this thesis.

Chapter 2 Background

2.1 Noise Metrics

2.1.1 Sound Pressure Level

Noise is defined as undesirable sound, and sound is caused by fluctuating pressure waves [8]. One of the most fundamental metrics for noise is sound pressure level (SPL), shown in Equation 1, where the reference pressure, P_{ref} , is 20 μ Pa root mean square and P_0 is the pressure amplitude of the sound wave [9]. SPL is a logarithmic metric so the units of measurement are decibels (dB).

$$SPL = 20 \log_{10} \left(\frac{P_0}{P_{ref}} \right)$$

Equation 1. Sound Pressure Level

2.1.2 Frequency Weighting

Humans respond to some noise frequencies more so than others, therefore weightings are applied to certain frequencies in sound pressure level for specific noise metrics. Weightings are applied by dividing frequencies into 1/3-octave bands and then increasing or reducing the sound pressure level by a factor. Common weightings include A-weighting and C-weighting; Figure 5 plots A-weighting, represented as the blue line, and C-weighting, represented as the magenta line. A-weighting is used in aircraft noise overflights studies and heavily weights the mid-range frequencies of 2,000-6,000 Hz, as this is the range of most human speech and is the range where the human ear is most sensitive [10].

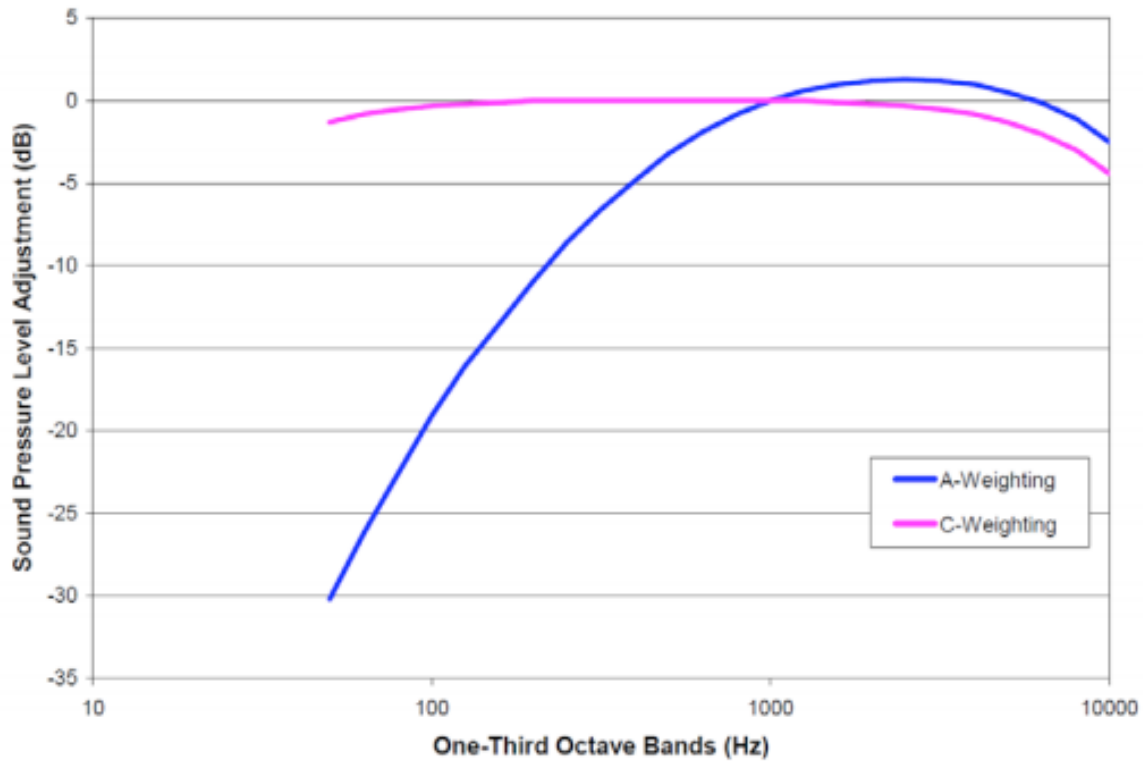


Figure 5. A-weighting and C-weighting Adjustment Curves [10]

2.1.3 Single Event Metrics: $L_{A,max}$ and Sound Exposure Level

While SPL is a measurement of instantaneous noise, additional metrics are used to communicate the overall noise level of an aircraft overflight. Figure 6 illustrates the metrics of $L_{A,max}$ and Sound Exposure Level (SEL). $L_{A,max}$ is the maximum A-weighted sound pressure level of an overflight. In Figure 6, the $L_{A,max}$ is the peak noise during the time of the overflight. SEL takes into account the duration of an overflight. SEL is calculated by integrating the A-weighted noise over time between the time when the A-weighted noise has risen to 10dB below the $L_{A,max}$ to the time when the A-weighted noise has fallen to 10dB below the $L_{A,max}$. In Figure 6, the SEL is the gray area shaded integration area. [11]

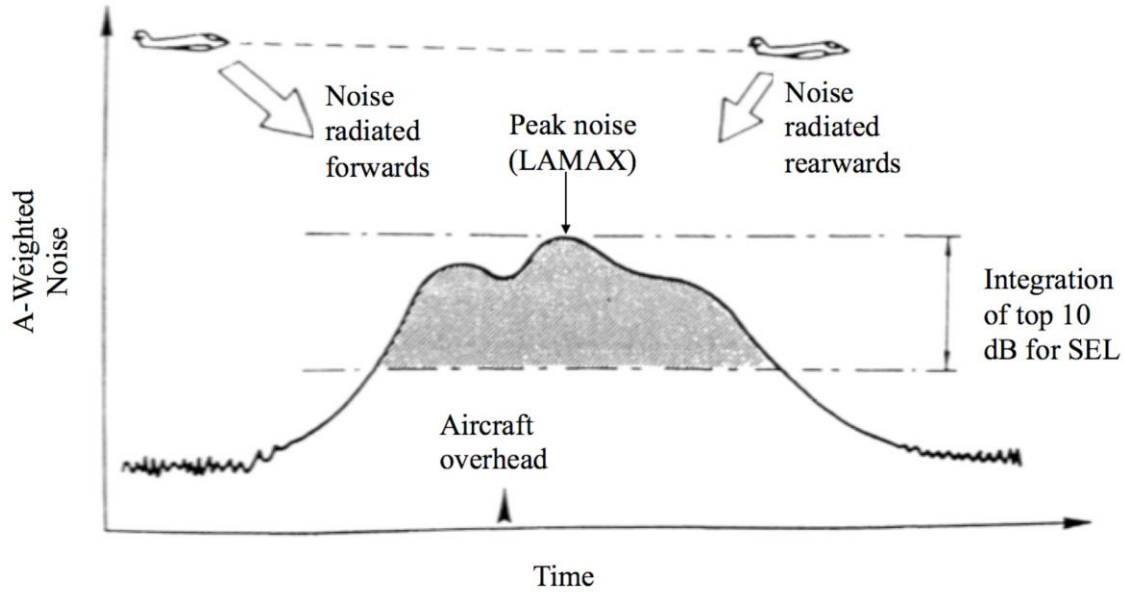


Figure 6. $L_{A,max}$ and Sound Exposure Level [11]

2.1.4 Integrated Exposure Metrics: Day-Night Average Sound Level and Number Above

In order to quantify the noise effects of multiple overflights, integrated exposure metrics are used. A commonly used integrated exposure metric is day-night average sound level (DNL). DNL is a summation of SEL that is then averaged over the time period of a day, 86,400 seconds. A 10dB penalty is applied to night time overflights, which occur between 10pm and 7am. The calculation for DNL is shown in Equation 2 [12].

$$DNL = 10 \log_{10} \left(\frac{1}{T} \left[\sum_{i=1}^n 10^{\frac{SEL_{day,i}}{10}} + \sum_{i=n+1}^m 10^{\frac{SEL_{night,i}+10}{10}} \right] \right)$$

Equation 2. Day Night Average Sound Level [12]

Another integrated exposure metric is N_x . N_x is a count of the number of overflights above a certain $L_{A,max}$ threshold. The x indicates the day time $L_{A,max}$ threshold

and then the night time threshold has a 10dB $L_{A,max}$ penalty [13]. Figure 7 illustrates an example of how N_{60} would be calculated.

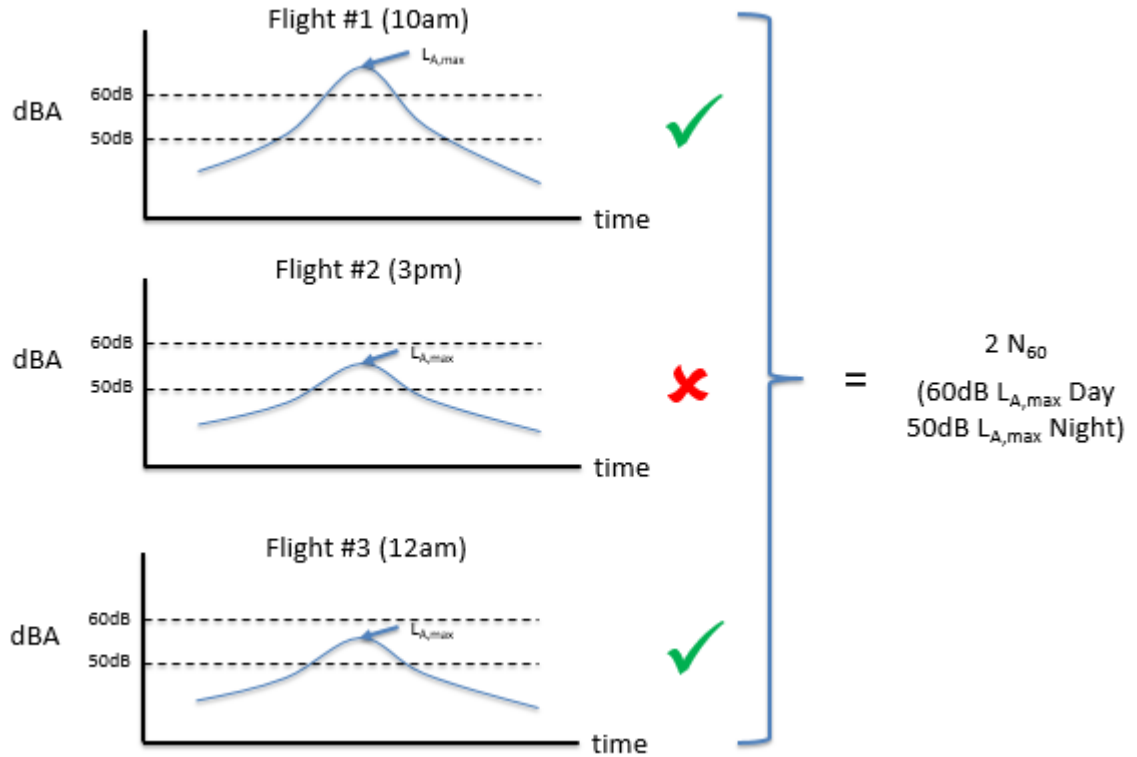


Figure 7. N_{60} Calculation

2.2 Literature Review

2.2.1 Annual Average DNL

One of the most commonly used noise metrics is annual average DNL at 65dB as this is the metric used to define significant noise exposure in United States policy. This threshold was adopted into regulation with the passing of the Aviation Safety and Noise Abatement Act of 1979. Annual average DNL at 65dB is the basis of billions of dollars in programs including sound insulation for homes and schools within the impact area of significant noise levels [6]. The threshold is based on the work of Schultz in “Synthesis

of social surveys on noise annoyance” in 1978. In his study, Schultz uses responses to surveys as the basis for quantifying how annoyed people are by noise [14].

2.2.2 Number Above

Since 1978, studies have been conducted on additional metrics to communicate noise impacts aside from DNL. Southgate published in 2011 “The Evolution of Aircraft Noise Descriptors in Australia over the Past Decade.” One of the metrics that has gained increasing popularity in Australia as well as other countries is, as Southgate describes, ‘Number Above’ N70 [15]. N70 was chosen because this was taken to correlate with the sound level of a conversation 60dB inside an insulated home [16], however there is increasing interest in other noise levels for the number above metric as indicated in other studies.

2.2.3 Alternative Representative Days

In the United Kingdom “Survey of noise attitudes 2014: Aircraft” N70 is determined to be a useful supplemental metric. Other noise levels are also considered for the number above metric including N65. Another point of note from this publication is that the annual average day is not the only representative day considered. In this publication, the representative day of an average summer day is also considered relating to the idea that some days are more representative of the annoyance mechanism to communities than the annual average day [17].

Chapter 3 Noise Modeling Methodology

In order to determine the noise impacts to communities to assess various noise metrics, a noise modeling framework was necessary. Figure 8 shows the noise modeling methodology used in this study. The noise modeling program used was the Federal Aviation Administration (FAA) standard tool the Aviation Environmental Design Tool (AEDT) [18].

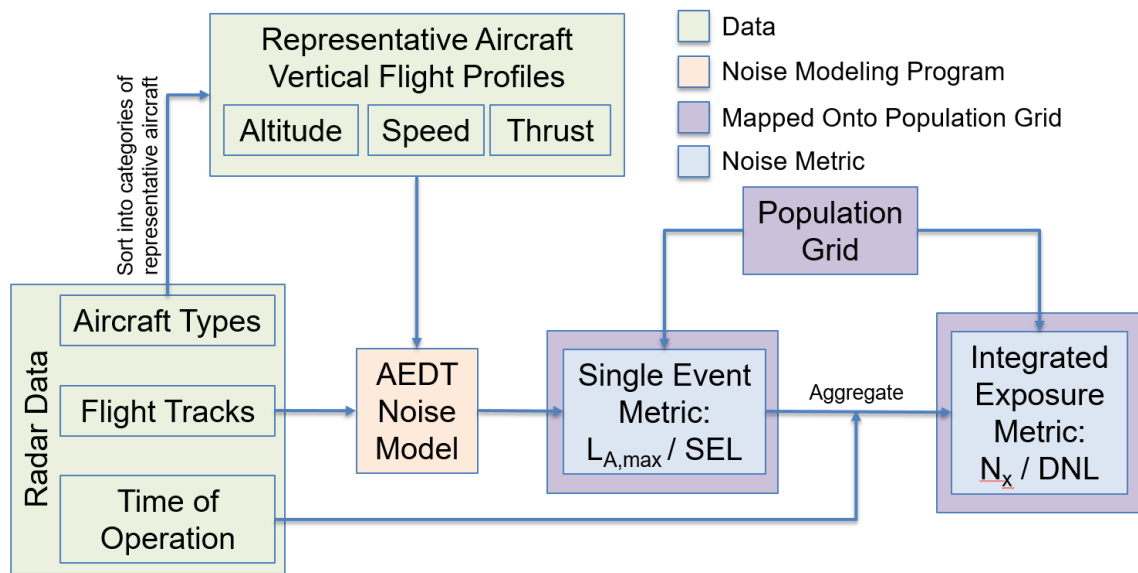


Figure 8. Noise Modeling Framework

Radar data includes information on the aircraft flown, which is then sorted into types of representative aircraft vertical flight profiles. The types of representative aircraft vertical flight profiles are shown in Table 1, which are B773 representing twin aisle jets, B757, A320, B738, MD88 representing older jets, E170 representing large regional jets, and E145 representing small regional jets. Brenner and Hansman also discuss the sorting of vertical flight profiles into aircraft bins as shown in Table 1 [19] and the full list for how aircraft are sorted into aircraft type bins is provided in Appendix A.

Table 1. Representative Aircraft Vertical Flight Profiles [19]

Representative Aircraft Type	Category Name	Category Description
B773	TA	Twin Aisle Jet
B752	B757	Boeing 757 Family
A320	A320	Airbus A320 Family
B738	B737	Boeing 737 Family
MD88	OJ	Older Jet
E170	LRJ	Large Regional Jet
E145	SRJ	Small Regional Jet, Business Jet, and Turboprop
--	PNJ UNK	Excluded (Piston Engine and Unknown)

On arrivals, the standard profiles from the noise modeling program AEDT were input into the noise model as the representative vertical flight profile for each aircraft type. For departures, the representative aircraft vertical flight profiles were generated by analyzing the altitude and speed data for each aircraft type and determining the median altitude and speed profiles. Using the median altitude and speed profiles from the data for each aircraft type, the thrust profile was calculated using the aircraft performance model BADA4. Thomas and Hansman [20] provides details on the vertical flight profile generation.

Radar data was also used to define each horizontal flight track. The data on the time of each operation was later used in calculating the integrated exposure metrics in determining if an overflight should be counted as a day time flight or a night time flight. In this study each radar data horizontal flight track was modeled individually.

The vertical flight profile data and the horizontal flight track data were then input into the noise model AEDT. AEDT output the results for a single event noise metric, in this case either $L_{A,max}$ or SEL. AEDT output the results in a grid format which could be matched with latitude and longitude. The noise results and the grid were then mapped onto a grid with population data from the 2010 census. Jensen and Hansman describes in further detail the population grid data from the 2010 census [21]. AEDT was run numerous times to represent each operation and then the noise results were aggregated on

the population grid to calculate the integrated exposure metrics, N_x or DNL, for the analysis in this study.

Chapter 4 Representative Averaging Day of Peak Day

During stakeholder meetings, communities often expressed an annoyance mechanism that was different from the annual averaging that is applied for a day in commonly used noise metrics. Complaints were often correlated with high intensity use periods; a community member might complain that there was a flight over his/her house every 90 seconds on a day starting at 6am. Therefore noise metrics were investigated during high intensity use periods in this thesis. Peak day will be further discussed in the following section and was investigated for both N_x and DNL.

4.1 Peak Day Identification

In order to capture the time period of high intensity use, it was necessary to determine a representative high utilization period. The peak day is defined as the day in a year during which a runway procedure had the most number of operations. The airports analyzed in this study were BOS, MSP, LHR, and CLT. The peak day was analyzed for the runway procedures at these airports. Further details on the airports and specific runway procedures analyzed in this study are discussed in Chapter 5. Table 2 compares the number of operations represented by the annual average day to the number of operations on a peak day for each of the runway procedures and airports analyzed in this study. Since runway configuration varies from day to day based on several factors including wind, there are days where a runway procedure has hundreds of operations and days where a runway procedure has no operations. Communities have expressed that the complaints are a result of the days on which there are hundreds of overflights over their homes, hence why the peak day was used as the representative time frame in the following analysis.

Table 2. Annual Average Day Operations vs Peak Day Operations*

	Procedure	Annual Average Day Operations	Peak Day Operations	Peak Day
BOS	33L dep	116	487	May 18th, 2017
	27 dep	71	345	September 18th, 2017
	4L/R arr	129	567	October 12th, 2017
MSP	17 dep	174	421	August 25th, 2017
	30L dep	151	394	July 13th, 2017
	12L/R arr	239	677	July 25th, 2017
	30R dep	128	302	June 15th, 2017
LHR	9R dep	125	690	July 17th, 2017
	27L/R arr	526	696	June 30th, 2017
CLT	18L/C/R arr	258	806	May 4th, 2017
	18C dep	156	439	April 4th, 2017
	18L dep	185	503	April 26th, 2017
	36R arr	146	343	October 12th, 2017

*Note: Operations for parallel runways are the sum of all operations on the parallel runways.

Chapter 5 Correlation of Complaint Locations with Runway Use

In order to analyze the noise impact of the peak day of each runway procedure, it was necessary to identify areas of impact associated with each runway procedure. Complaint location data was used in this study for the sole purpose of understanding the spatial extent of noise impacts of runway procedures. Complaint data was provided by the airports in this study. The complaint data set is all the complaints in 2017.

Multiple complaints from the same location are only counted as one complaint location, in order to gain an understanding of the distribution of complaint locations without being skewed by hypersensitive individuals. In the noise metric analysis, the goal is not to represent within the noise contour 100% of the complaint locations since there are hypersensitive complainants. Rather the goal of the noise metric analysis is to represent within the noise contour between 80% to 90% of the complaint locations.

To associate complaint locations with specific runway procedures, the complaint location data was clustered using a k-means algorithm. Cluster seeds were assigned along the approach and departure paths to determine if unique clusters of complaints could be identified for each runway. The cluster seeds were assigned 6.5nmi from the Airport Reference Point (ARP) along the approach and departure paths, as shown in Figure 9 through Figure 12. The distance 6.5nmi was observed to be the distance which was sufficient to uniquely define individual runway procedures while still within the area of significant complaints. The k-means algorithm logic assigned complaint location data to the cluster seeds, which serve as centroids, and then calculated the distance from each complaint location to the cluster centroid; the algorithm iterated under the cluster assignments did not change [22].

The complaint location clusters were then identified by runway procedure. Clusters were only correlated if uniquely defined by a single runway procedure. Clusters over low population density areas where the sample size was small and less than one hundred complaint locations were observed were not considered in this analysis. The following subsections describe the complaint locations clusters analyzed in this study; in

the following figures, the magenta diamonds represent the cluster seeds, the yellow lines represent the arrival paths and the cyan lines represent the departure paths.

5.1 BOS Clusters

At BOS the identifiable clusters of impact are 33L departures, 27 departures, and 4L/R arrivals. The non-identifiable and confounded clusters of impact are generally to the east of the airport near the harbor where both arrival and departure routes are present. Figure 9 shows the radar data and the clusters of impact for BOS in 2017, with 33L departures complaint locations shown as yellow dots, 27 departures complaint locations shown as orange dots, and 4L/R arrivals complaint locations shown as red dots; the non-identifiable and confounded clusters of complaint locations are represented by the white dots to the east of the airport.

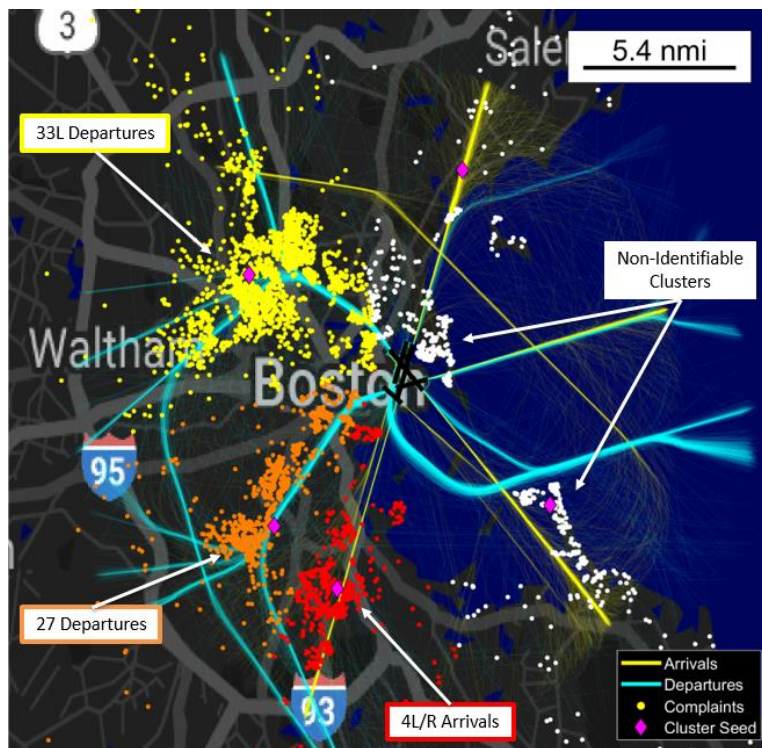


Figure 9. BOS Complaint Locations and Radar Data 2017

5.2 MSP Clusters

At MSP the identifiable clusters of impact are 30R departures, 12L/R arrivals, 30L departures, and 17 departures. The non-identifiable clusters of impact are generally to the east of the airport which is much less population dense than the northwest of the airport, so the clusters were not used in the N_x analysis due to the small sample size. There is also a non-identifiable cluster of complaint locations to the south of the airport which appears to be caused by both 17 departures and 35 arrivals. MSP uses RNAV approach procedures but does not use RNAV departure procedures. Figure 10 shows the clusters of impact and radar data for MSP in 2017, with 30R departures shown as green dots, 12L/R arrivals shown as magenta dots, 30L departures shown as orange dots, and 17 departures shown as red dots; the clusters of complaint locations that were not used for the N_x analysis are shown as white dots and gray dots.

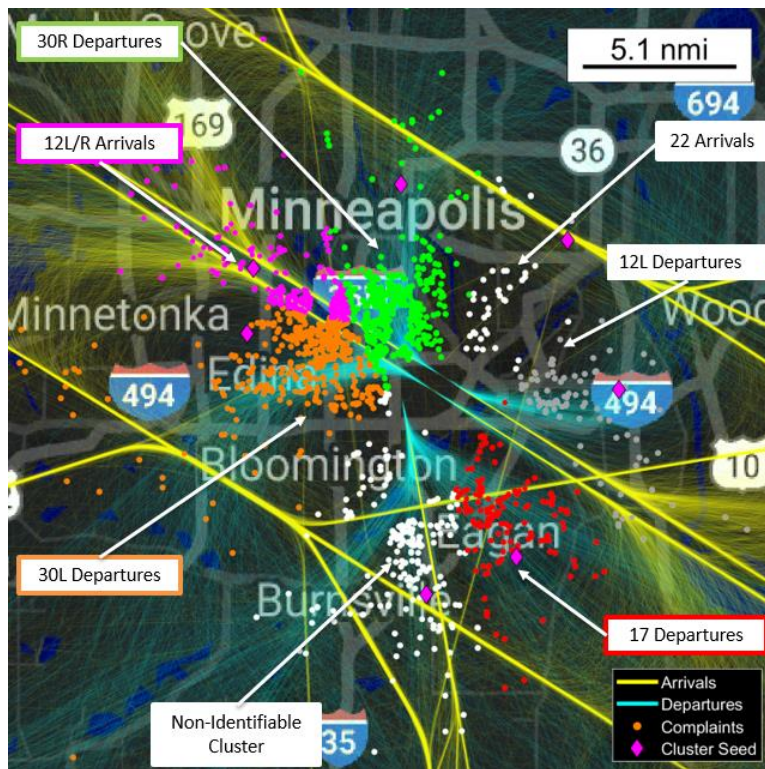


Figure 10. MSP Complaint Locations and Radar Data 2017

5.3 LHR Clusters

At LHR the clusters of complaint locations used in the N_x analysis are the 09 departures and the 27 arrivals to the east of the airport. The west of the airport is much less population dense so the clusters of complaint locations to the west of the airport were not used in the N_x analysis due to the small sample size. The complaint location data is from the “2017 Noise Complaint Report” for LHR [23]. Figure 11 shows the clusters of impact and radar data for LHR in 2017, with the 09 departures shown as orange dots, the 27 arrivals shown as blue dots; the clusters of complaint locations that are not used are the 27 departures shown as white dots and the 09 arrivals shown as red dots.

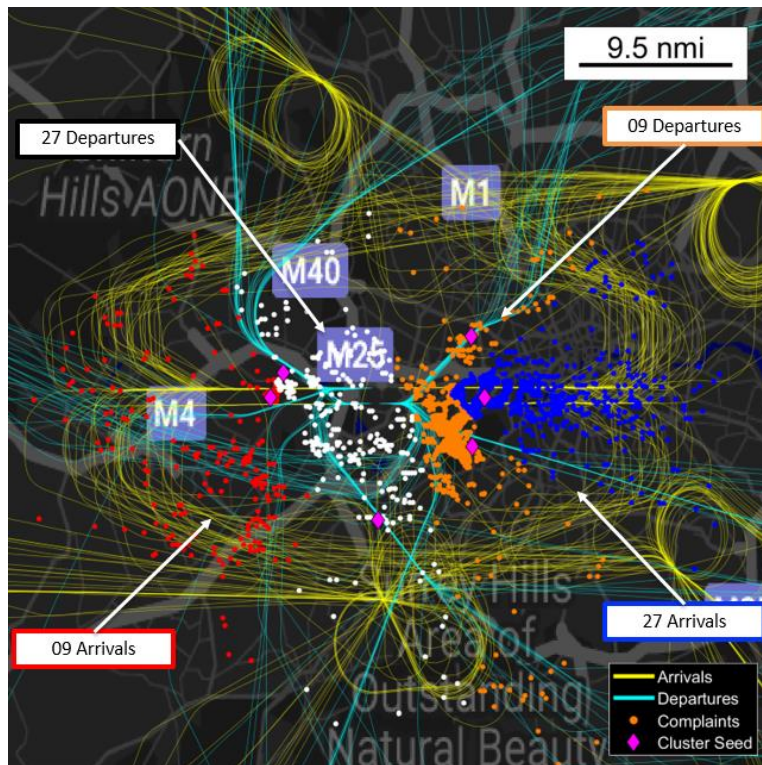


Figure 11. LHR Complaint Locations and Radar Data 2017

5.4 CLT Clusters

At CLT the identifiable area of impact is 18L/C/R arrivals. Additional clusters of impact seem to be correlated with 18C departures and 18L departures or 36R arrivals. Figure 12 shows the complaint location clusters and radar data for CLT in 2017; the 18L/C/R arrival complaint locations are shown as green dots, the 18C departure complaint locations are shown as red dots, and the cluster of complaint locations that appears to be correlated with either 18L departures or 36R arrivals is shown as blue dots.

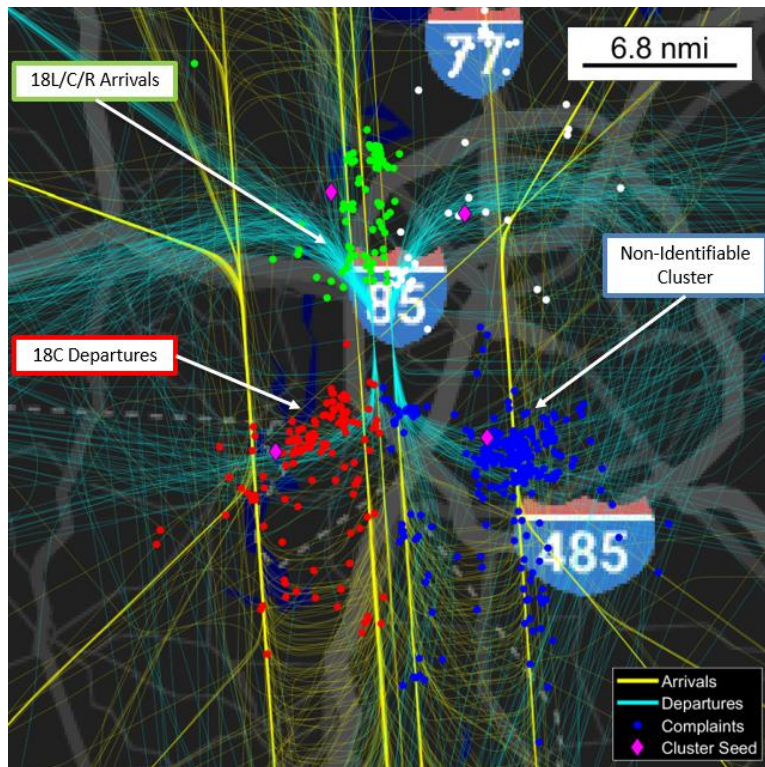


Figure 12. CLT Complaint Locations and Radar Data 2017

Chapter 6 Annoyance Noise Threshold Determination: Peak Day N_x

Parametric analysis was performed in order to determine the noise thresholds for the N_x metric. The sound levels of N_{55} , N_{60} , and N_{65} were analyzed, representing daytime thresholds of $L_{A,max}$ 55dB, 60dB, and 65dB and nighttime thresholds of $L_{A,max}$ 45dB, 50dB, and 55dB. The number of overflights was also swept through 25 overflights, 50 overflights, and 100 overflights for each sound level.

The results of the parametric sweep of N_{55} , N_{60} , and N_{65} for 25, 50, and 100 overflights are shown in Table 3 through Table 5 and are described in further detail in the following sections. The cells of the table were highlighted as red if less than 60% of the complaint locations were represented by the noise contour. Cells were highlighted as yellow in the results table if between 60% to 80% of the complaint locations were represented by the noise contour. Cells were highlighted as green in the results tables if greater than 80% of the complaint locations were represented by the noise contour.

Table 3. Peak Day N_{55}

		25 N_{55}	50 N_{55}	100 N_{55}
BOS	33L dep	91.9%	89.5%	84.4%
	27 dep	97.6%	95.7%	92.9%
	4L/R arr	98.3%	95.8%	86.1%
MSP	17 dep	98.1%	94.8%	85.2%
	30L dep	95.7%	94.1%	82.6%
	12L/R arr	95.5%	90.7%	85.8%
	30R dep	97.7%	94.4%	84.9%
LHR	9R dep	96.1%	94.3%	84.2%
	27L/R arr	96.6%	92.4%	88.0%
CLT	18L/C/R arr	85.3%	83.5%	82.6%
	18C dep	77.2%	67.3%	48.8%
	18L dep	69.0%	55.5%	18.6%
	36R arr	39.5%	11.2%	9.1%

Table 4. Peak Day N₆₀

		25 N ₆₀	50 N ₆₀	100 N ₆₀
BOS	33L dep	87.3%	80.9%	59.4%
	27 dep	95.4%	92.1%	78.8%
	4L/R arr	97.7%	94.7%	81.0%
MSP	17 dep	90.3%	83.2%	53.5%
	30L dep	92.7%	83.1%	55.7%
	12L/R arr	85.4%	77.6%	70.7%
	30R dep	91.9%	87.2%	69.4%
LHR	9R dep	91.0%	82.6%	61.4%
	27L/R arr	93.2%	84.9%	80.2%
CLT	18L/C/R arr	83.5%	80.7%	59.6%
	18C dep	53.1%	34.0%	13.6%
	18L dep	9.7%	7.1%	6.2%
	36R arr	9.7%	7.4%	3.5%

Table 5. Peak Day N₆₅

		25 N ₆₅	50 N ₆₅	100 N ₆₅
BOS	33L dep	71.5%	51.0%	24.0%
	27 dep	90.8%	78.3%	43.1%
	4L/R arr	72.1%	65.2%	43.2%
MSP	17 dep	69.7%	41.9%	5.2%
	30L dep	74.9%	50.0%	28.3%
	12L/R arr	72.4%	59.3%	45.1%
	30R dep	78.0%	63.6%	29.2%
LHR	9R dep	76.0%	57.1%	29.2%
	27L/R arr	84.0%	72.4%	65.8%
CLT	18L/C/R arr	78.9%	26.6%	4.6%
	18C dep	17.9%	6.2%	3.7%
	18L dep	6.2%	5.9%	3.2%
	36R arr	7.1%	3.2%	1.8%

6.1 Noise Level Threshold

The sensitivity of each noise level is indicated by the results of the parametric sweep. N₅₅ is shown in Table 3 to be too sensitive since there is little discrimination in the represented area between the 25 overflights threshold to the 100 overflight threshold. N₆₅ is shown in Table 5 to be not sensitive enough since even at 25 overflights, the noise

metric under-represents the complaint locations and thus the impacted area. N_{60} is shown in Table 4 to have reasonable sensitivity to reflect changes in the impacted area based on changes in the number of overflights.

6.2 Overflight Count Threshold

Given that peak day N_{60} was the sensitivity level to count as an overflight, the number of overflights was also parametrically varied. As shown in Table 4, peak day N_{60} with 25 overflights is shown to over-represent the impacted area, while peak day N_{60} with 100 overflights is shown to under-represent the impacted area; however several procedures at CLT appear to be anomalous. N_{60} on a peak day with 50 overflights is shown to capture the majority but not all of the impacted area, thus representing the goal of 80% to 90% of complaint locations for each runway procedure area of impact.

6.3 Peak Day N_{60} Overflight Contours

Because N_{60} was seen as the most diagnostic noise level, the N_{60} contours were further evaluated at each airport. Figure 13 through Figure 25 show the N_{60} contours for each of the airports and runway procedures in this study. The contours represented are the peak day N_{60} contours at 25 overflights, 50 overflights, and 100 overflights. The complaint locations associated with each runway procedure are represented by the red dots. The peak day flight tracks are represented as gray lines.

6.3.1 BOS

At BOS the analyzed runway procedures are 33L departures, 27 departures, and 4L/R arrivals shown in Figure 13 through Figure 15. The 33L departures in Figure 13 are a good visual example of the varying overflight levels for the N_{60} metric. The 100 overflight contour for N_{60} , the innermost contour, appears too small for the representative area. The 25 overflight contour for N_{60} , the outermost contour, appears to represent too much area. While the 50 overflight contour for N_{60} , the middle contour, appears to represent well the area impacted by the overflights, as indicated by the complaint locations.

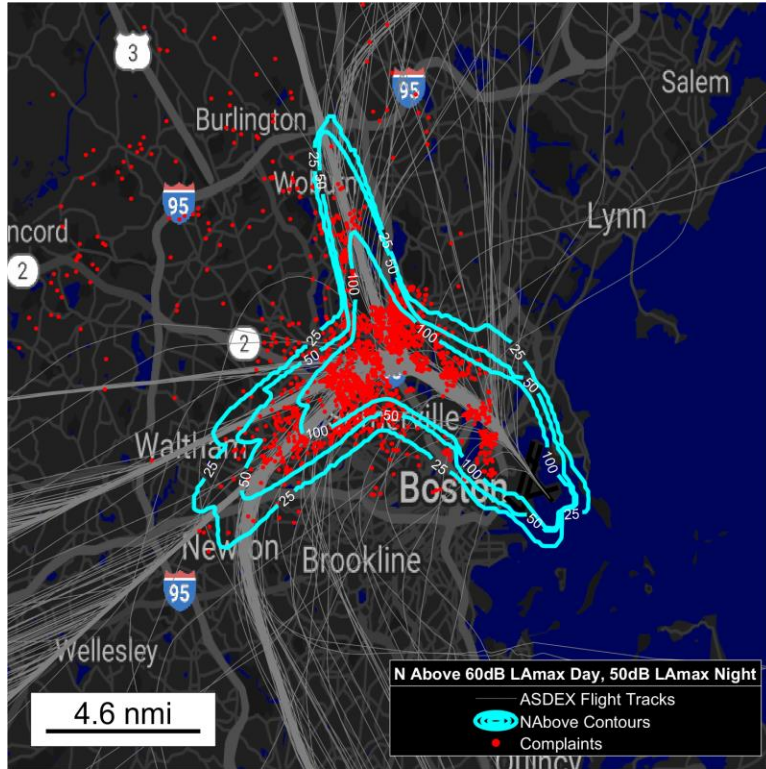


Figure 13. BOS 33L Departures Peak Day N_{60} at 25, 50, and 100 Overflights

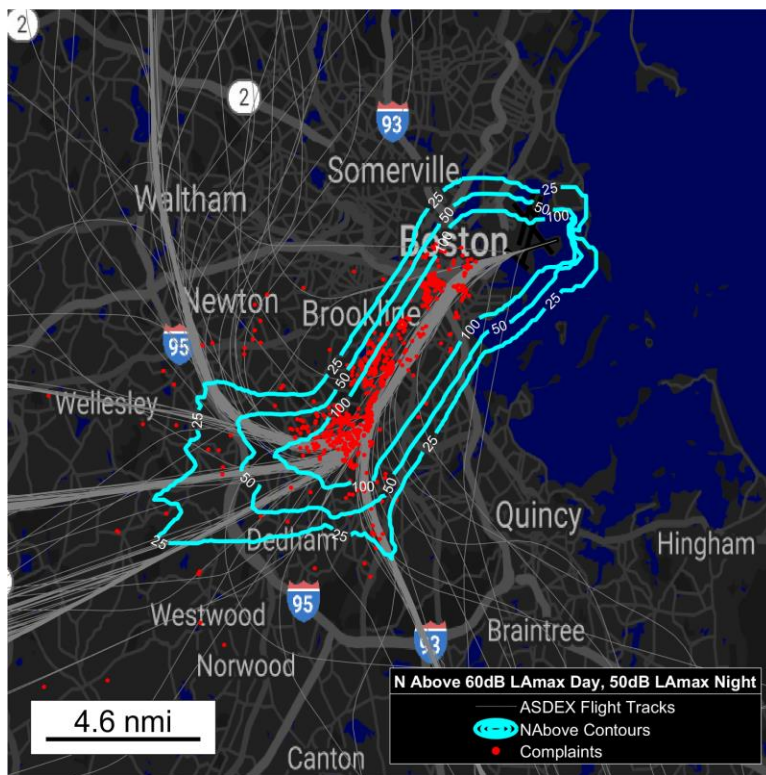


Figure 14. BOS 27 Departures Peak Day N_{60} at 25, 50, and 100 Overflights

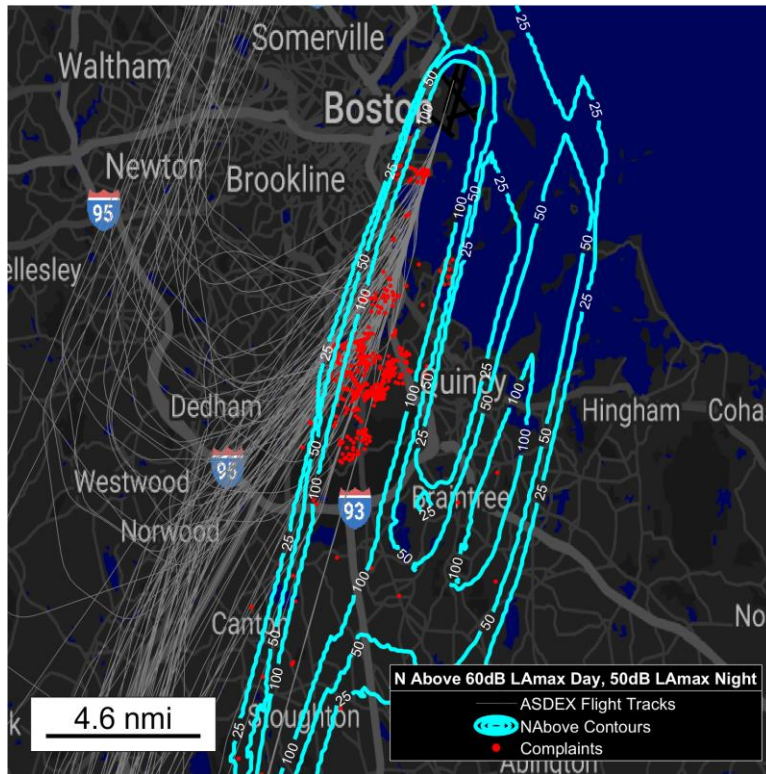


Figure 15. BOS 4L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights

6.3.2 MSP

At MSP the analyzed runway procedures were 17 departures, 30L departures, 12L/R arrivals, and 30R departures, shown in Figure 16 through Figure 19. At MSP, RNAV departures have never been implemented, however the threshold of N_{60} on a peak day with 50 overflights still appears to be a representative metric of impact. On the 12L/R arrivals, the 50 overflights at the N_{60} level on a peak day does not quite capture at least 80% of the complaints, however this could be due in part to confounding during the clustering process because the 12L/R arrivals have some overlap with the 30L and 30R departures.

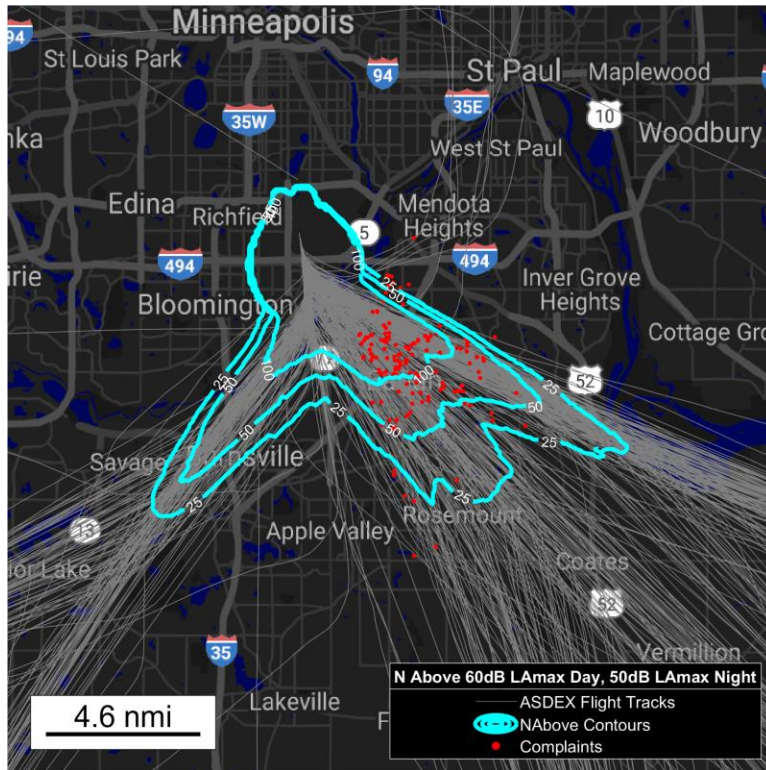


Figure 16. MSP 17 Departures Peak Day N₆₀ at 25, 50, and 100 Overflights

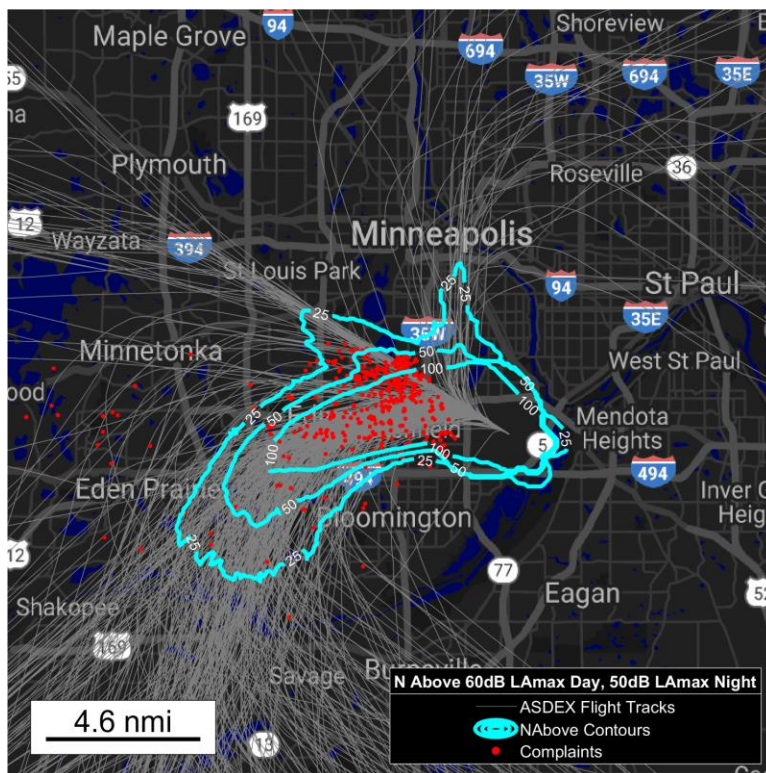


Figure 17. MSP 30L Departures Peak Day N₆₀ at 25, 50, and 100 Overflights

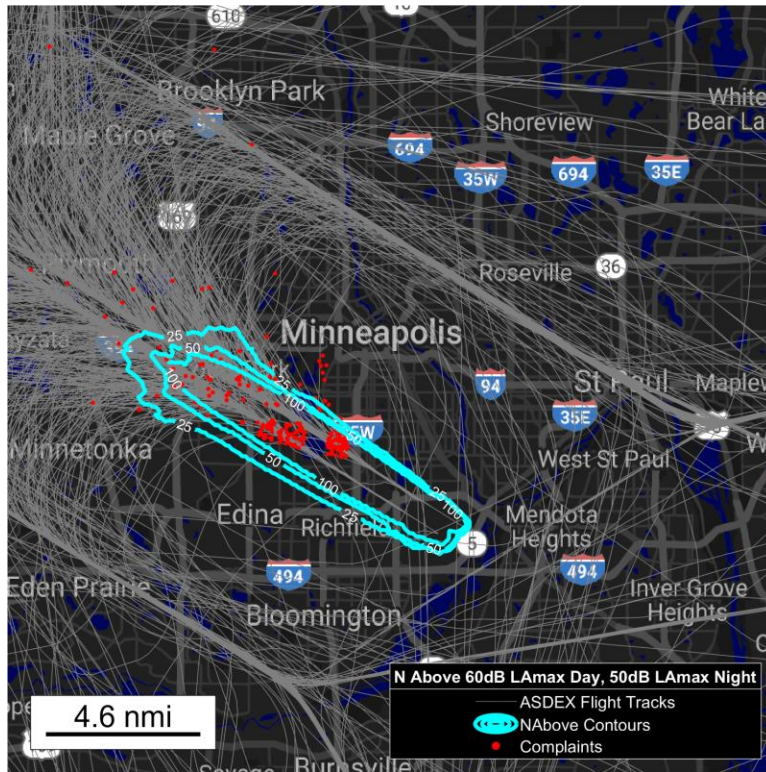


Figure 18. MSP 12L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights

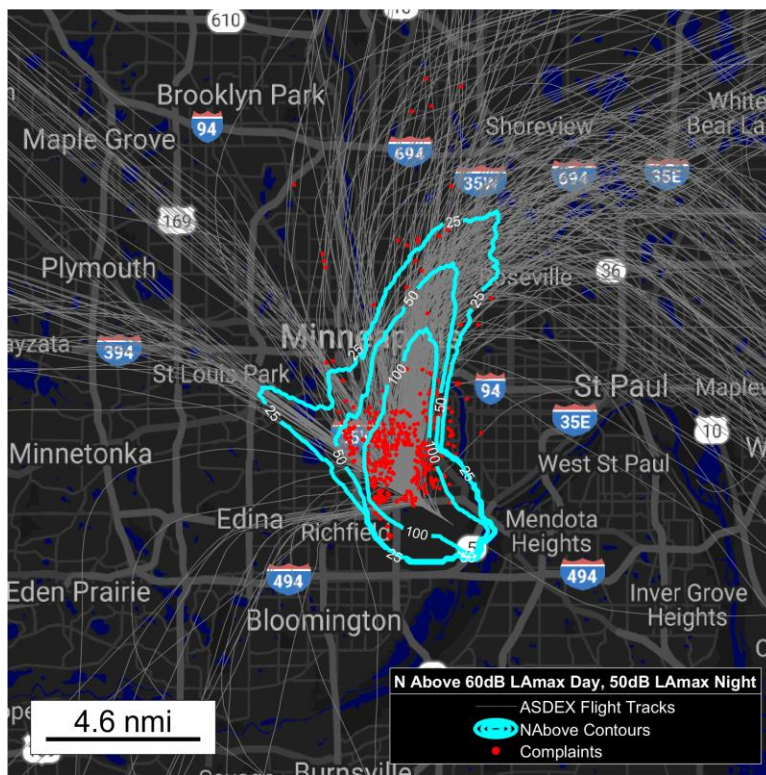


Figure 19. MSP 30R Departures Peak Day N_{60} at 25, 50, and 100 Overflights

6.3.3 LHR

At LHR analysis was performed on 9R departures and 27L/R arrivals, shown in Figure 20 and Figure 21. LHR has a runway use plan for noise purposes, so 9L is not used for departures. The metric 50 overflights on a peak day at the N_{60} level represents at least 80% of the complaint locations for the two runway procedures to the east of the airport. The west of the airport is a low population area causing a small sample size, while the east of the airport is a high population area being near London. It is worth noting that the metric of 50 overflights on a peak day at the N_{60} level appears to be a valid metric both within the United States and in another country.

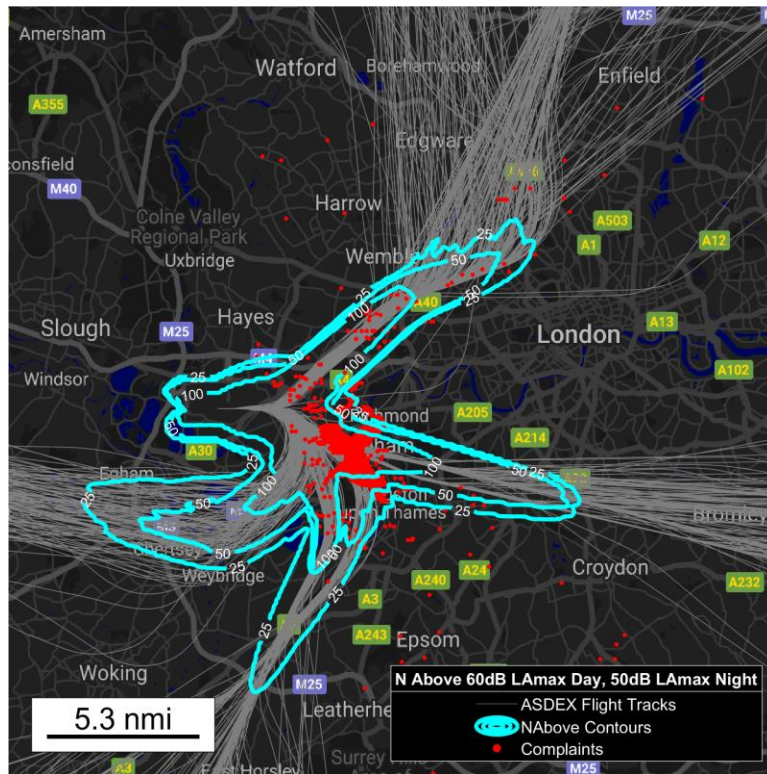


Figure 20. LHR 9R Departures Peak Day N_{60} at 25, 50, and 100 Overflights

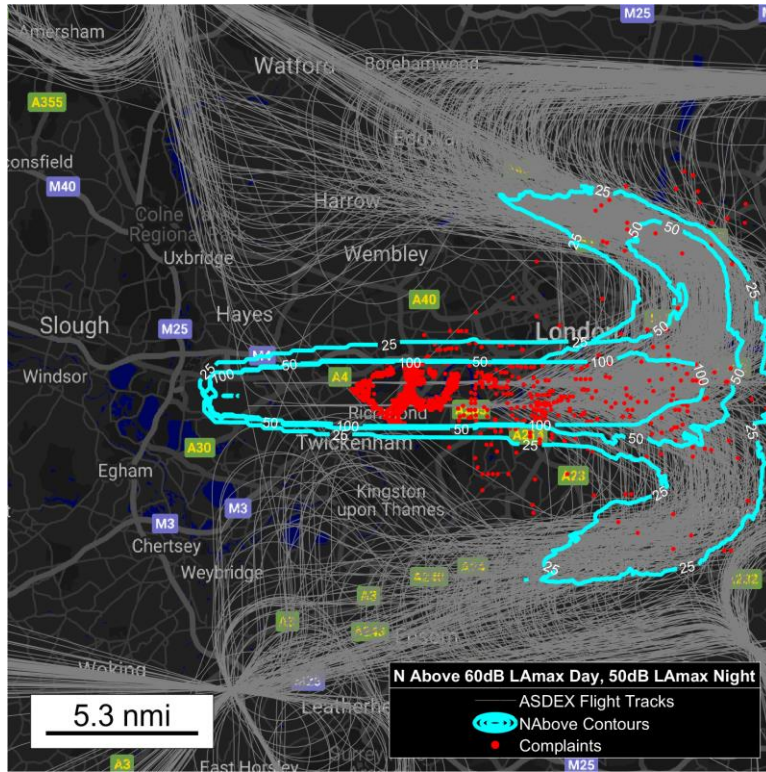


Figure 21. LHR 27L/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights

6.3.4 CLT

The results for CLT 18L/C/R arrivals are consistent with other airports, shown in Figure 22, where 50 overflights on a peak day at the N_{60} level represents at least 80% of complaint locations. However the communities to the south of the airport do not appear to reflect this pattern.

For the 18C departures, shown in Figure 23, there seems to be some possible effect from the turn, and this is also a low population density area. To the southeast of the airport, there is confounding of noise impacts because both 18L departures and 36R arrivals fly over this community, however a significant number of the complaints to the southeast of CLT are outside of the N_{60} contours even down to the 25 overflight level indicating a higher level of sensitivity, as shown in Figure 24 and Figure 25.

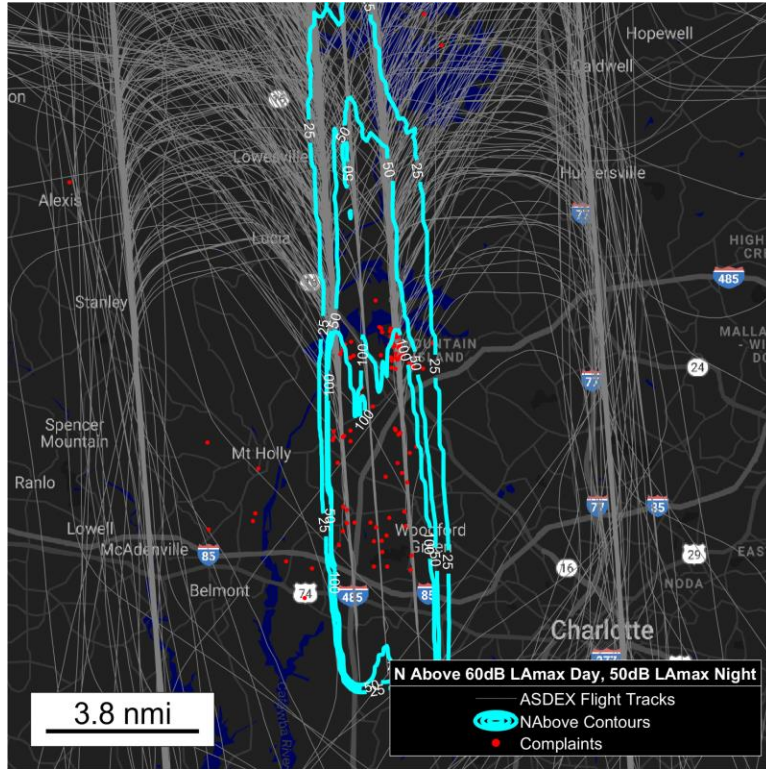


Figure 22. CLT 18L/C/R Arrivals Peak Day N_{60} at 25, 50, and 100 Overflights

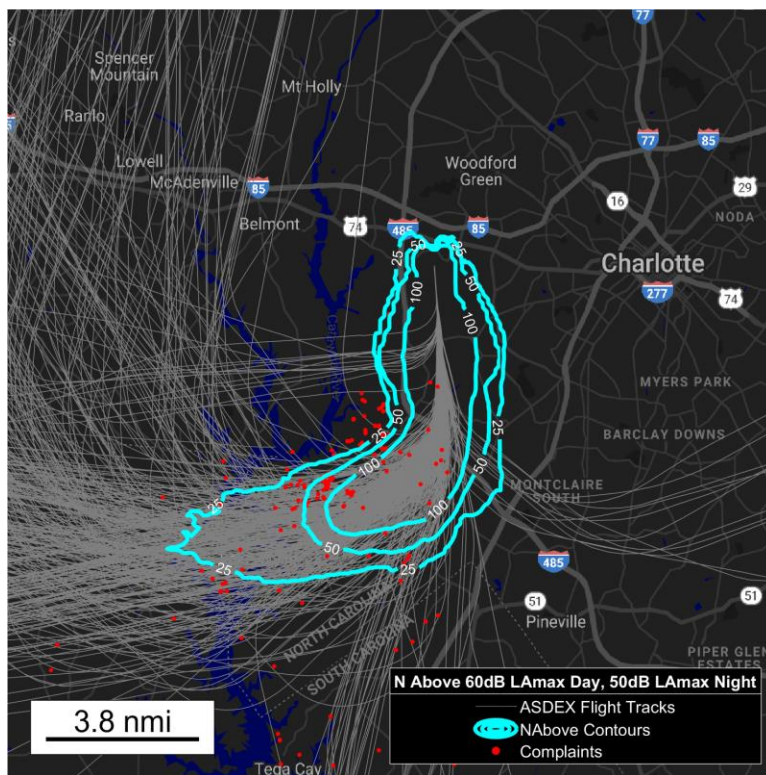


Figure 23. CLT 18C Departures Peak Day N_{60} at 25, 50, and 100 Overflights

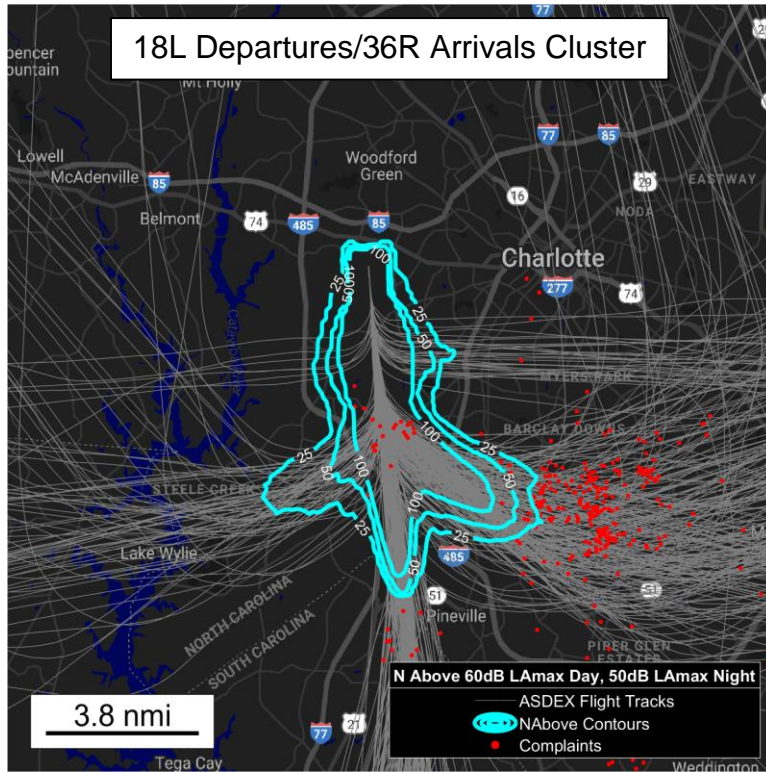


Figure 24. CLT 18L Departures Peak Day N₆₀ at 25, 50, and 100 Overflights

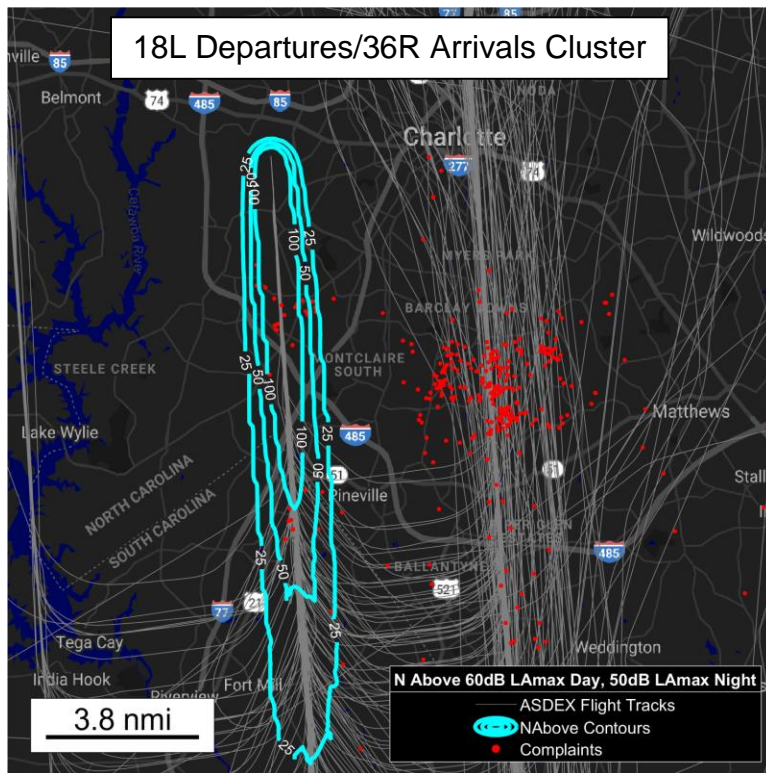


Figure 25. CLT 36R Arrivals Peak Day N₆₀ at 25, 50, and 100 Overflights

6.3.4.1 CLT Peak Day N_{50}

In order to further understand the anomalous runway communities at CLT, peak day N_x was also analyzed at the lower noise level of N_{50} for those communities. Table 6 shows the results of the peak day N_{50} analysis for the anomalous runway communities at CLT. The results indicate that the anomalous runway communities at CLT appear to be 10dB more sensitive to noise than all the other runway communities analyzed in this thesis. The fact that the overflight count sensitivity still appears to be 50 overflights thus further supports the idea that the anomalous runway communities at CLT are more sensitive in regards to the noise threshold. The peak day N_{50} results also indicate that the cluster of complaints to the southeast of CLT are primarily caused by 18L departures rather than 36R arrivals. Figure 26 through Figure 28 show the peak day N_{50} contours at the levels of 25 overflights, 50 overflights, and 100 overflights for the anomalous runway communities at CLT.

Table 6. CLT Peak Day N_{50}

		25 N_{50}	50 N_{50}	100 N_{50}
	18C dep	84.6%	82.1%	75.3%
CLT	18L dep	87.6%	82.6%	64.6%
	36R arr	69.9%	38.9%	11.5%

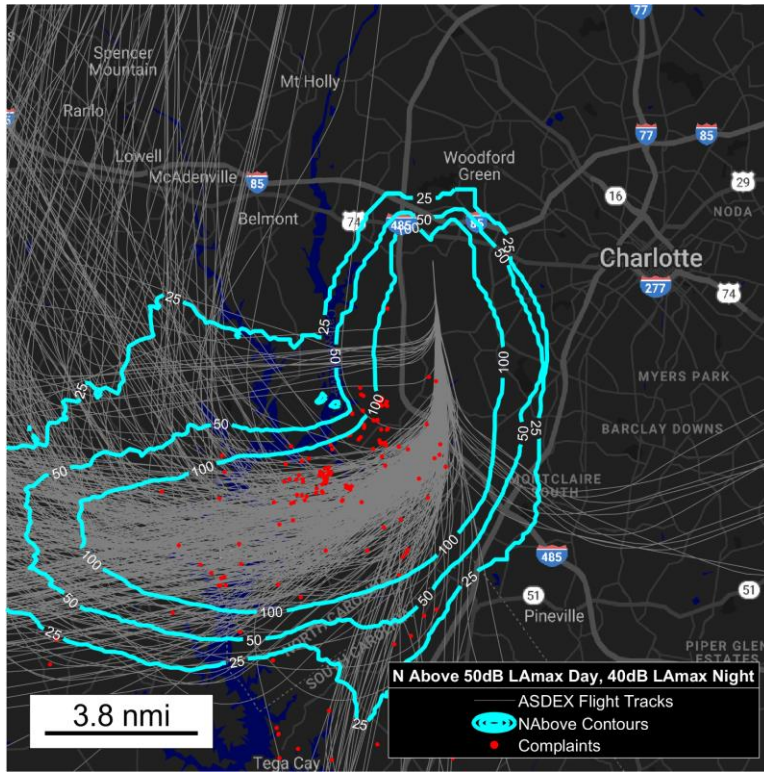


Figure 26. CLT 18C Departures Peak Day N₅₀ at 25, 50, and 100 Overflights

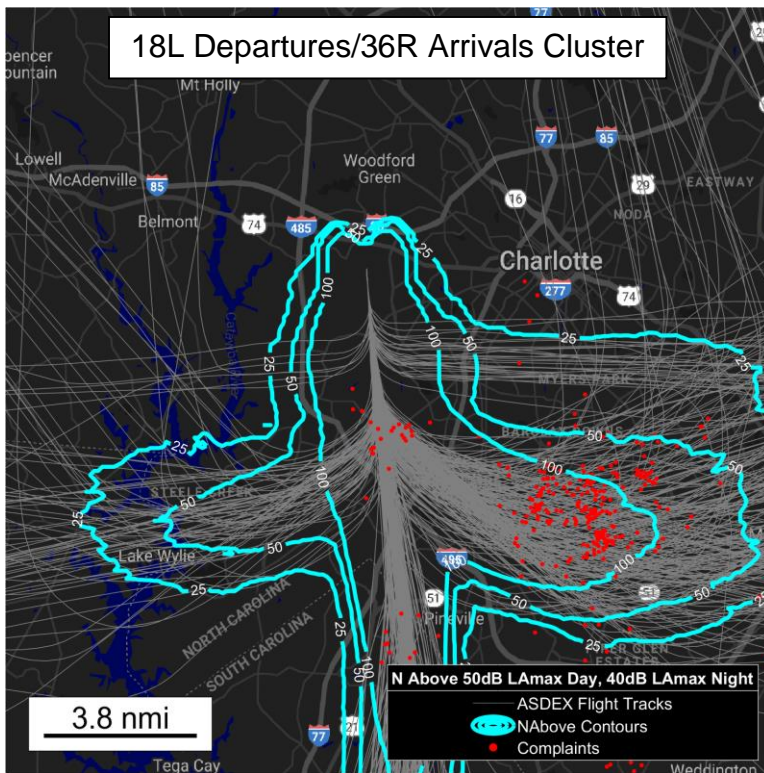


Figure 27. CLT 18L Departures Peak Day N₅₀ at 25, 50, and 100 Overflights

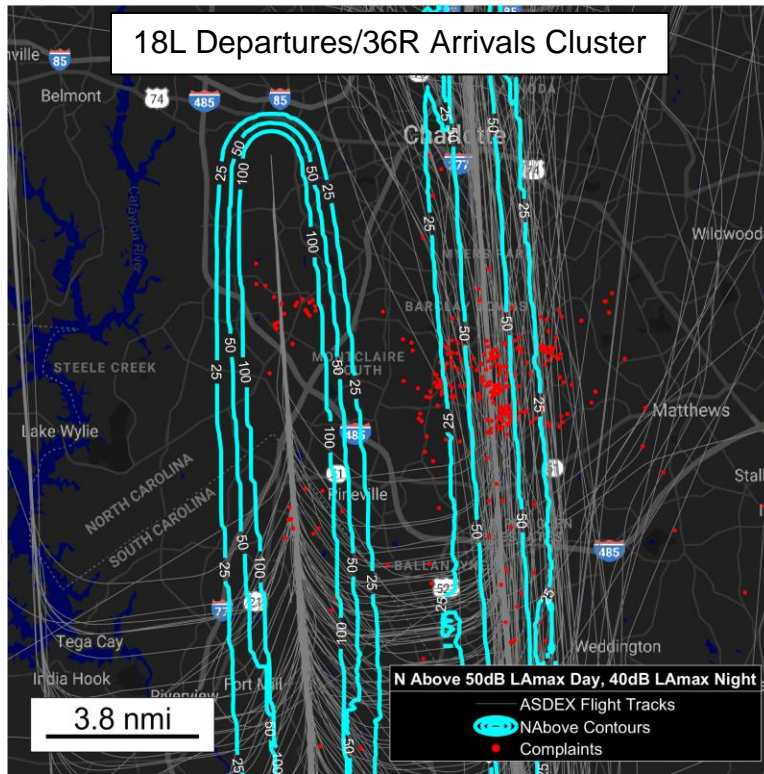


Figure 28. CLT 36R Arrivals Peak Day N_{50} at 25, 50, and 100 Overflights

6.4 Discussion

The threshold of peak day N_{60} with 50 overflights appears to represent the annoyance mechanism of frequent overflights at BOS, MSP, LHR, and one runway at CLT. However, the communities to the south of CLT appear to have increased noise sensitivity and a different noise threshold for annoyance impacts. CLT is the only airport that implemented RNAV departures and then implemented dispersed departures [24]. The communities experiencing the changes to the RNAV procedures have shown increased political sensitivity [25]. Part of the motivation for the analysis in this study is to have a metric for analyzing dispersed flight tracks, as communities have requested. However the CLT example begs the question of whether or not dispersed flight tracks will really have the desired effects.

Chapter 7 Annoyance Noise Threshold Determination:

Peak Day DNL

As an alternative to the N_x metric, evaluating DNL on a peak day could be considered. Table 7 through Table 10 show the analysis for peak day DNL. Peak day DNL was analyzed at the noise levels of 35dB to 75dB in 5dB increments. The cells of the table were highlighted as red if less than 60% of the complaint locations were represented by the noise contour. Cells were highlighted as yellow in the results tables if between 60% to 80% of the complaint locations were represented by the noise contour. Cells were highlighted as green in the results tables if greater than 80% of the complaint locations were represented by the noise contour. In order to capture more than 80% of complaint locations, the noise level of peak day DNL at 45dB is necessary, except for the anomalous runways at CLT.

In discussions with community stakeholder groups, it was found to be difficult for the communities to separate peak day DNL from the traditional annual average DNL. The use of peak day DNL at 45dB is both a different representative day and a different noise threshold from the metric that people are most used to seeing due to United States policy. DNL is also a logarithmic metric and can be more difficult to use to communicate impacts of procedures to communities compared to an arithmetic metric. For these reasons the peak day N_x metric is preferred over the peak day DNL metric in communicating analysis results with stakeholders, i.e. regarding dispersion,

Table 7. BOS Peak Day DNL

	BOS		
	33L dep	27 dep	4L/R
	Peak	Peak	Peak
	Day	Day	Day
	DNL	DNL	DNL
35dB	98.3%	99.8%	99.9%
40dB	96.3%	98.8%	98.7%
45dB	91.4%	95.5%	92.9%
50dB	64.1%	84.9%	73.1%
55dB	20.1%	44.6%	45.1%
60dB	7.2%	4.2%	5.4%
65dB	2.1%	3.0%	0.0%
70dB	0.1%	0.0%	0.0%
75dB	0.0%	0.0%	0.0%

Table 8. MSP Peak Day DNL

	MSP			
	17 dep	30L dep	12L/R	30R dep
	Peak	Peak	Peak	Peak
	Day	Day	Day	Day
	DNL	DNL	DNL	DNL
35dB	100.0%	96.8%	98.8%	98.4%
40dB	98.7%	95.9%	95.5%	97.7%
45dB	83.9%	90.0%	89.8%	90.0%
50dB	39.4%	56.8%	76.4%	65.9%
55dB	0.0%	13.5%	42.0%	15.5%
60dB	0.0%	0.9%	0.0%	4.4%
65dB	0.0%	0.0%	0.0%	0.0%
70dB	0.0%	0.0%	0.0%	0.0%
75dB	0.0%	0.0%	0.0%	0.0%

Table 9. LHR Peak Day DNL

	LHR	
	9R dep	27L/R
	Peak	Peak
	Day	Day
	DNL	DNL
35dB	96.8%	100.0%
40dB	96.7%	99.4%
45dB	92.5%	94.9%
50dB	69.8%	84.8%
55dB	32.4%	71.6%
60dB	0.7%	45.5%
65dB	0.0%	1.0%
70dB	0.0%	0.0%
75dB	0.0%	0.0%

Table 10. CLT Peak Day DNL

	CLT			
	18L/C/R	18C dep	18L dep	36R arr
	Peak	Peak	Peak	Peak
	Day	Day	Day	Day
	DNL	DNL	DNL	DNL
35dB	91.7%	85.8%	88.5%	79.1%
40dB	87.2%	82.1%	68.1%	28.9%
45dB	82.6%	66.0%	8.8%	9.1%
50dB	80.7%	14.8%	6.2%	6.2%
55dB	17.4%	3.7%	1.8%	2.4%
60dB	0.0%	0.6%	0.0%	0.9%
65dB	0.0%	0.0%	0.0%	0.0%
70dB	0.0%	0.0%	0.0%	0.0%
75dB	0.0%	0.0%	0.0%	0.0%

7.1 Peak Day DNL Contours

Figure 29 through Figure 41 show the peak day DNL contours for the airports and runway procedures in this study. The outermost contour is the 35dB peak day DNL contour and then each contour increments by 5dB. The gray lines are the peak day radar flight tracks, and the red dots are the complaint locations.

7.1.1 BOS

At BOS, the peak day DNL at 45dB captures at least 80% of the complaint location for 33L departures, 27 departures, and 4L/R arrivals as shown in Figure 29 through Figure 31. In these figures for BOS, the peak day DNL at 45dB is shown as a magenta contour.

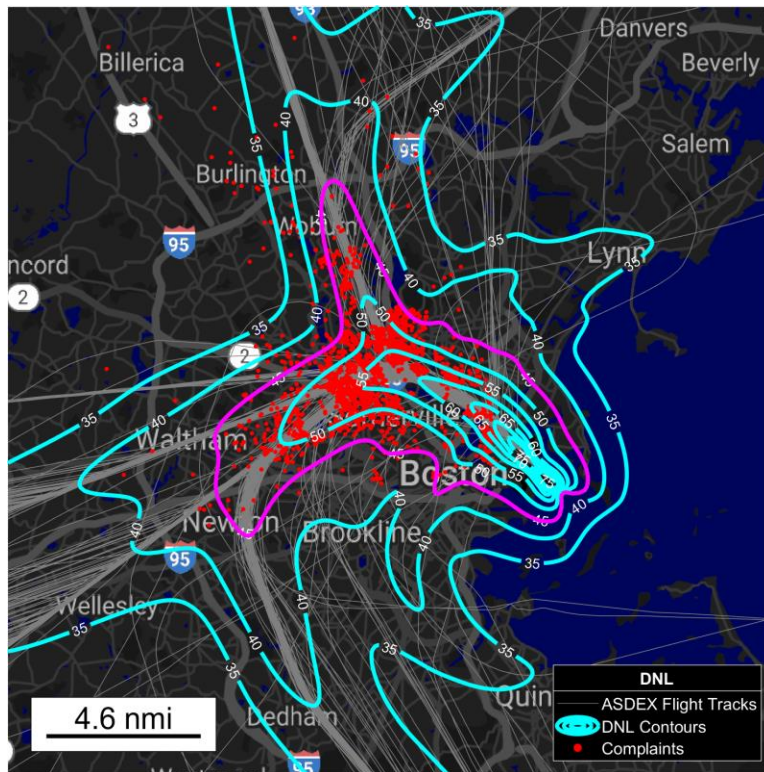


Figure 29. BOS 33L Departures Peak Day DNL Contours

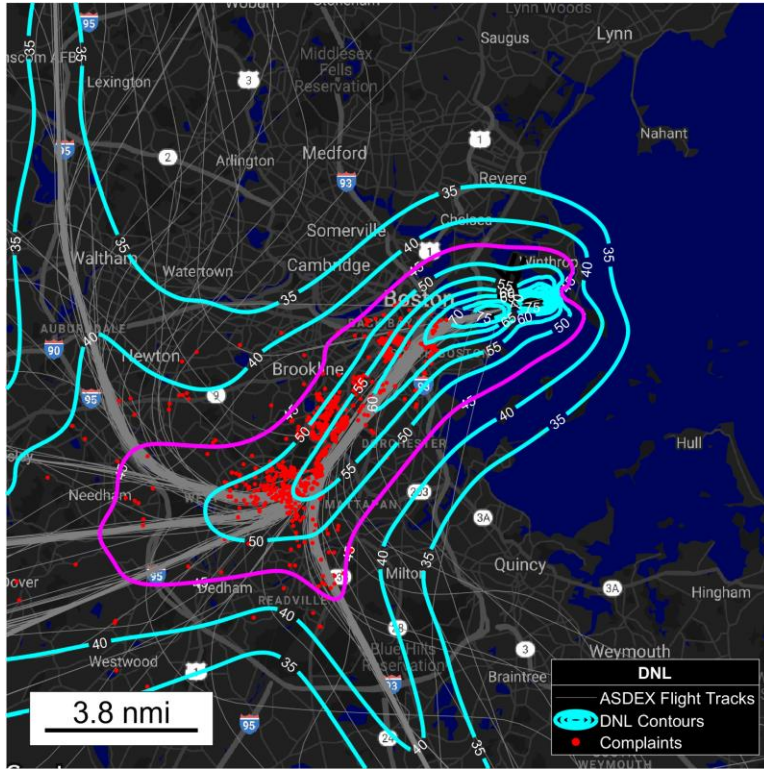


Figure 30. BOS 27 Departures Peak Day DNL Contours

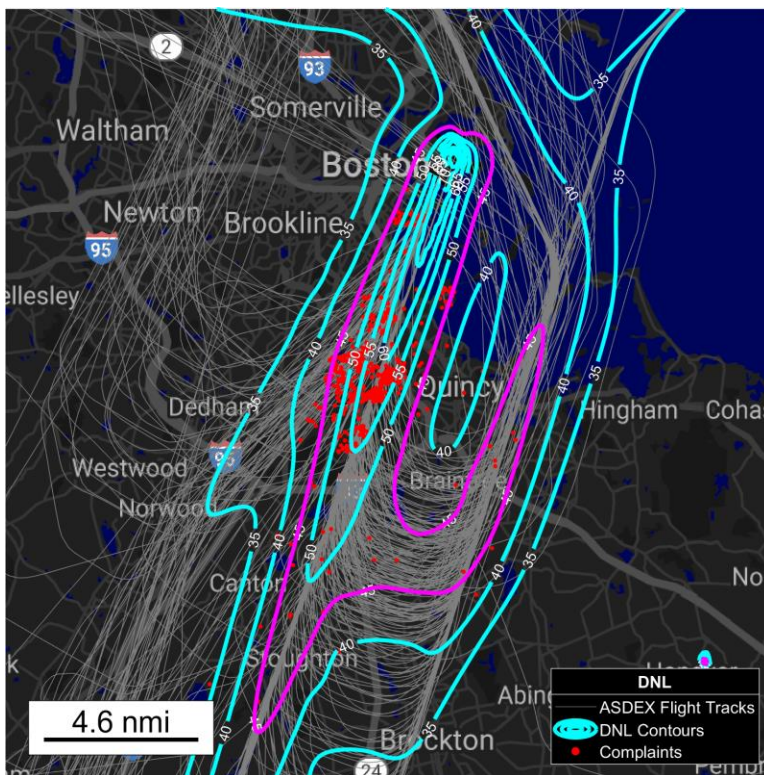


Figure 31. BOS 4L/R Arrivals Peak Day DNL Contours

7.1.2 MSP

At MSP, the peak day DNL at 45dB represents at least 80% of the complaint locations for 17 departures, 30L departures, 12L/R arrivals, and 30R departures as shown in Figure 32 through Figure 35. The threshold of peak day DNL at 45dB is representative of the complaint locations for both the dispersed departures and for the RNAV arrivals at MSP.

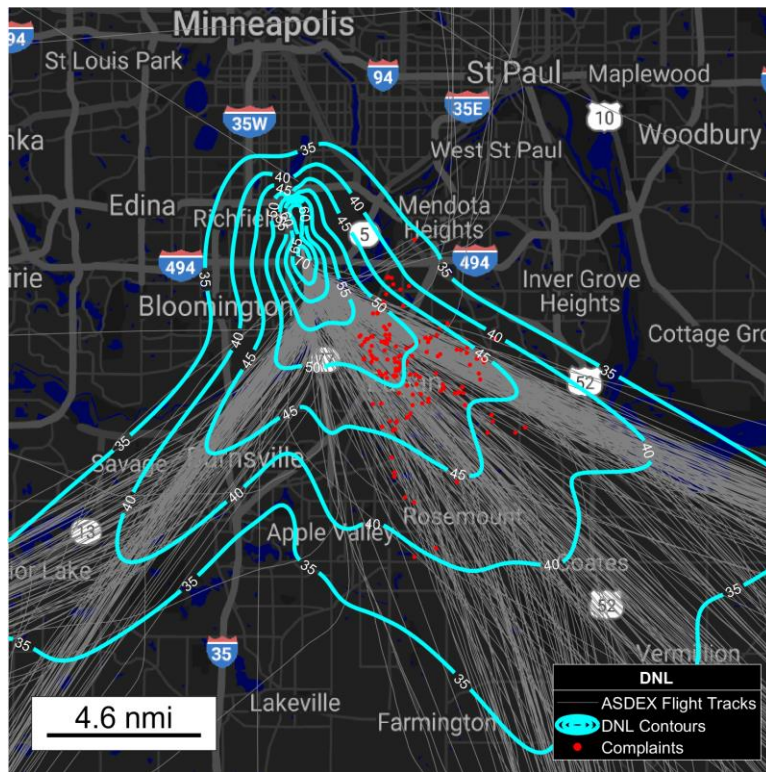


Figure 32. MSP 17 Departures Peak Day DNL Contours

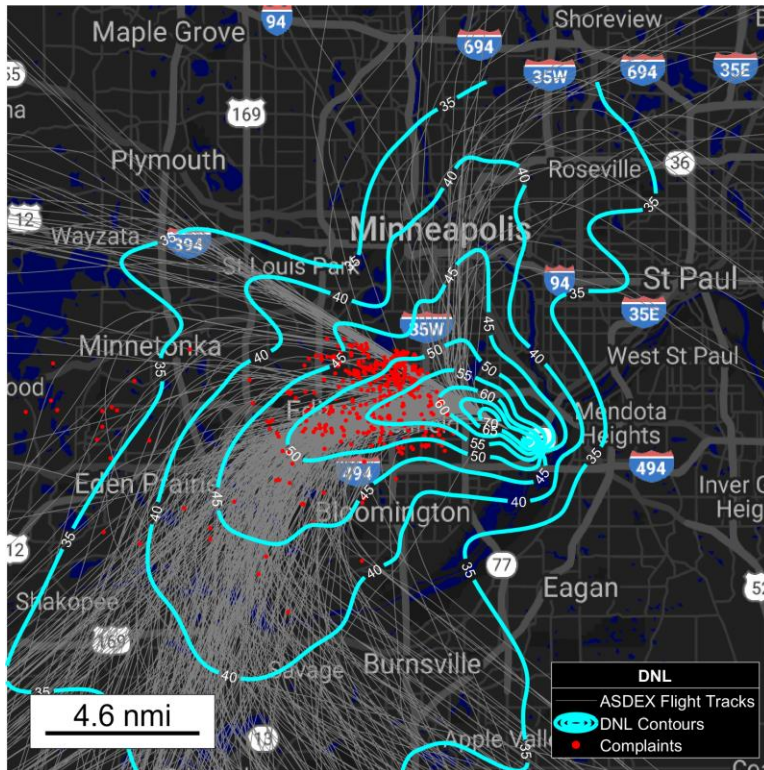


Figure 33. MSP 30L Departures Peak Day DNL Contours

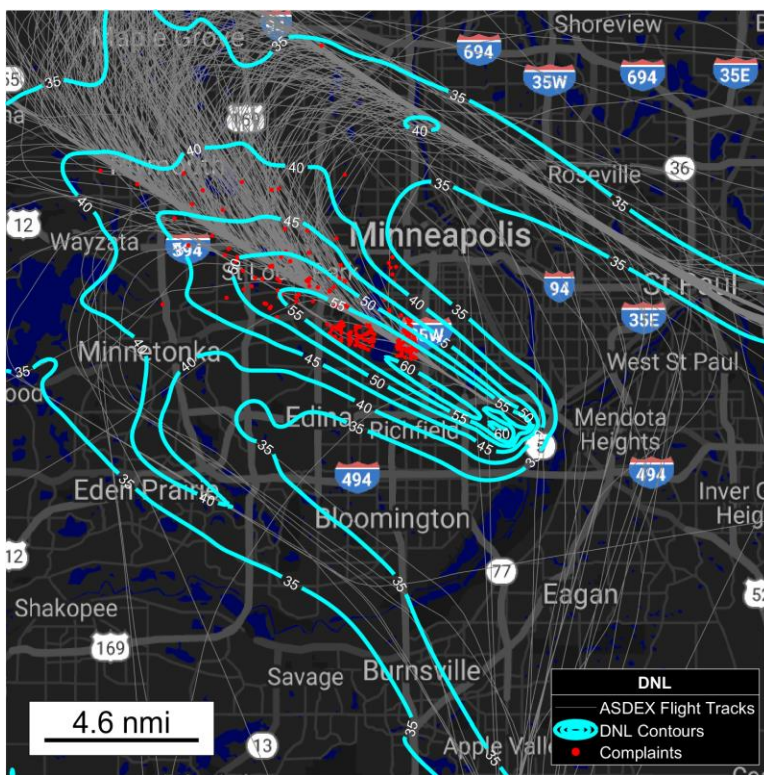


Figure 34. MSP 12L/R Arrivals Peak Day DNL Contours

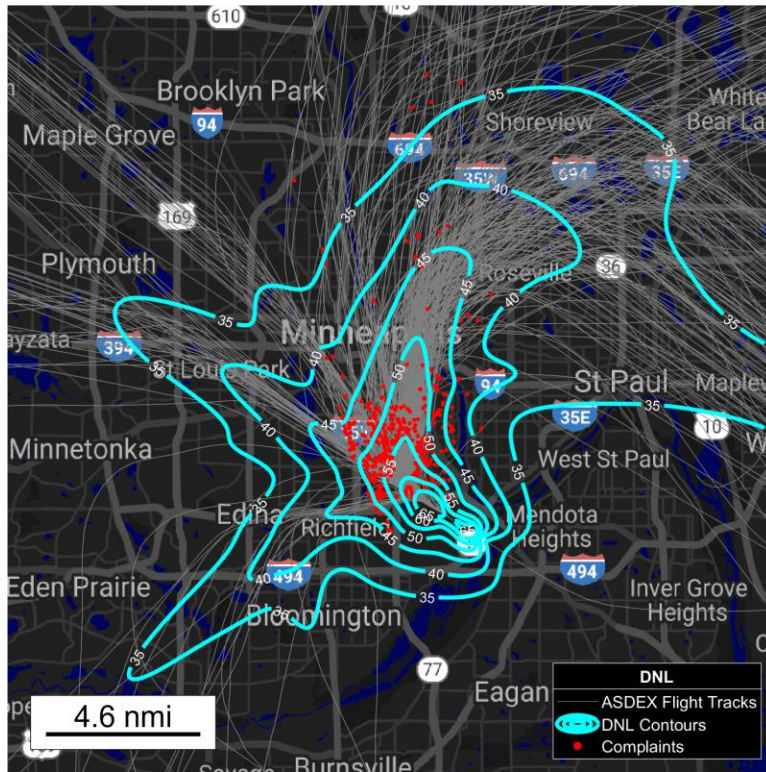


Figure 35. MSP 30R Departures Peak Day DNL Contours

7.1.3 LHR

At LHR, peak day DNL at 45dB is representative of at least 80% of the complaint locations for both 9R departures and 27 arrivals, as shown in Figure 36 and Figure 37.

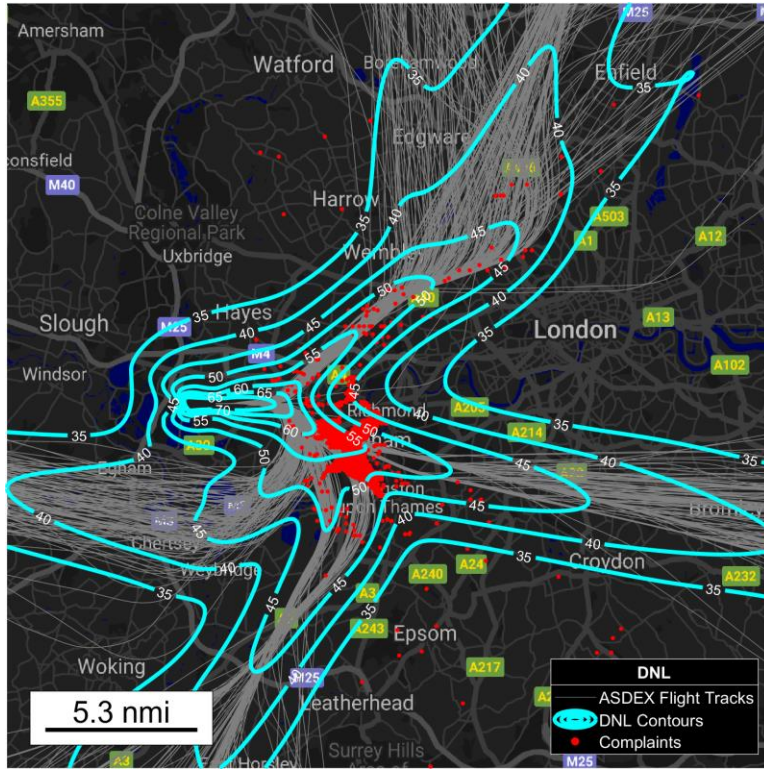


Figure 36. LHR 9R Departures Peak Day DNL Contours

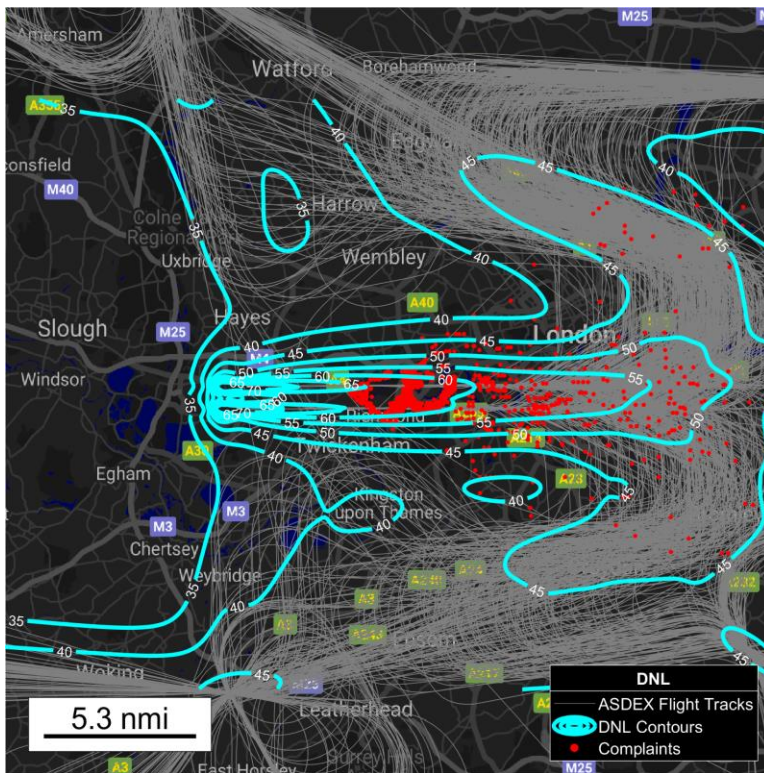


Figure 37. LHR 27 Arrivals Peak Day DNL Contours

7.1.4 CLT

At CLT, peak day DNL at 45dB is representative of at least 80% of the complaint locations for 18L/C/R arrivals, as shown in Figure 38. However, this is not true for the anomalous runway procedures 18C departures, 18L departures, and 36R arrivals, as shown in Figure 39 through Figure 41. If the lower noise level of peak day DNL at 35dB is used, then at least 80% of the complaint locations are represented for the three anomalous runways. This analysis further supports the idea also shown in the N_x analysis that the CLT neighborhoods are 10dB more sensitive than the other airports and runway procedures analyzed in this study.

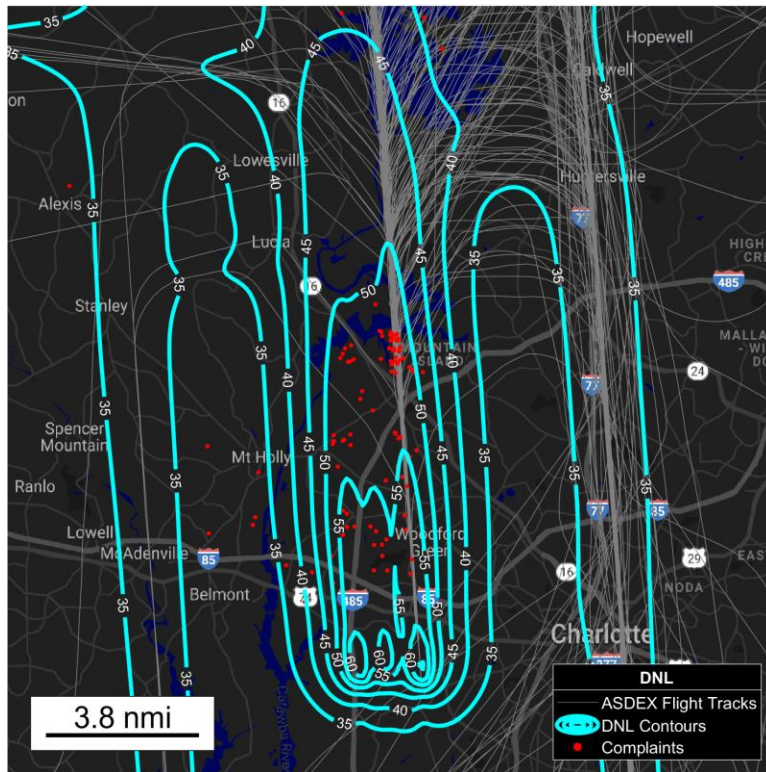


Figure 38. CLT 18L/C/R Arrivals Peak Day DNL Contours

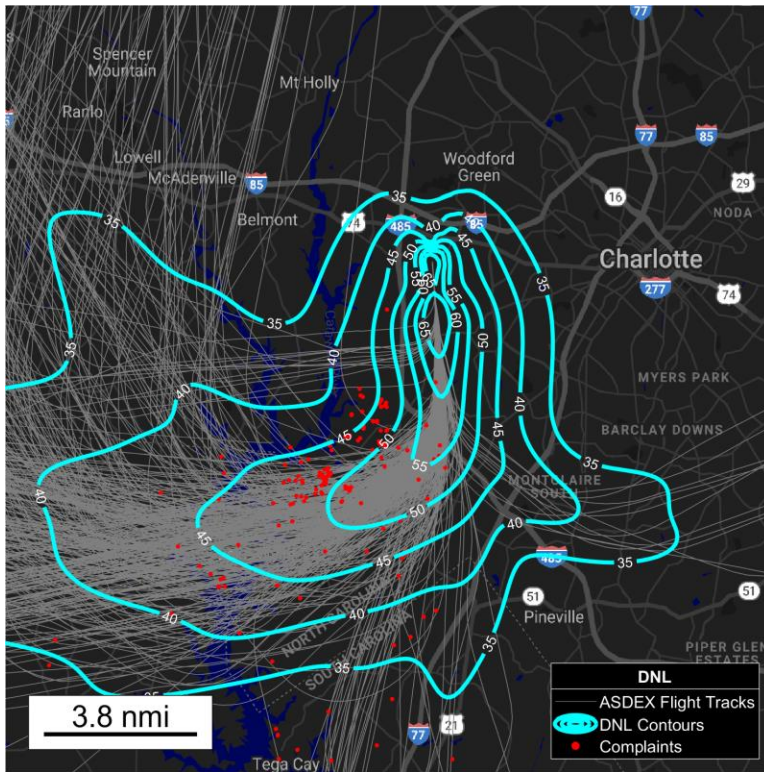


Figure 39. CLT 18C Departures Peak Day DNL Contours

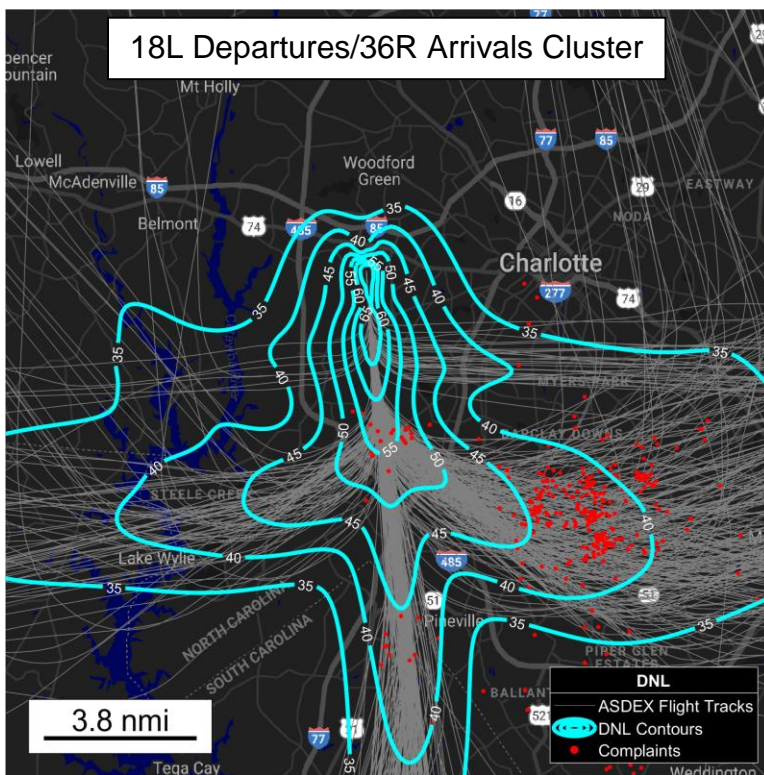


Figure 40. CLT 18L Departures Peak Day DNL Contours

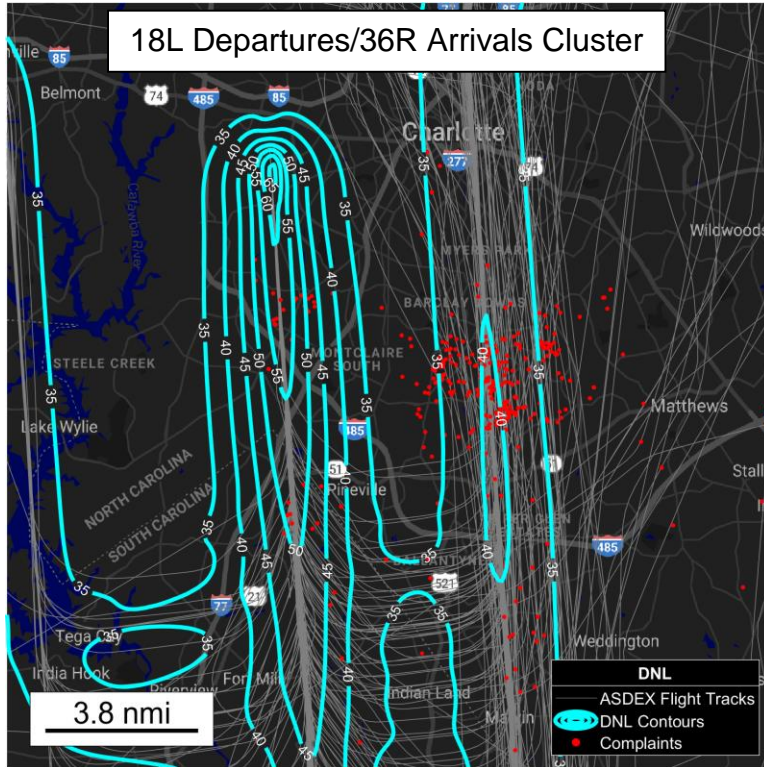


Figure 41. CLT 36R Arrivals Peak Day DNL Contours

Chapter 8 Dispersion Analysis

Once peak day N_{60} with 50 overflights had been determined as the metric to communicate impact threshold, methods of modeling dispersion were investigated. Peak day DNL could have also been a defensible choice of metric to communicate the results of dispersion analysis; however for the reasons described in Chapter 7, peak day N_x is the preferred metric.

The dispersion analysis was completed for 33L departures and 27 departures at BOS, the two overland departure procedures. The examples will focus on 33L departures at BOS and the analysis for 27 departures at BOS is available in Appendix D.

8.1 Dispersion Analysis Communication Tools

The following tools were developed to communicate dispersion analysis results with stakeholders. In order to provide communities context for understanding the impacts of the changes due to RNAV, a comparison between pre-RNAV conditions and RNAV conditions was analyzed. The pre-RNAV to RNAV comparison was analyzed by comparing the 2010 conditions with the 2017 conditions, normalizing to the 2017 traffic levels as further described in following sections. The pre-RNAV to RNAV comparison for 33L departures will be used in the following sections as an example of the tools used to communicate dispersion analysis.

8.1.1 Population Exposure to N_{60} with 50 Overflights on a Peak Day

The overall impact of each dispersion concept was communicated by showing the number of people exposed to the metric of N_{60} on a peak day with 50 overflights. The population exposure numbers were calculated for the example of pre-RNAV to RNAV comparison, where the pre-RNAV flight tracks were normalized to match the RNAV traffic levels and fleet mix. The results of this analysis indicate that the RNAV conditions allow for a benefit of more than 12,000 people that are no longer exposed to the impact threshold of N_{60} with 50 overflights on a peak day compared to the pre-RNAV conditions. Table 11 shows an example of the population exposure for 33L departures from pre-RNAV conditions to RNAV conditions. When the pre-RNAV conditions are normalized

to match the traffic levels of RNAV conditions, RNAV leads to an overall decrease in the number of people exposed to 50 overflights at the N_{60} level on a peak day.

Table 11. Population Exposure to N_{60} on a Peak Day with 50 Overflights for BOS 33L Departures Pre-RNAV to RNAV Conditions

N_{60}	50x
Dispersion	356,960
RNAV	344,244
RNAV Benefit	12,716

8.1.2 Change in Peak Day N_{60} Maps

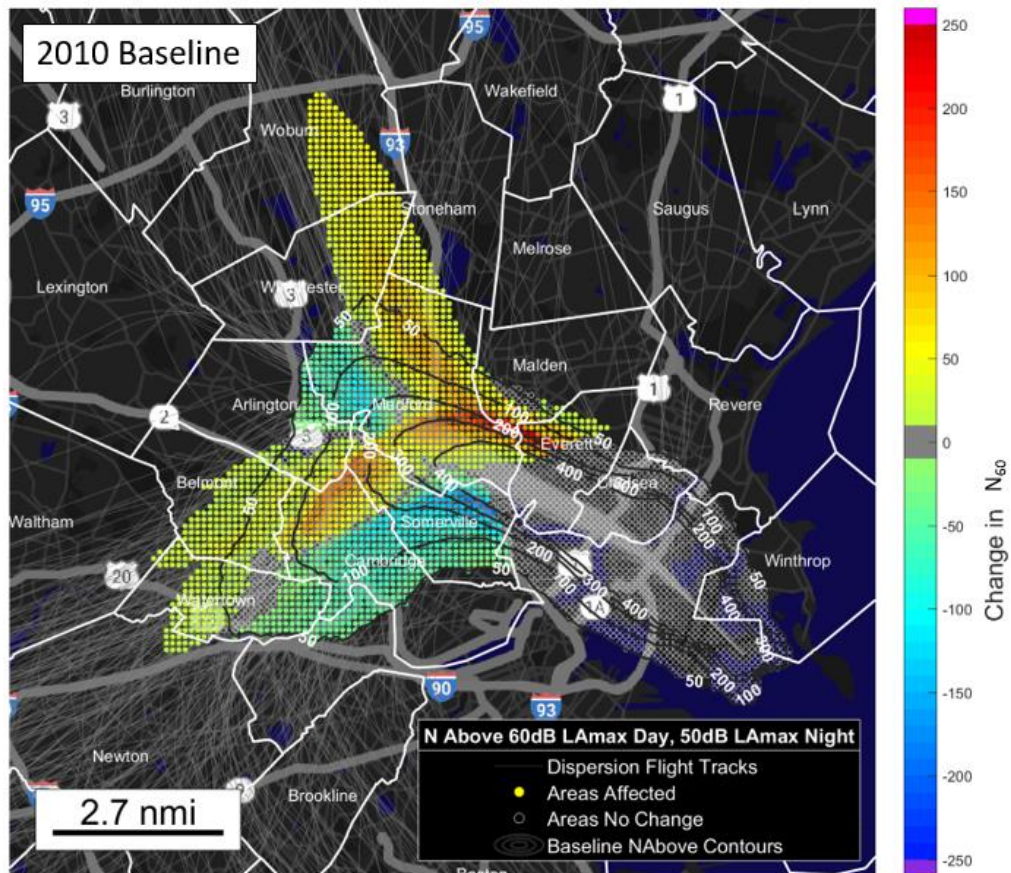
Maps are also shown to communicate the change in N_{60} on a peak day for the impacted areas. Figure 42 shows an example of the map used to communicate the change in N_{60} on a peak day when comparing pre-RNAV conditions to RNAV conditions.

The analysis is performed and communicated at the resolution of grid spacing that is 0.1nmi by 0.1nmi for each grid cell. This grid spacing allows for higher resolution than the census block level, which has previously been mentioned by stakeholders. Jensen and Hansman provides further detail on the population grid calculation method used [21].

The dots in warm colors indicate areas that will receive an increase on a peak day in N_{60} overflights as a result of the new procedure. The dots in cool colors indicate areas that will receive a decrease on a peak day in N_{60} overflights as a result of the new procedure. The white circles indicate areas that received no change or a change of less than an absolute value of 10 N_{60} overflights. If an area received an increase of greater than 250 overflights, then a dot was plotted in the color magenta. If an area received a decrease of more than 250 overflights, then a dot was plotted in purple. When RNAV was introduced, the areas under the RNAV tracks generally received an increase in overflights, while the areas under the previously dispersed flight tracks received a decrease in the number of overflights.

Information is also communicated about the absolute N_{60} overflight count. The N_{60} contours at 50 overflights, 100 overflights, 200 overflights, 300 overflights, and 400 overflights for the baseline conditions are plotted as dark gray contours over the colored dots. In Figure 42 this means that the baseline N_{60} contours are plotted for the pre-RNAV conditions, which have been normalized to the 2017 RNAV traffic levels. Additionally, dots are only plotted if they are within the impact threshold of 50 overflights at the N_{60} count for either the baseline conditions or the new procedure conditions. An ideal new procedure would be one which allowed for no new dots outside of the baseline contour at the 50 overflights at the N_{60} level.

The town boundaries are also provided on the map to allow decision-makers to understand how their specific constituents are impacted. The communication of town specific information will also be further discussed in Section 8.1.3.



Analysis based on peak day operations; only includes 33L departures

Figure 42. BOS 33L Departures Pre-RNAV to RNAV Comparison Change in Peak Day N_{60}

8.1.3 Town by Town Analysis

In order to allow towns to further understand how their specific constituents are impacted, histograms were provided for each town showing the changes in N_{60} and the number of people who will receive that change. An example of these histograms are provided in Figure 43 for BOS 33L departures pre-RNAV to RNAV comparison. The columns in blue represent people who will receive a reduction in the number of N_{60} overflights, and the columns in red represent people who will receive an increase in the number of N_{60} overflights. All the dispersion histograms are provided in Appendix E.

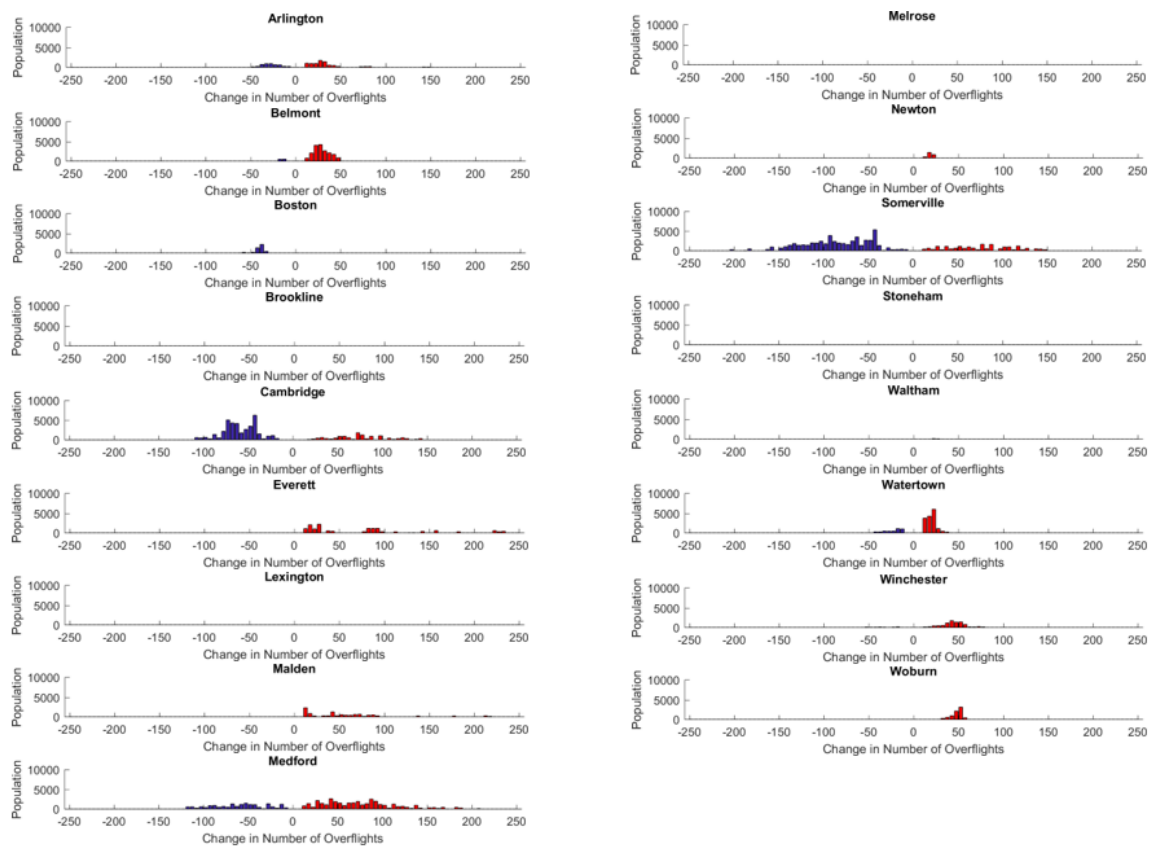


Figure 43. BOS 33L Departures Pre-RNAV to RNAV Comparison Change in N_{60} Town Histograms

8.2 Peak Day Analysis for Dispersion Modeling

In order to model the noise impacts of dispersed flight tracks, the peak days of runway operations were analyzed. The peak day in 2017 for runway 33L departures at BOS was May 18th, 2017 on which day there were 487 departures from runway 33L. The peak day in 2017 for runway 27 departures at BOS was September 18th, 2017 on which day there were 345 departures from runway 27. The peak day for runway 4L/R arrivals at BOS was October 12th, 2017 on which day there were a total of 567 arrivals to the two runways. The peak day analysis on departures is described in this section, and further detail is given on the arrival dispersion analysis in Appendix C.

To analyze the peak day in further detail, the radar data was analyzed to determine the transition waypoint of the flight tracks, the type of aircraft being flown, and whether the aircraft was flying during day time or night time. The peak day analysis for runway 33L departures is shown as an example of how the analysis was performed. Runway 27 departures peak day analysis is shown in Appendix B.

The transition waypoint was determined by clustering the flight tracks at the point where the track distance travelled reached 15nmi. Figure 44 shows the runway 33L departure flight tracks sorted by their transition waypoints. The radar data was then further sorted, as shown in Table 12, to count the number of each type of aircraft and whether those aircraft were flying during the day, defined between 7am and 10pm, or during the night, defined as before 7am or after 10pm. Table 13 shows verification that the peak day was not an outlier in terms of numbers of procedures compared to the top five peak days of use for that runway.

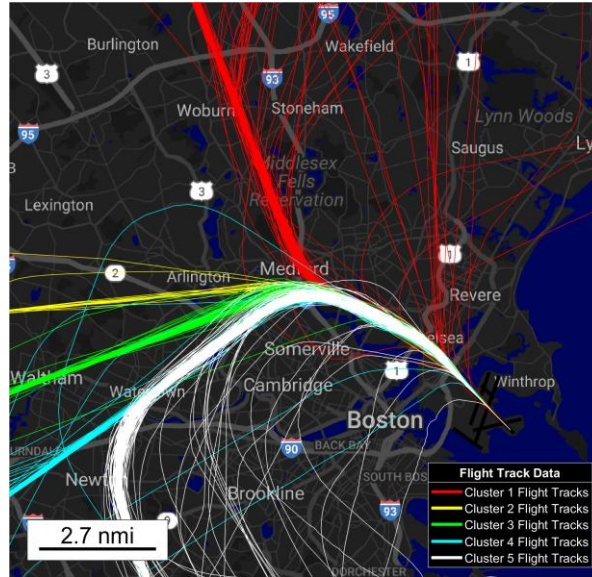


Figure 44. BOS 33L Departures Peak Day Flight Tracks Clustered by Transition Waypoint

Table 12. BOS 33L Departures Peak Day Sorted by Transition Waypoint Clusters

1	Day	Night	2	Day	Night	3	Day	Night
TA	6	2	TA	0	0	TA	2	0
B757	2	0	B757	1	0	B757	1	0
A320	40	6	A320	5	0	A320	24	4
B737	32	7	B737	0	0	B737	10	3
OJ	3	0	OJ	0	0	OJ	2	0
LRJ	35	2	LRJ	7	1	LRJ	24	1
SRJ	26	0	SRJ	2	0	SRJ	14	1

4	Day	Night	5	Day	Night
TA	1	1	TA	5	0
B757	1	0	B757	2	0
A320	25	2	A320	33	5
B737	11	2	B737	25	6
OJ	2	0	OJ	2	1
LRJ	21	4	LRJ	35	1
SRJ	14	0	SRJ	22	3

Table 13. BOS 33L Departures Peak Days Comparison

	Day	Night
Peak Day	435	52
Average of Top 5 Peak Days	433.8	48.8

8.3 Arrivals Dispersion

Dispersion was analyzed for both arrivals and departures as requested by the communities. However because of the design restriction of 15° maximum final intercept angle for RNAV arrivals, the dispersion possibilities for arrivals are far more restricted. Rather than providing relief to the communities under the current arrival path, the possibilities for dispersion on arrivals were only able to move the noise to another part of the same community. Arrivals dispersion is discussed in Appendix C.

8.4 Altitude-Based Dispersion

For departure procedures that have a change in heading to the desired final track, one way to introduce dispersion is altitude-based dispersion. In the dispersion modeling, the aircraft flight tracks are routed direct to the transition waypoint once reaching the a chosen altitude, in this study either 3000ft or 4000ft. Because of the natural variability in aircraft climb rates, an example of which is shown in Figure 45, aircraft would reach the defined altitude at varying points along the ground and therefore be sent to the transition waypoint at different points thus introducing dispersion [26]. Figure 45 shows the natural variability in climb rates for B738 aircraft at BOS [27].

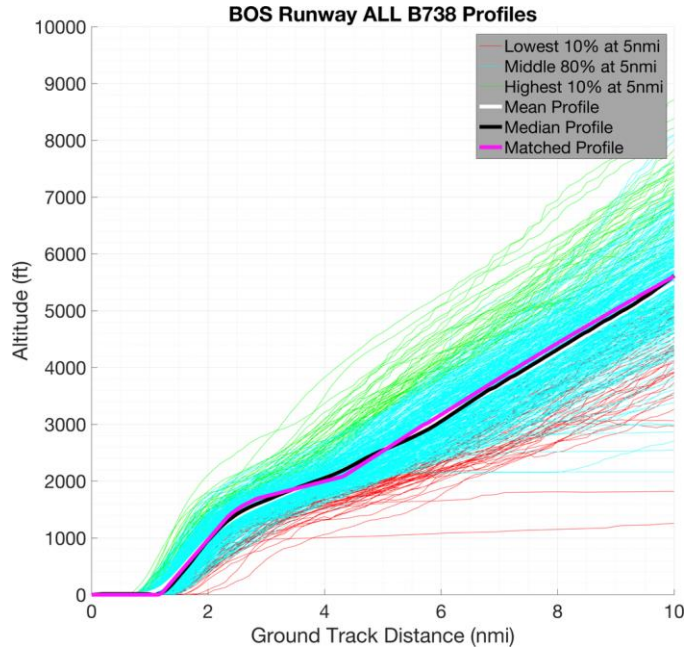


Figure 45. Natural Variability in Aircraft Climb Rates [27]

The flight tracks for BOS 33L departures altitude-based dispersion at 3000ft are shown as magenta lines in Figure 46. The flight tracks for BOS 33L departures altitude-based dispersion at 4000ft is shown in Figure 47. For all the following flight track figures, the dispersed flight tracks are shown as magenta lines. The white lines are the peak day radar data flight tracks. The orange contour is the annual average DNL at 65dB to show that the dispersion occurs outside of this threshold

Altitude-based dispersion at 3000ft for 33L departures at BOS results in an increase of over 5,000 people exposed to the impact threshold of 50 overflights at the N_{60} level on a peak day, as shown in Table 14. Figure 48 shows the change in N_{60} overflights for the areas impacted. In general the areas under the current RNAV tracks receive a reduction in the number of N_{60} overflights while the areas under the new dispersed flight tracks receive and increase in the number of N_{60} overflights.

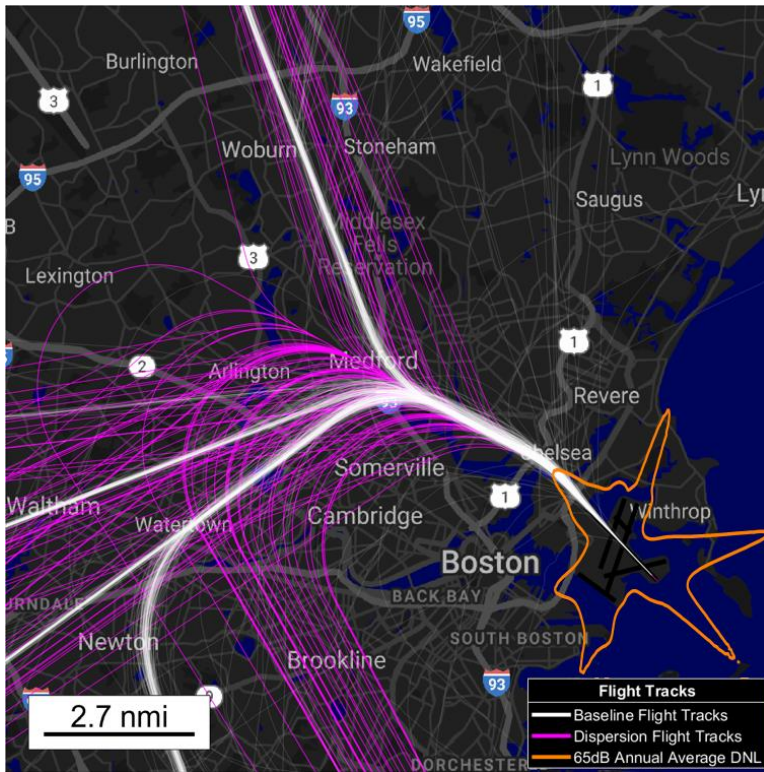


Figure 46. BOS 33L Departures Altitude-Based Dispersion at 3000ft Flight Tracks

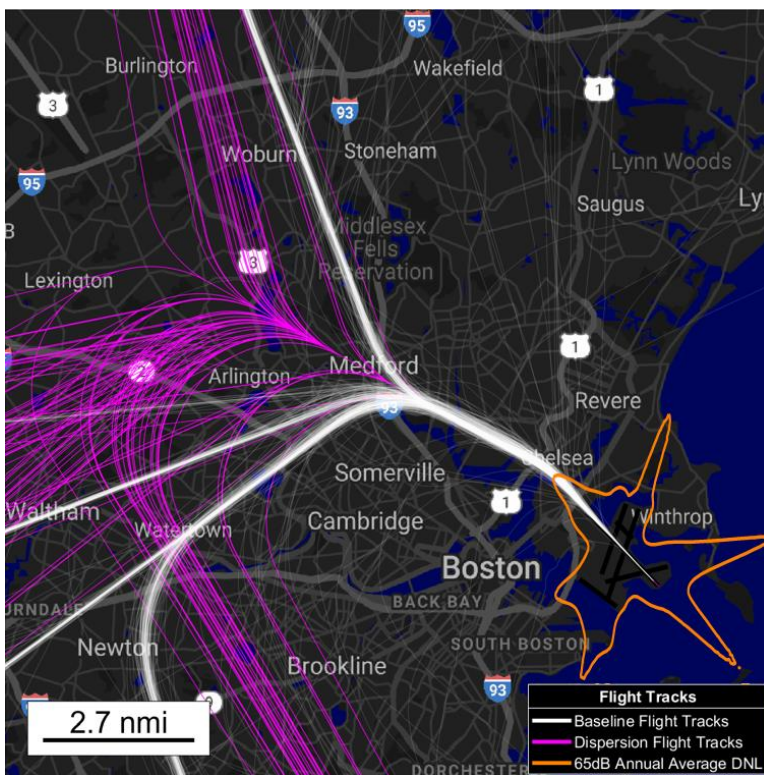
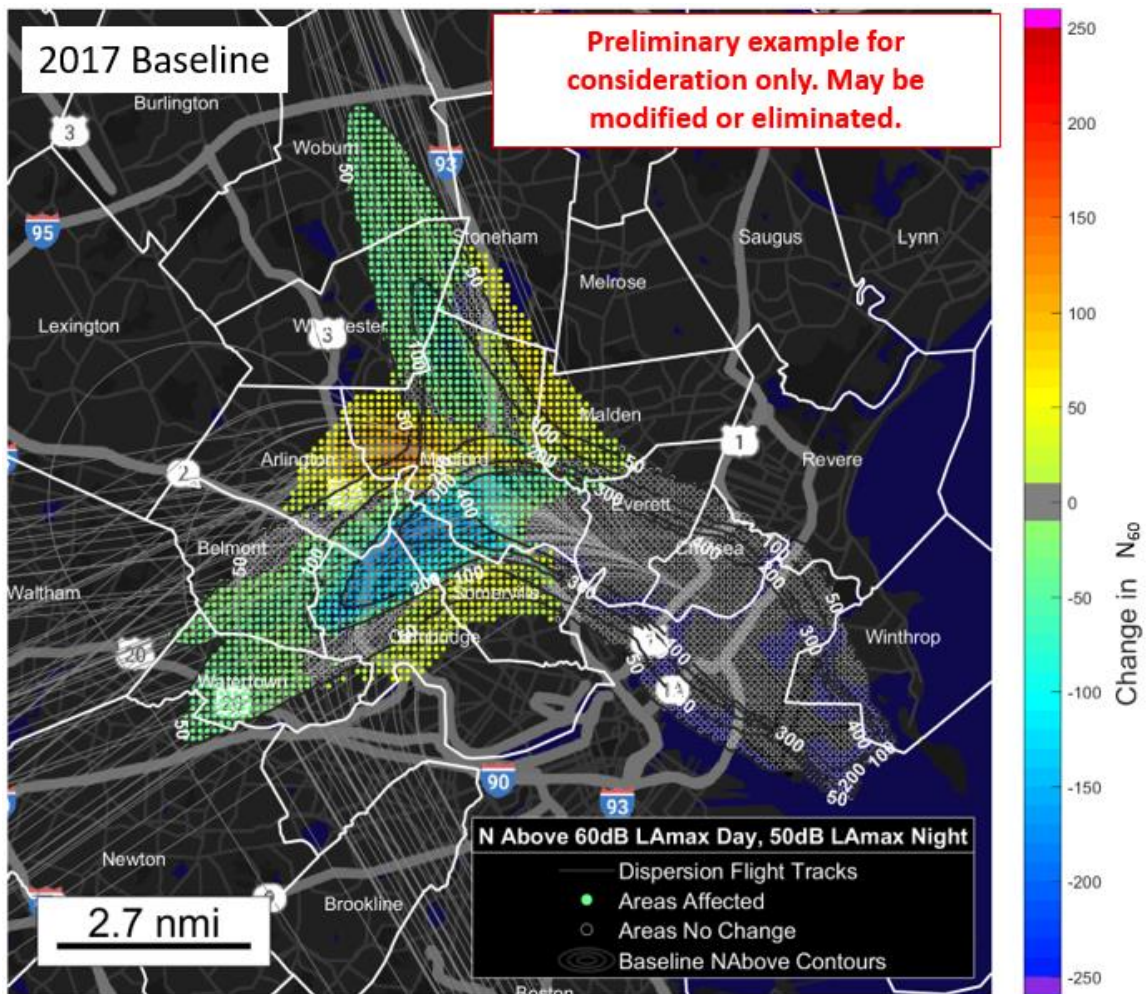


Figure 47. BOS 33L Departures Altitude-Based Dispersion at 4000ft Flight Tracks

Table 14. BOS 33L Departures Altitude-Based Dispersion at 3000ft Population Exposure to N₆₀ with 50 Overflights on a Peak Day

N ₆₀	50x
Baseline 2017	336,643
Dispersion	342,387
Baseline - Dispersion	-5,744



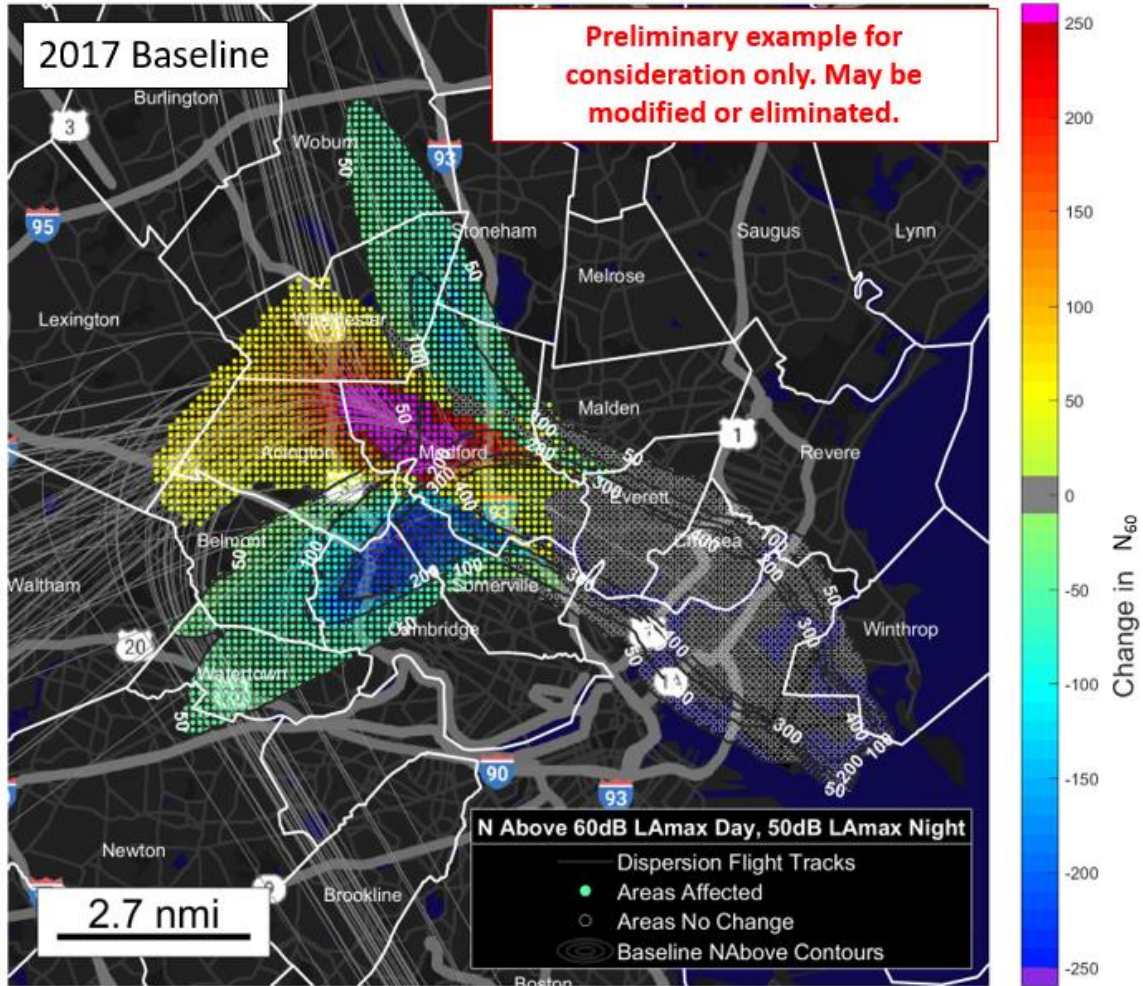
Analysis based on peak day operations; only includes 33L departures

Figure 48. BOS 33L Departures Altitude-Based Dispersion at 3000ft Change in N₆₀ Overflights on a Peak Day

Altitude-based dispersion at 4000ft for 33L departures at BOS results in an over 62,000 person reduction in exposure to 50 overflights at the N₆₀ level on a peak day. Altitude-based dispersion at 4000ft is effectively a concentration of flight tracks compared to the current RNAV flight tracks, since the flights stay along one track for a longer amount of time going west. The area further west of the airport is also less population dense thus resulting in the population exposure decrease. Figure 49 shows that while the people under the current RNAV tracks receive a significant reduction of about a 200 overflight reduction, the people under the westward track from the airport receive a significant increase in N₆₀ overflights of over a 250 overflight increase at the N₆₀ level.

Table 15. BOS 33L Departures Altitude-Based Dispersion at 4000ft Population Exposure to N₆₀ with 50 Overflights on a Peak Day

N₆₀	50x
Baseline 2017	336,643
Dispersion	273,878
Baseline - Dispersion	62,765



Analysis based on peak day operations; only includes 33L departures

Figure 49. BOS 33L Departures Altitude-Based Dispersion at 4000ft Change in N_{60} Overflights on a Peak Day

8.5 Controller-Based Dispersion

Controller-based dispersion was modelled based on pre-RNAV flight tracks that were normalized against RNAV flight tracks. Conversations with controllers indicated that this would be the closest model to controller-based dispersion. To model the pre-RNAV flight tracks and to make a fair comparison with the 2017 peak day, the 2010 peak day was analyzed and normalized against the 2017 data. Data was normalized by the aircraft destination direction and the type of aircraft, the day night counts were based on

the 2017 peak day data. Table 16 shows the 2010 and 2017 peak days analysis for BOS 33L departures, and the same analysis is shown for BOS 27 departures in Appendix B. If there were too many flight tracks represented on the 2010 peak day, then the appropriate number of flight tracks were randomly selected from the 2010 data; and if there were too few flight tracks represented on the 2010 peak day, then randomly selected flight tracks were counted twice. In Table 16, for northbound B757s only two of the flight tracks from 2010 were selected; and for northbound A320s, fifteen of the flight tracks were counted twice to represent the same number of northbound A320s as in 2017.

Table 16. BOS 33L Departures 2010 Peak Day Normalized Against 2017 Peak Day

2010		2017			
Northbound	Total	Northbound	Day	Night	Total
TA	8	TA	6	2	8
B757	13	B757	2	0	2
A320	31	A320	40	6	46
B737	23	B737	32	7	39
OJ	2	OJ	3	0	3
LRJ	20	LRJ	35	2	37
SRJ	43	SRJ	26	0	26
Southbound	Total	Southbound	Day	Night	Total
TA	9	TA	8	1	9
B757	25	B757	5	0	5
A320	62	A320	87	11	98
B737	41	B737	46	11	57
OJ	19	OJ	6	1	7
LRJ	73	LRJ	87	7	94
SRJ	60	SRJ	52	4	56

The flight tracks for controller-based dispersion are shown in Figure 50. Table 17 shows that controller-based dispersion would result in an increase of over 12,000 people exposed to the impact threshold of 50 overflights at the N₆₀ level on a peak day. Figure 51 shows that in controller-based dispersion, the southbound flights are often turned earlier than the current RNAV turn, and the northbound flights are often turned later than the current RNAV turn.

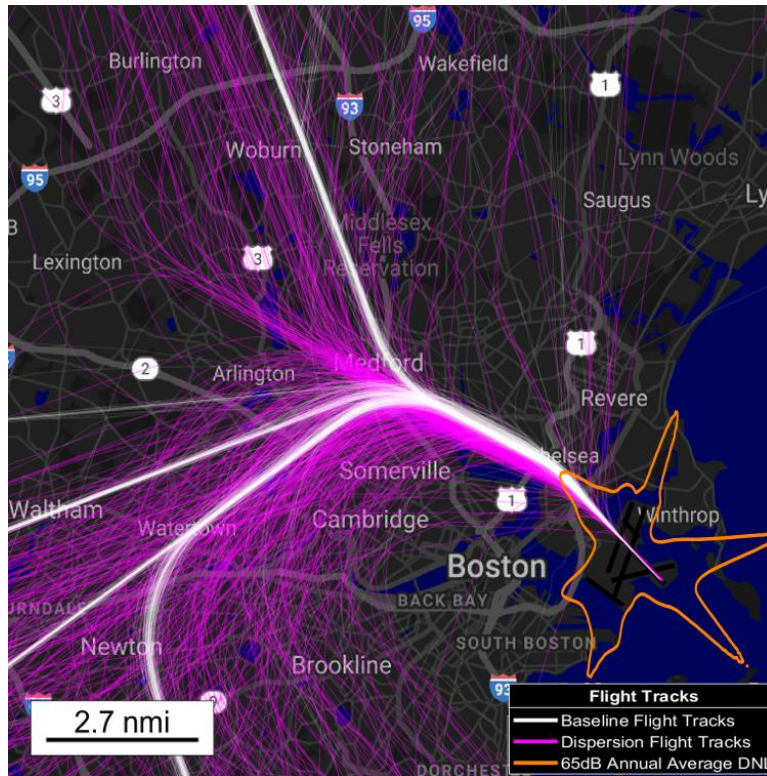
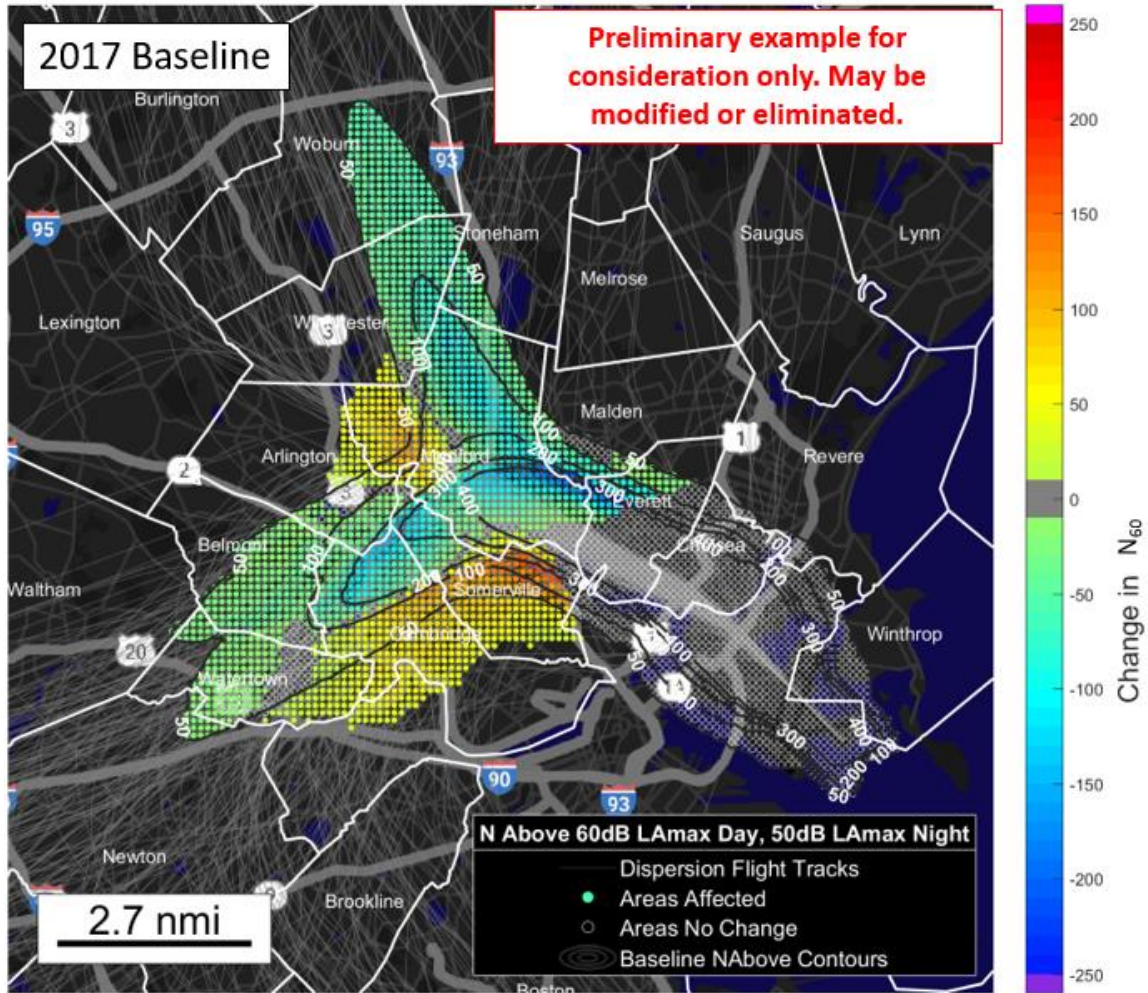


Figure 50. BOS 33L Departures Controller-Based Dispersion Flight Tracks

Table 17. BOS 33L Departures Controller-Based Dispersion Population Exposure to N_{60} with 50 Overflights on a Peak Day

N_{60}	50x
Baseline 2017	336,643
Dispersion	349,359
Baseline - Dispersion	-12,716



Analysis based on peak day operations; only includes 33L departures

Figure 51. BOS 33L Departures Controller-Based Dispersion Change in N_{60} Overflights on a Peak Day

8.6 Divergent Heading Dispersion

Another approach would be to do programmed divergent headings of 15° or greater depending on the trajectory. Divergent headings help to maintain aircraft separation requirements, since once the aircraft are on divergent headings of 15° or greater then the aircraft are considered separated. Maintaining separation requirements is especially important for dispersion procedures where the flight path length may be variable. Divergent headings could be assigned by the tower who know which aircraft

will follow on the runway and thus also help to maintain separation requirements. 15° or greater divergent headings could be assigned based on the aircraft destination. In the divergent heading dispersion modeling, the aircraft are sent to the transition waypoint upon reaching 3000ft altitude [26]. The flight track modeling for 33L departures divergent heading dispersion is shown in Figure 52 where the dispersion flight tracks are shown as magenta lines.

Table 18 shows that the divergent heading dispersion concept would result in a 2,000 person reduction for the exposure to 50 overflights at the N₆₀ level for the 33L departure communities at BOS. This is a result of the divergent heading flight tracks overflying less population dense areas. Figure 53 shows that there would be areas that would be newly exposed to noise due to the divergent headings.

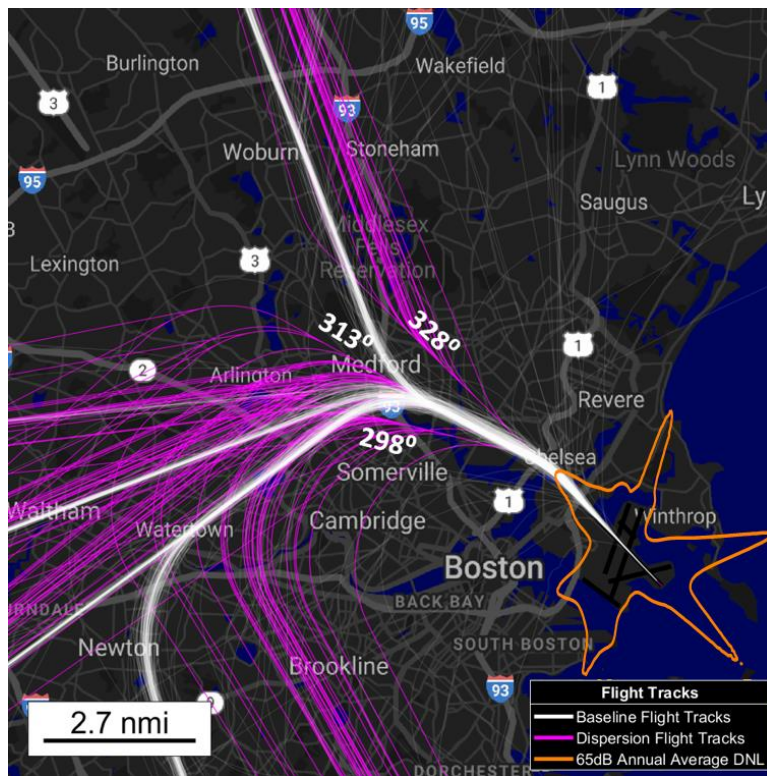
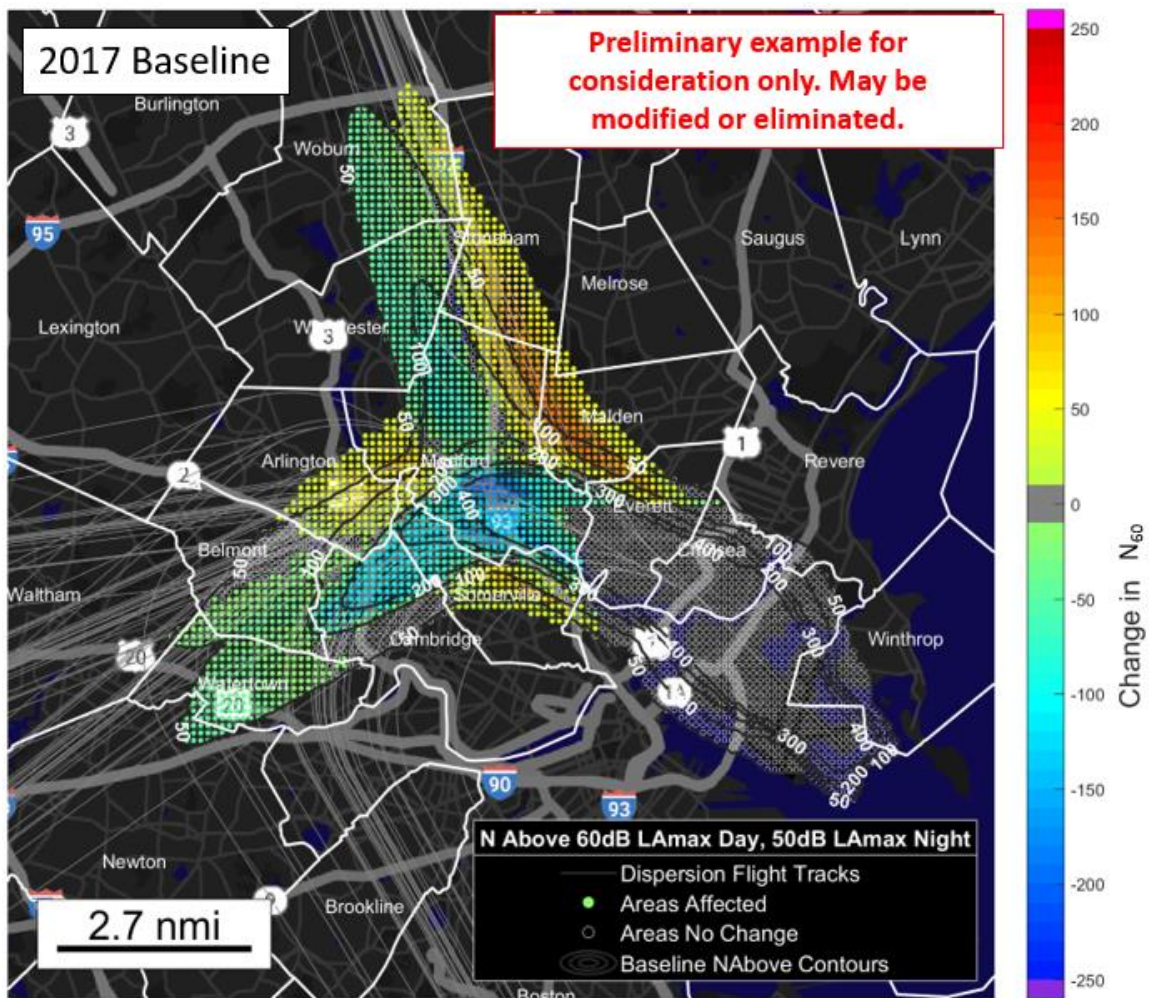


Figure 52. BOS 33L Departures Divergent Heading Dispersion Flight Tracks

Table 18. BOS 33L Departures Divergent Heading Dispersion Population Exposure to N_{60} with 50 Overflights on a Peak Day

N_{60}	50x
Baseline 2017	336,643
Dispersion	334,305
Baseline - Dispersion	2,338



Analysis based on peak day operations; only includes 33L departures

Figure 53. BOS 33L Departures Divergent Heading Dispersion Change in N_{60} Overflights on a Peak Day

8.7 RNAV Turning Waypoint Relocation

Dispersion could be introduced by changing the location of a turning waypoint, thus changing the location where RNAV procedures begin to branch. The concept was motivated by runway 27 departures at BOS where the introduction of RNAV also introduced a new waypoint that moved the turning waypoint further along the departure path and resulted in increased noise exposure to a population dense area. The idea is to move the waypoint back to the previous location prior to RNAV to provide relief to this community by allowing the departure paths to branch sooner. This idea is further discussed in the 27 departures analysis in Appendix D. For runway 33L departures at BOS, the choice of waypoint relocation is not as clear, so the analysis was done parametrically by moving the current fly-by waypoint closer to the airport 1nmi and 0.5nmi and also further from the airport 1nmi and 0.5nmi, as shown in Figure 54 through Figure 57.

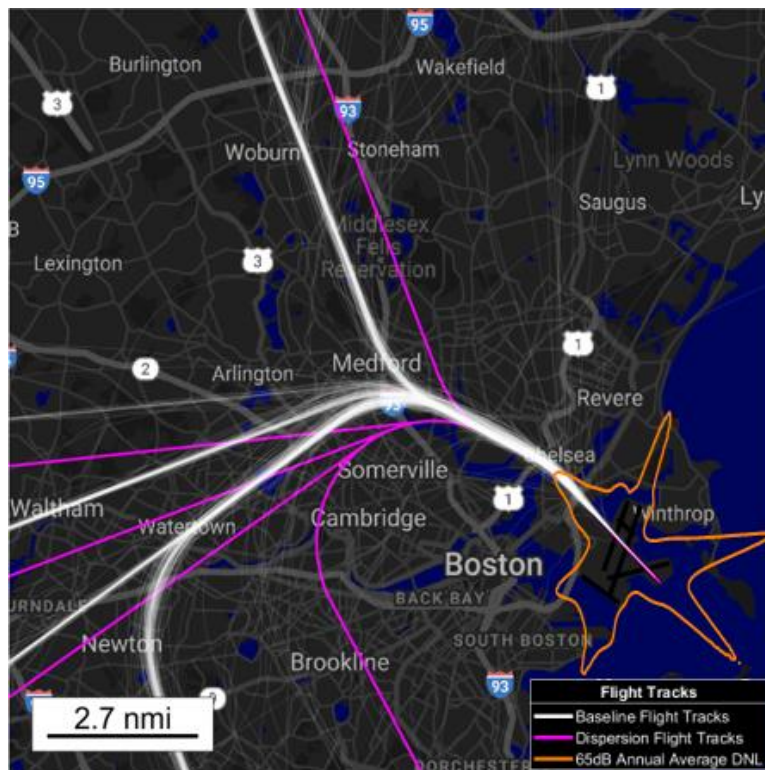


Figure 54. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks -1nmi

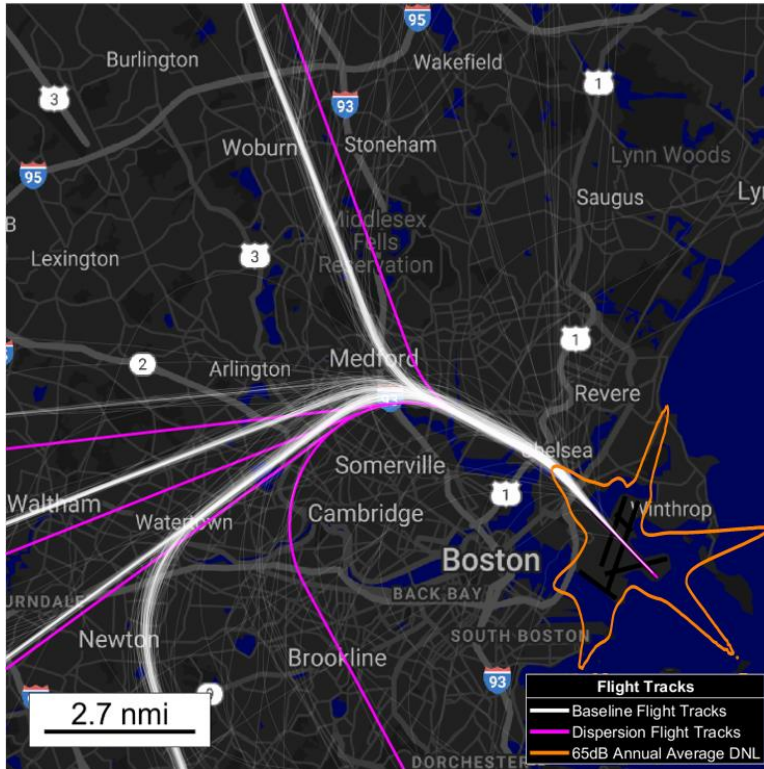


Figure 55. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks -0.5nmi

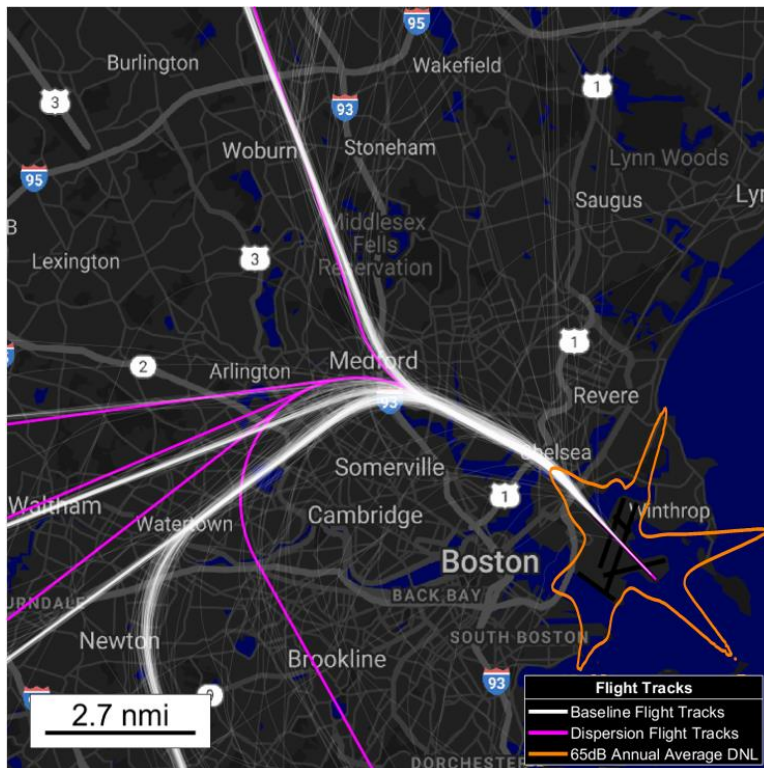


Figure 56. BOS 33L Dep. RNAV Turning Waypoint Reloc. Flight Tracks +0.5nmi

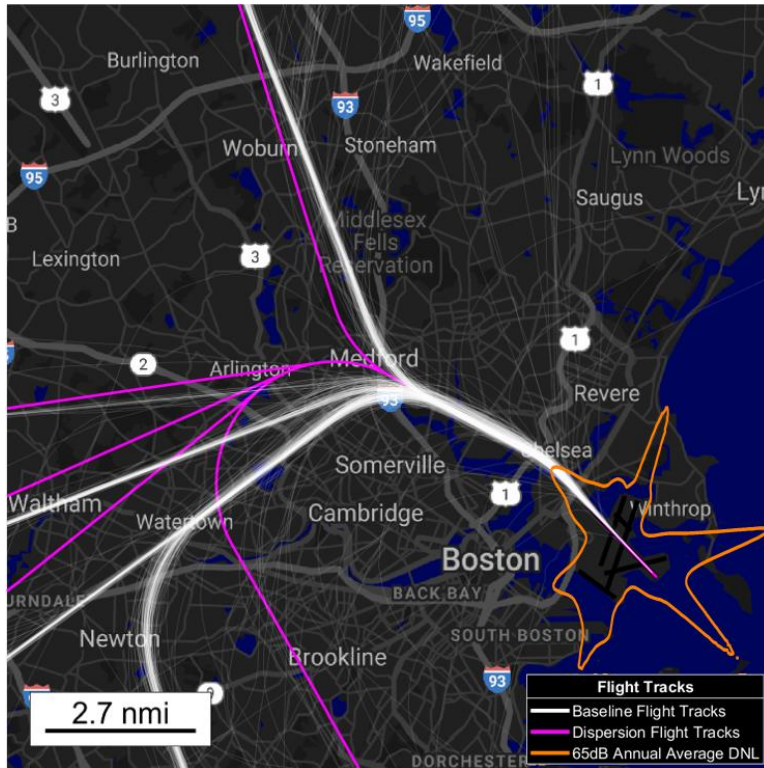
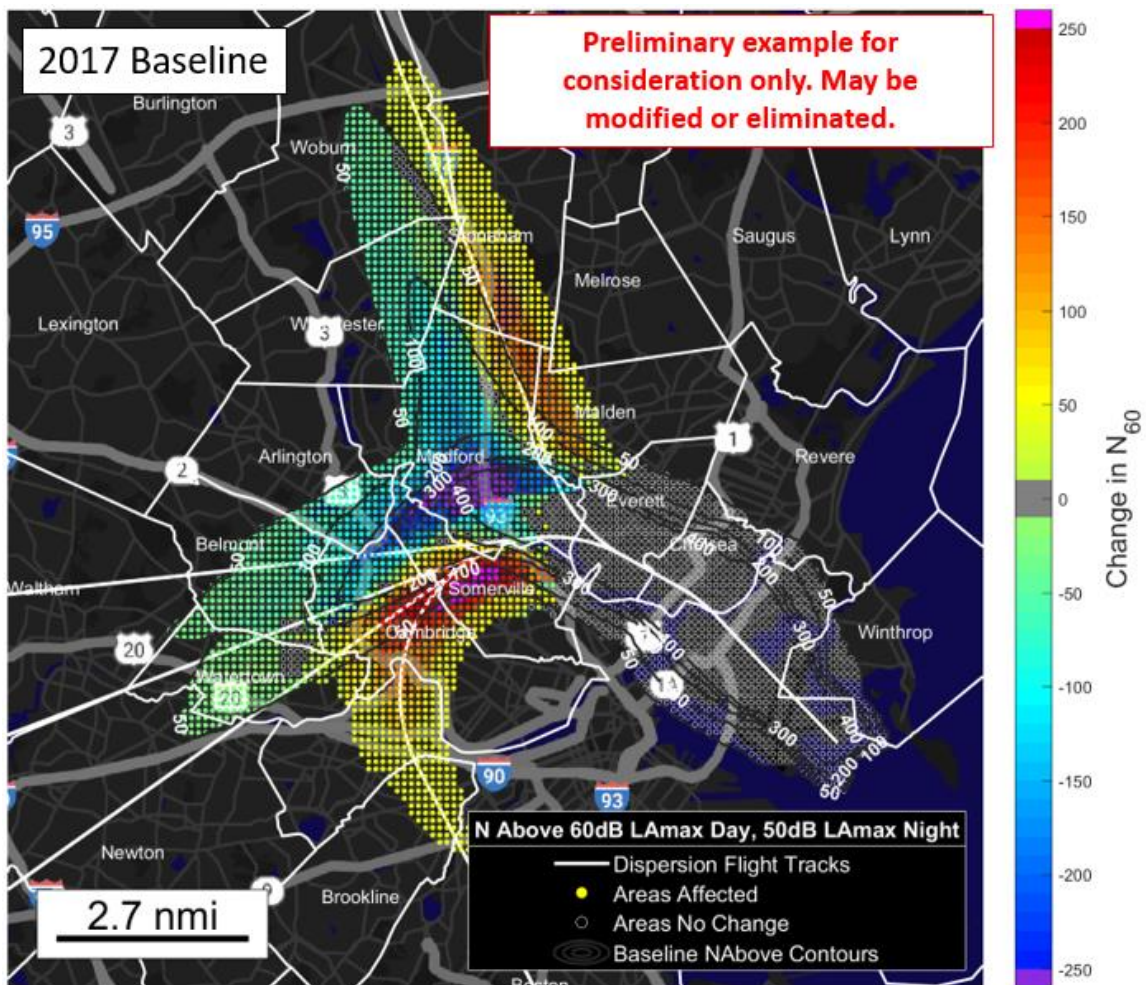


Figure 57. BOS 33L Dep. RNAV Turning Waypoint Relocation Flight Tracks +1nmi

The population exposure numbers and the change in number of N_{60} overflights are shown in Table 19 through Table 22 and in Figure 58 through Figure 61. In general the areas further west from BOS are less population dense, so moving the waypoint further west results in a reduction in the number of people exposed to the impact threshold of 50 overflights at the N_{60} level. The figures showing change in N_{60} show that some of the waypoint relocations would result in more drastic changes in number of overflights, changes as great 250 overflights in magnitude. The parametric sweep of RNAV turning waypoint locations illustrates the sensitivity of population exposure to RNAV procedure design.

Table 19. BOS 33L Departures RNAV Turning Waypoint Relocation -1nmi Population Exposure to N₆₀ with 50 Overflights on a Peak Day

N ₆₀	50x
Baseline 2017	336,643
Dispersion	380,478
Baseline - Dispersion	-43,835

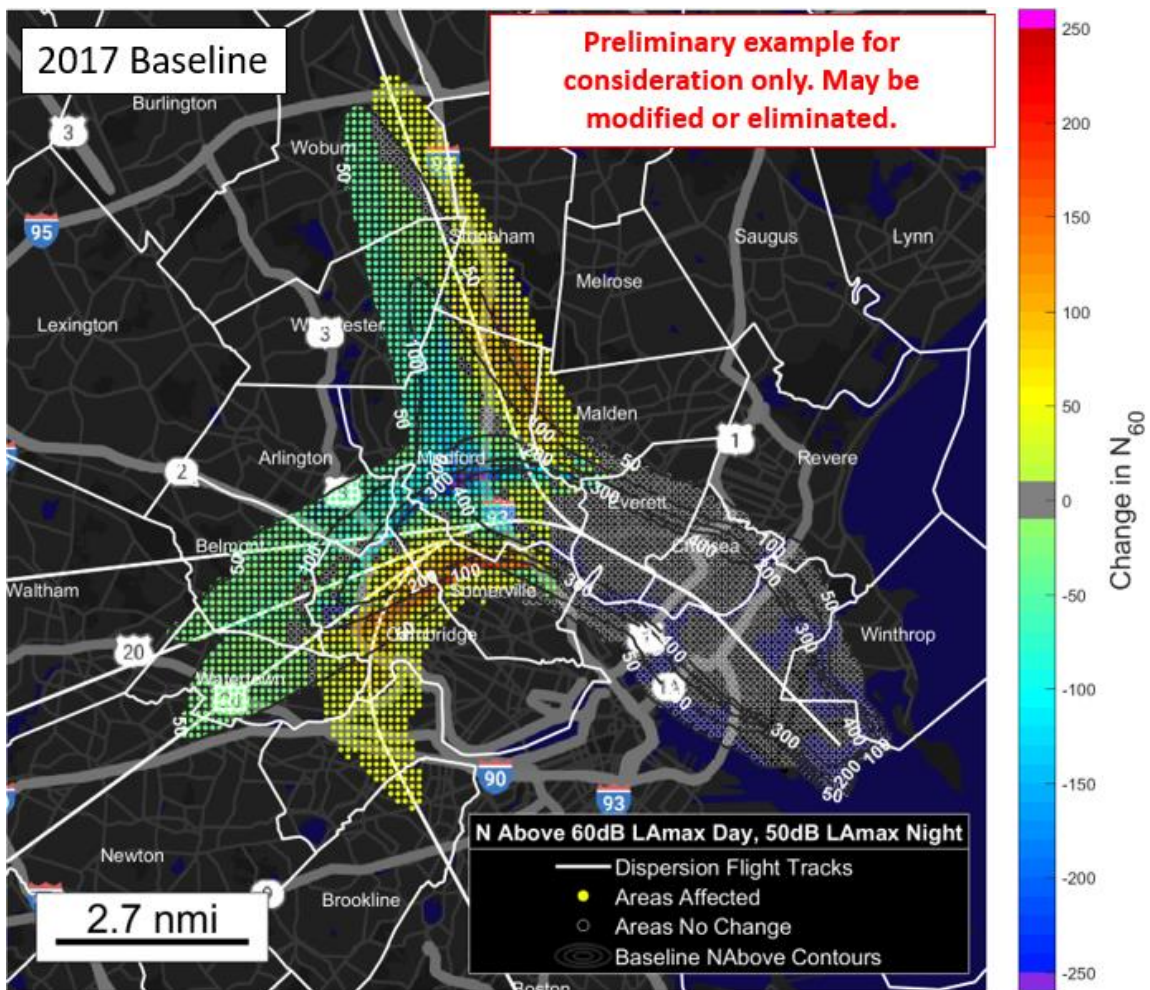


Analysis based on peak day operations; only includes 33L departures

Figure 58. BOS 33L Departures RNAV Turning Waypoint Relocation -1nmi Change in N₆₀ Overflights on a Peak Day

Table 20. BOS 33L Departures RNAV Turning Waypoint Relocation -0.5nmi Population Exposure to N₆₀ with 50 Overflights on a Peak Day

N ₆₀	50x
Baseline 2017	336,643
Dispersion	338,219
Baseline - Dispersion	-1,576

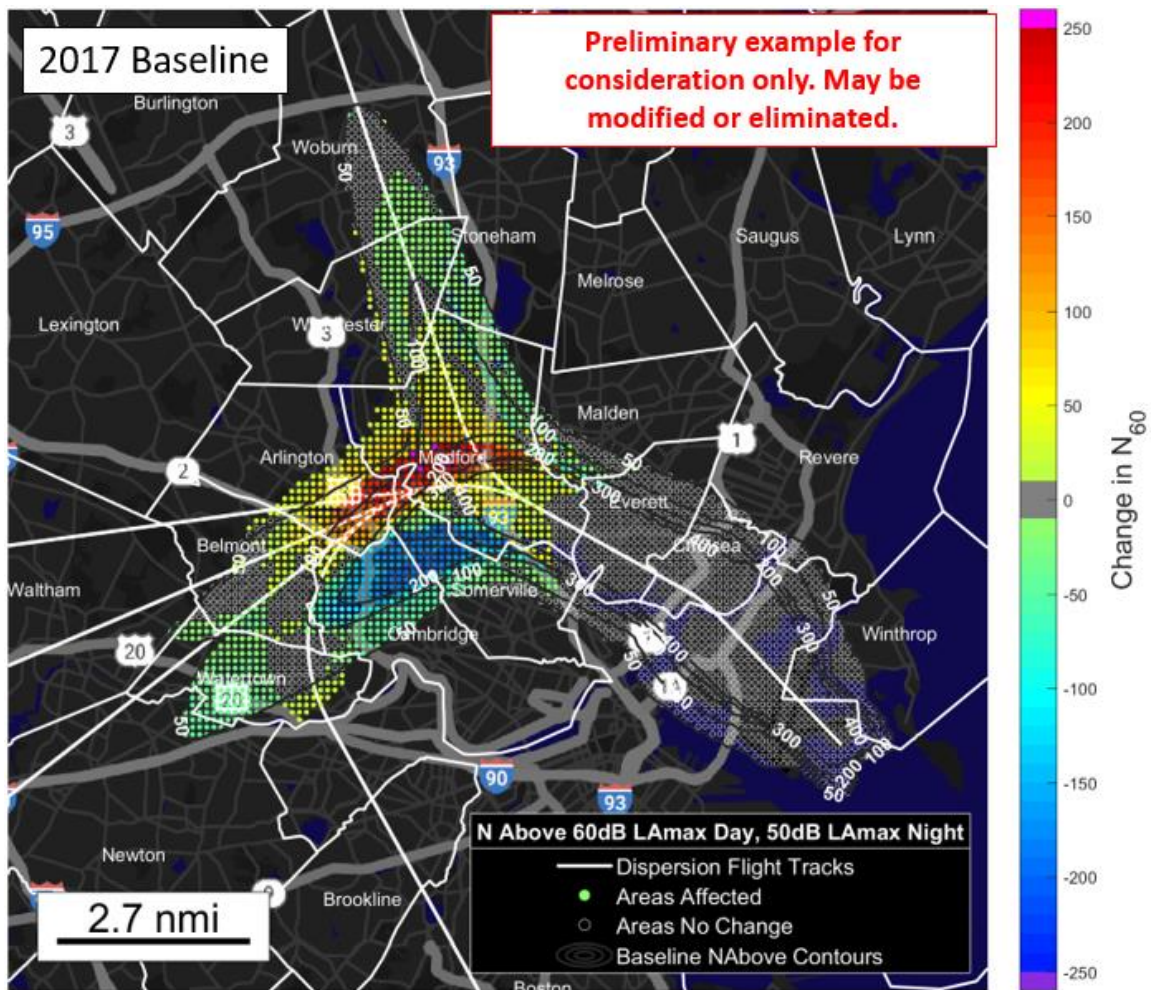


Analysis based on peak day operations; only includes 33L departures

Figure 59. BOS 33L Departures RNAV Turning Waypoint Relocation -0.5nmi Change in N₆₀ Overflights on a Peak Day

**Table 21. BOS 33L Departures RNAV Turning Waypoint Relocation +0.5nmi
Population Exposure to N₆₀ with 50 Overflights on a Peak Day**

N ₆₀	50x
Baseline 2017	336,643
Dispersion	300,637
Baseline - Dispersion	36,006

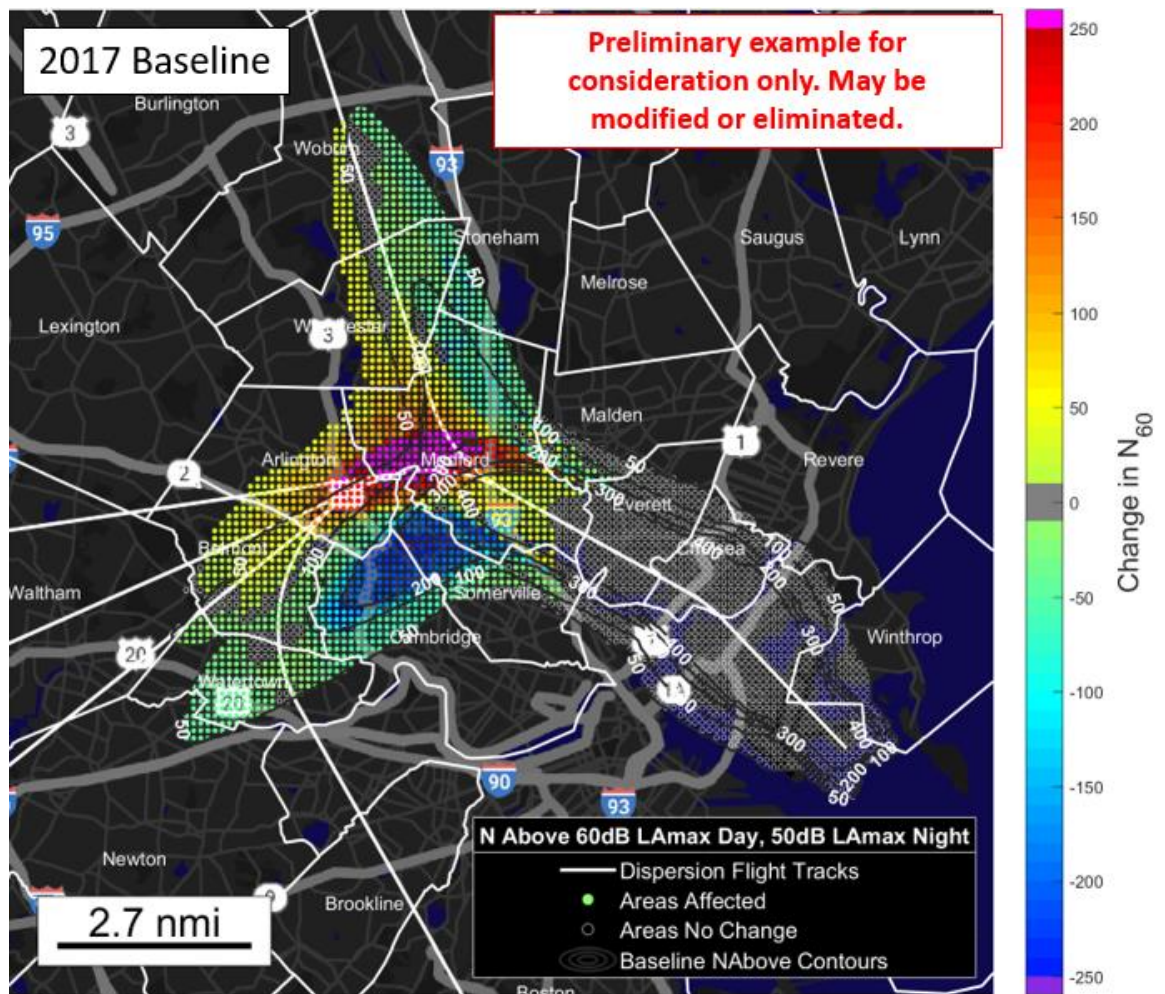


Analysis based on peak day operations; only includes 33L departures

**Figure 60. BOS 33L Departures RNAV Turning Waypoint Relocation +0.5nmi
Change in N₆₀ Overflights on a Peak Day**

Table 22. BOS 33L Departures RNAV Turning Waypoint Relocation +1nmi Population Exposure to N₆₀ with 50 Overflights on a Peak Day

N ₆₀	50x
Baseline 2017	336,643
Dispersion	293,984
Baseline - Dispersion	42,659



Analysis based on peak day operations; only includes 33L departures

Figure 61. BOS 33L Departures RNAV Turning Waypoint Relocation +1nmi Change in N₆₀ Overflights on a Peak Day

Chapter 9 Conclusion

Metrics for assessing the impacts of frequent overflights are determined. A metric representing a number of events above an annoyance noise threshold is defined. This metric is N_{60} on a peak day with 50 overflights. Alternatively the metric of peak day DNL at 45dB is also shown to represent the impact threshold of frequent overflights. At BOS, MSP, LHR, and one runway at CLT, this threshold represented at least 80% of complaint locations. This impact threshold was used to analyze various concepts of implementing dispersed flight tracks.

Dispersion is a politically attractive idea due to perceived similarity to pre-RNAV conditions. Methods of implementing dispersion are analyzed including altitude-based dispersion, controller-based dispersion, and divergent heading dispersion; these concepts were developed in conversations with air traffic controllers and stakeholders. Methods of communicating the dispersion analysis results to stakeholders include overall population exposure to N_{60} with 50 overflights on a peak day, maps showing how the N_{60} count will change for constituents, and histograms showing how each town will specifically be affected. While dispersion may appear to be a politically attractive idea, there is uncertainty and precedent to lead to the question of whether or not dispersed flight tracks will have the desired effect. The analysis tools developed in this thesis will support the stakeholders during the decision making processes.

References

- [1] "NextGen," Federal Aviation Administration, https://www.faa.gov/nextgen/what_is_nextgen/, Accessed: 2019-04-24.
- [2] "Performance Based Navigation (PBN) Implementation and Usage," <https://www.faa.gov/nextgen/pbn/dashboard/#>, Accessed: 2019-05-15.
- [3] "RNAV review," Ladacan, www.ladacan.org/rnav-review/, Accessed: 2019-04-24.
- [4] Aratani, L., "New report says noise complaints are up at National, Dulles airports," *The Washington Post* [online] 16 September 2017, https://www.washingtonpost.com/local/trafficandcommuting/new-report-says-noise-complaints-are-up-at-national-dulles-airports/2017/09/16/78f221e8-9962-11e7-b569-3360011663b4_story.html?utm_term=.45be8ad7cade. Accessed: 2019-04-24.
- [5] Nav Canada, <http://www.navcanada.ca/EN/about-us/Pages/CYOWFAQ.aspx>, Accessed: 2019-04-24.
- [6] "Federal Government's Method of Assessing Noise Impacts," <http://www.airportnoiselaw.org/65dnl.html>, Accessed: 2019-05-07.
- [7] Hansman, R. J., et al, "Procedure Design Concepts for Logan Airport Community Noise Reduction," 23 April 2019.
- [8] Brooks, C. T., and Hansman, R. J., "Modeling the Effects of Aircraft Flight Track Variability on Community Noise exposure," Massachusetts Institute of Technology, 2017.
- [9] Beranek, L. L., Mellow, T. J., "Chapter 1 – Introduction and Terminology," *Acoustics: Sound Fields and Transducers*, 2012, pp. 1-19.
- [10] Fleming, G. G., "Aviation Environmental Design Tool (AEDT) Technical Manual, Version 2c," 2016.
- [11] Smith, M. T. J., *Aircraft Noise*. Cambridge, JK: Cambridge University Press, 1989.
- [12] Reindel, G., "Overview of Noise Metrics and Acoustical Objectives," *AAAE Sound Insulation Symposium*, 2001.

- [13] “What is the “Number Above” noise metric?,” *MAC Noise*, <https://www.macnoise.com/faq/what-number-above-noise-metric>, Updated: 3 December 2018, Accessed: 18 May 2019.
- [14] Schultz, T. J., “Synthesis of social surveys on noise annoyance,” *The Journal of the Acoustical Society of America*, Vol. 64, No. 377, 1978.
- [15] Southgate, D., “The Evolution of Aircraft Noise Descriptors in Australia over the Past Decade,” *Proceedings of ACOUSTICS*, Gold Coast, Australia, 2011, p. 52.
- [16] “N70 Noise Contours,” *Archerfield Brisbane’s Metropolitan Airport*, http://www.archerfieldairport.com.au/Downloads/Masterplan2011/FS4_N70%20Noise%20Contours.pdf, Accessed: 20 May 2019.
- [17] “Survey of noise attitudes 2014: Aircraft,” *Civil Aviation Authority*, 2017, <http://publicapps.caa.co.uk/docs/33/CAP%201506%20FEB17.pdf>, Accessed: 20 May 2019.
- [18] “Aviation Environmental Design Tool,” Federal Aviation Administration, <https://aedt.faa.gov/>, Accessed: 2019-05-06.
- [19] Brenner, M. A., Hansman, R. J., “Comparison of Methods for Evaluating Impacts of Aviation Noise on Communities,” Massachusetts Institute of Technology, 2017.
- [20] Thomas, J., and Hansman, R. J., “Modeling Performance and Noise of Advanced Operational Procedures for Current and Future Aircraft,” Massachusetts Institute of Technology, 2017.
- [21] Jensen, L., and Hansman, R. J., “Data-Driven Flight Procedure Simulation and Noise Analysis in a Large-Scale Air Transportation System,” Massachusetts Institute of Technology, 2018.
- [22] “kmeans,” <https://www.mathworks.com/help/stats/kmeans.html>, Accessed: 2019-05-08.
- [23] “2017 Noise Complaints Report,” https://www.heathrow.com/file_source/HeathrowNoise/Static/Noise_complaints_report_2017.pdf, Accessed: 2019-01-09.

- [24] “Charlotte Metroplex Meeting,” *Federal Aviation Administration*, July 2016, https://www.faa.gov/nextgen/nextgen_near_you/community_involvement/clt/media/Pbase_III_Radar_Tracks.pdf. [Retrieved 09 May 2019].
- [25] Harrison, S., “Here’s why your Charlotte neighborhood may be hearing more aircraft noise,” *The Charlotte Observer* [online], 12 Jan. 2018, <https://www.charlotteobserver.com/news/politics-government/article194438979.html>. [retrieved 19 April 2019].
- [26] Thomas, J., Yu, A., Li, C., Maddens Toscano, P., Hansman, R. J., “Advanced Operational Procedure Design Concepts for Noise Abatement,” *Thirteenth USA/Europe Air Traffic Management Research and Development Seminar*, 2019.
- [27] Hansman, R. J., et al., “Procedure Design Concepts for Logan Airport Community Noise Reduction,” 28 September 2017.
- [28] “Congressional Briefing Presentation,” *Boston Overflight Noise Study*, 18 July 2014, <http://www.bostonoverflightnoisestudy.com/docs/CongressionalBriefingPresentationJuly182014.pdf>, Accessed: 1 December 2018.

[Page Intentionally Left Blank]

Appendix A Aircraft Types Table [19]

A320 – Airbus 320

B737 – Boeing 737

B757 – Boeing 757

LRJ – Large Regional Jet

OJ – Older Jet

PNJ – Piston Engine (not included in noise models)

SRJ – Small Regional Jet

TA – Twin Aisle

UNK – Unknown

A124	TA	AEST	PNJ	B763	TA
A306	OJ	ASTR	SRJ	B764	TA
A310	OJ	AT43	SRJ	B767	TA
A318	A320	AT72	SRJ	B772	TA
A319	A320	B190	SRJ	B773	TA
A320	A320	B350	SRJ	B777	TA
A321	A320	B38M	B737	B77L	TA
A332	TA	B712	OJ	B77W	TA
A333	TA	B717	OJ	B787	TA
A340	TA	B722	OJ	B788	TA
A342	TA	B732	B737	B789	TA
A343	TA	B733	B737	BE9	SRJ
A345	TA	B734	B737	BE10	SRJ
A346	TA	B735	B737	BE20	SRJ
A350	TA	B737	B737	BE23	PNJ
A359	TA	B738	B737	BE24	PNJ
A36	PNJ	B739	B737	BE30	SRJ
A388	TA	B744	TA	BE33	PNJ
A400	TA	B747	TA	BE35	PNJ
AA5	PNJ	B748	TA	BE36	PNJ
AC11	PNJ	B74S	TA	BE40	SRJ
AC50	PNJ	B752	B757	BE55	PNJ
AC69	PNJ	B753	B757	BE56	PNJ
AC90	SRJ	B757	B757	BE58	PNJ
AC95	SRJ	B762	TA	BE60	PNJ

BE65	PNJ	C525	SRJ	E170	LRJ
BE76	PNJ	C550	SRJ	E190	LRJ
BE80	PNJ	C551	SRJ	E35L	SRJ
BE88	PNJ	C560	SRJ	E45X	SRJ
BE90	SRJ	C56X	SRJ	E500	PNJ
BE95	PNJ	C650	SRJ	E50P	SRJ
BE99	SRJ	C680	SRJ	E545	SRJ
BE9L	SRJ	C68A	SRJ	E550	SRJ
BE9T	SRJ	C72R	PNJ	E55P	SRJ
BL17	PNJ	C750	SRJ	E75L	LRJ
C130	PNJ	C82R	PNJ	E75S	LRJ
C150	PNJ	CL30	SRJ	EA50	SRJ
C152	PNJ	CL35	SRJ	EVOT	SRJ
C160	PNJ	CL60	SRJ	F2TH	SRJ
C172	PNJ	CL65	SRJ	F900	SRJ
C177	PNJ	CN35	SRJ	FA10	SRJ
C180	PNJ	COL3	PNJ	FA20	SRJ
C182	PNJ	COL4	PNJ	FA50	SRJ
C206	PNJ	CRJ	SRJ	FA7X	SRJ
C207	PNJ	CRJ1	SRJ	FA8X	SRJ
C208	SRJ	CRJ2	SRJ	FALC	PNJ
C210	PNJ	CRJ7	LRJ	FBA2	PNJ
C25	SRJ	CRJ9	LRJ	G150	SRJ
C25A	SRJ	D328	SRJ	G280	SRJ
C25B	SRJ	DA40	PNJ	G400	SRJ
C25C	SRJ	DA42	PNJ	GA7	SRJ
C25M	SRJ	DA50	PNJ	GALX	SRJ
C303	PNJ	DA7X	SRJ	GL5T	SRJ
C30J	PNJ	DC10	OJ	GLEX	SRJ
C310	PNJ	DC91	OJ	GLF2	SRJ
C337	PNJ	DC93	OJ	GLF3	SRJ
C340	PNJ	DEFI	PNJ	GLF4	SRJ
C402	PNJ	DH8	PNJ	GLF5	SRJ
C414	PNJ	DH8A	SRJ	GLF6	SRJ
C421	PNJ	DH8C	SRJ	GLST	PNJ
C425	PNJ	DH8D	SRJ	H25A	SRJ
C441	SRJ	E110	SRJ	H25B	SRJ
C500	SRJ	E120	SRJ	H25C	SRJ
C501	SRJ	E135	SRJ	HA4T	SRJ
C510	SRJ	E145	SRJ	HDJT	SRJ

J328	SRJ	P46T	SRJ	WW24	SRJ
JS31	SRJ	PA23	PNJ		
JS32	SRJ	PA24	PNJ		
K35R	TA	PA27	PNJ		
LJ25	SRJ	PA28	PNJ		
LJ31	SRJ	PA30	PNJ		
LJ35	SRJ	PA31	PNJ		
LJ40	SRJ	PA32	PNJ		
LJ45	SRJ	PA34	PNJ		
LJ55	SRJ	PA44	PNJ		
LJ60	SRJ	PA46	PNJ		
LJ70	SRJ	PA60	PNJ		
LJ75	SRJ	PASE	UNK		
LNCE	PNJ	PAY1	SRJ		
M020	PNJ	PAY2	SRJ		
M20	PNJ	PAY3	SRJ		
M20A	PNJ	PAY4	SRJ		
M20P	PNJ	PAZT	UNK		
M20R	PNJ	PC12	SRJ		
M20T	PNJ	PRM1	SRJ		
M7	PNJ	RV6	PNJ		
MAUL	PNJ	S22T	PNJ		
MD11	OJ	SB20	LRJ		
MD80	OJ	SBR1	SRJ		
MD81	OJ	SF34	SRJ		
MD82	OJ	SF50	PNJ		
MD83	OJ	SR20	PNJ		
MD87	OJ	SR22	PNJ		
MD88	OJ	SW3	SRJ		
MD90	OJ	SW4	SRJ		
MO20	PNJ	T154	OJ		
MU2	SRJ	T206	PNJ		
MU30	SRJ	TB20	PNJ		
P180	SRJ	TB21	PNJ		
P28A	PNJ	TBM7	SRJ		
P28B	PNJ	TBM8	SRJ		
P28R	PNJ	TBM9	SRJ		
P28T	PNJ	TEX2	PNJ		
P32A	PNJ	TRIN	UNK		
P32R	PNJ	VTUR	PNJ		

Appendix B Peak Day Analysis for Dispersion Modeling

The peak day analysis for runway 27 at BOS is provided here in Appendix B. The peak day analysis for runway 33L at BOS was provided previously in Chapter 8.

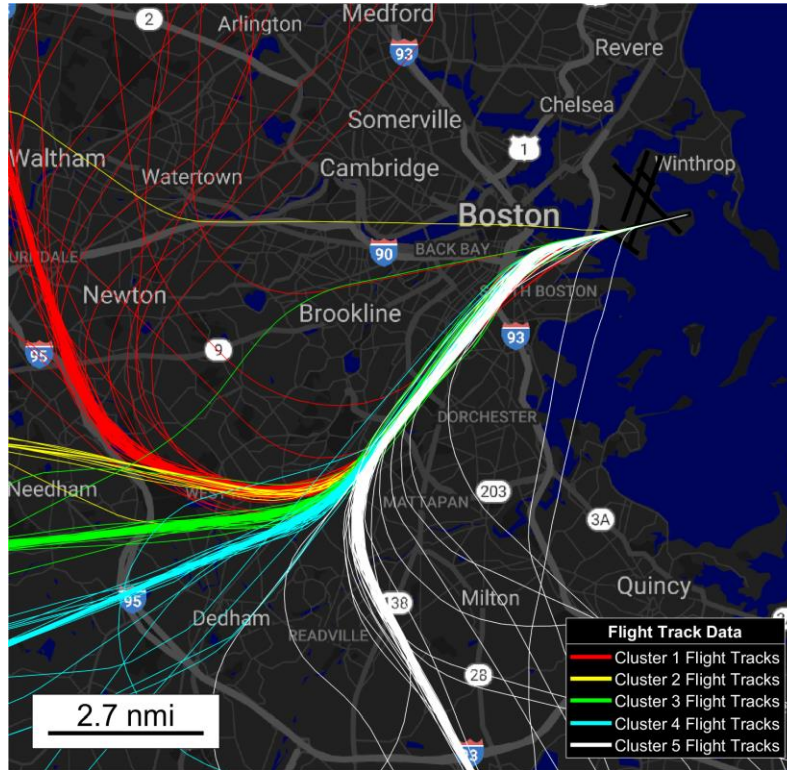


Figure B1. BOS 27 Departures Peak Day Flight Track Clustering by Transition Waypoint

Table B1. BOS 27 Departures Peak Day Sorted by Transition Waypoint Clusters

1	Day	Night	2	Day	Night	3	Day	Night
TA	0	0	TA	0	0	TA	0	0
B757	1	0	B757	0	0	B757	0	1
A320	19	1	A320	1	1	A320	13	2
B737	16	3	B737	2	1	B737	15	2
OJ	1	1	OJ	0	0	OJ	0	1
LRJ	20	10	LRJ	4	4	LRJ	15	9
SRJ	8	4	SRJ	1	0	SRJ	8	1

4	Day	Night	5	Day	Night
TA	0	0	TA	0	0
B757	1	0	B757	1	0
A320	17	4	A320	19	3
B737	12	7	B737	12	8
OJ	2	0	OJ	3	0
LRJ	26	7	LRJ	29	5
SRJ	11	1	SRJ	10	2

Table B2. BOS 27 Departures Peak Days Comparison

	Day	Night
Peak Day	267	78
Average of Top 5 Peak Days	212	52

Table B3. BOS 27 Departures 2010 Peak Day Normalized Against 2017 Peak Day

2010		2017			
Westbound	Total	Westbound	Day	Night	Total
TA	2	TA	0	0	0
B757	21	B757	2	1	3
A320	40	A320	50	8	58
B737	30	B737	45	13	58
OJ	22	OJ	3	2	5
LRJ	57	LRJ	65	30	95
SRJ	46	SRJ	28	6	34

Eastbound	Total	Eastbound	Day	Night	Total
TA	0	TA	0	0	0
B757	4	B757	1	0	1
A320	25	A320	19	3	22
B737	14	B737	12	8	20
OJ	3	OJ	3	0	3
LRJ	20	LRJ	29	5	34
SRJ	16	SRJ	10	2	12

Appendix C Arrivals Dispersion

The peak day for BOS 4L/R arrivals was October 12th, 2017, on which day there were 92 arrivals to 4L and 475 arrivals to 4R for a total of 567 arrivals. Dispersion is modeled for the primary arrival runway, 4R. 51% of the arrivals to 4R were from the direction of PVD on the peak day. Figure C1 shows the flight tracks on the peak day of BOS 4L/R arrivals. Table C1 shows the fleet mix on the peak day of BOS 4L/R arrivals and Table C2 compares the top five peak days of BOS 4L/R arrivals to the peak day.

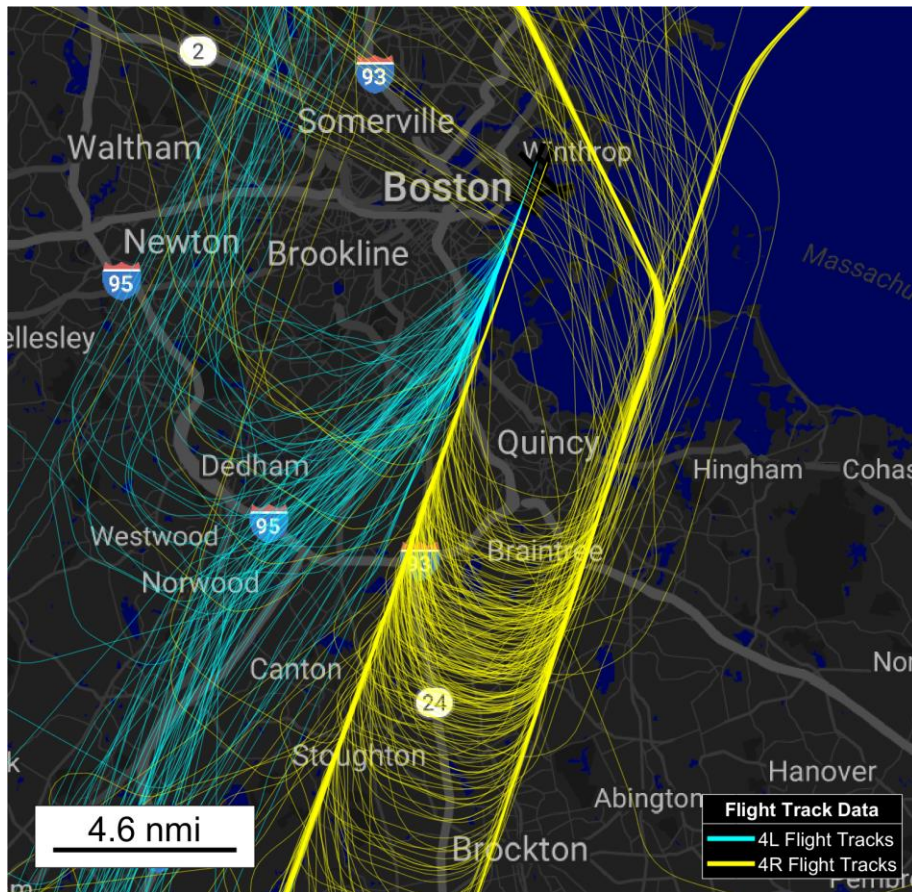


Figure C1. BOS 4L/R Arrivals Peak Day

Table C1. BOS 4L/R Arrivals Peak Day Fleet Mix

<u>4L</u>	Day	Night	<u>4R</u>	Day	Night
TA	0	0	TA	34	2
B757	0	0	B757	11	5
A320	21	0	A320	97	30
B737	5	0	B737	75	24
OJ	1	0	OJ	12	6
LRJ	22	0	LRJ	112	18
SRJ	43	0	SRJ	47	2

Table C2. BOS 4L/R Arrivals Peak Days Comparison

	Day	Night
4L/R Peak Day	480	87
Average of Top 5 Peak Days	461	92.2

Figure C2 shows the flight tracks for dispersion on BOS 4L/R Arrivals. Five approach paths are defined within the RNAV maximum final approach intercept angle of 15°; further detail on RNAV approach design criteria is documented extensively in Jensen and Hansman [21]. Dispersion is modeled for the primary approach runway, 4R. Two arrival dispersion concepts were considered:

- 1) Equally distributing the flight tracks between the five arrival paths during a day
- 2) Selecting one of the arrival paths to use for an entire day

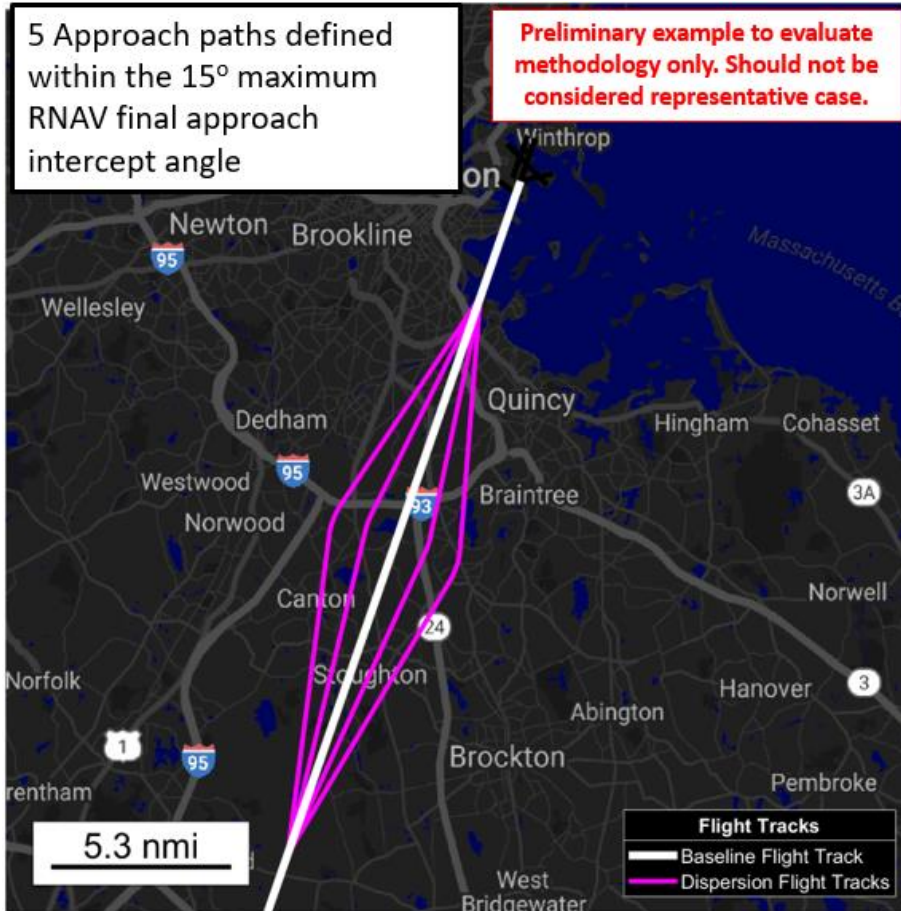


Figure C2. BOS 4L/R Arrival Dispersion Flight Tracks

Preliminary analysis was presented to the communities, however because of the restrictive design criteria on RNAV approaches, the noise was shifted from one side of the impacted community to the other side of the impacted community, rather than sharing the noise amongst the communities as intended. For these reasons, arrival dispersion was not further pursued.

Appendix D BOS 27 Departures Dispersion Analysis and Record of Decision

The dispersion analysis for 27 departures at BOS is discussed here in Appendix D.

The dispersion analysis for 33L departures at BOS was previously discussed in Chapter 8. The details for each dispersion concept and the modeling were also previously discussed in Chapter 8.

In the flight track figures, the magenta lines indicate the dispersed flight tracks. The white lines are the flight tracks from the radar data for the peak day of operations, in this case 27 departures at BOS. The orange contour is the annual average DNL contour at 65dB to indicate that the dispersion is occurring outside of this threshold level.

Runway 27 departures at BOS have a record of decision (ROD) corridor until slightly past the WYLYY waypoint, as shown in Figure D1, which was set in place by a legal decision in 1996. As a result, the runway 27 departures at BOS were already concentrated along the ROD corridor prior to the implementation of RNAV.

When RNAV was implemented for 27 departures at BOS, in order to ensure compliance with the ROD corridor, the RNAV departure procedure navigates to the KIRAA waypoint, which is past the WYLYY waypoint. As a result, the community between the WYLYY and KIRAA waypoint now receives noise from all the flights following the RNAV departure procedure whereas previously this community would receive some relief from the dispersed flight tracks. Both waypoints WYLYY and KIRAA will be labelled on the figures for dispersion analysis for 27 departures at BOS.

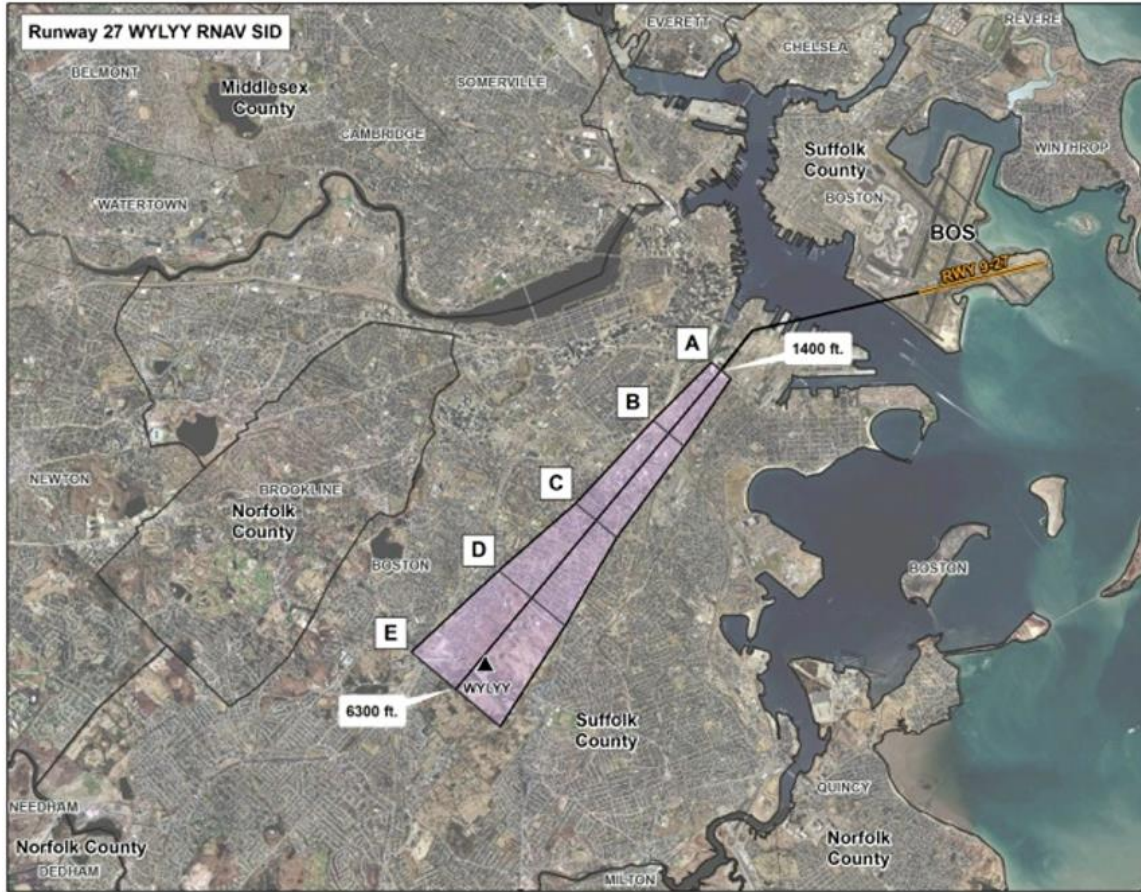


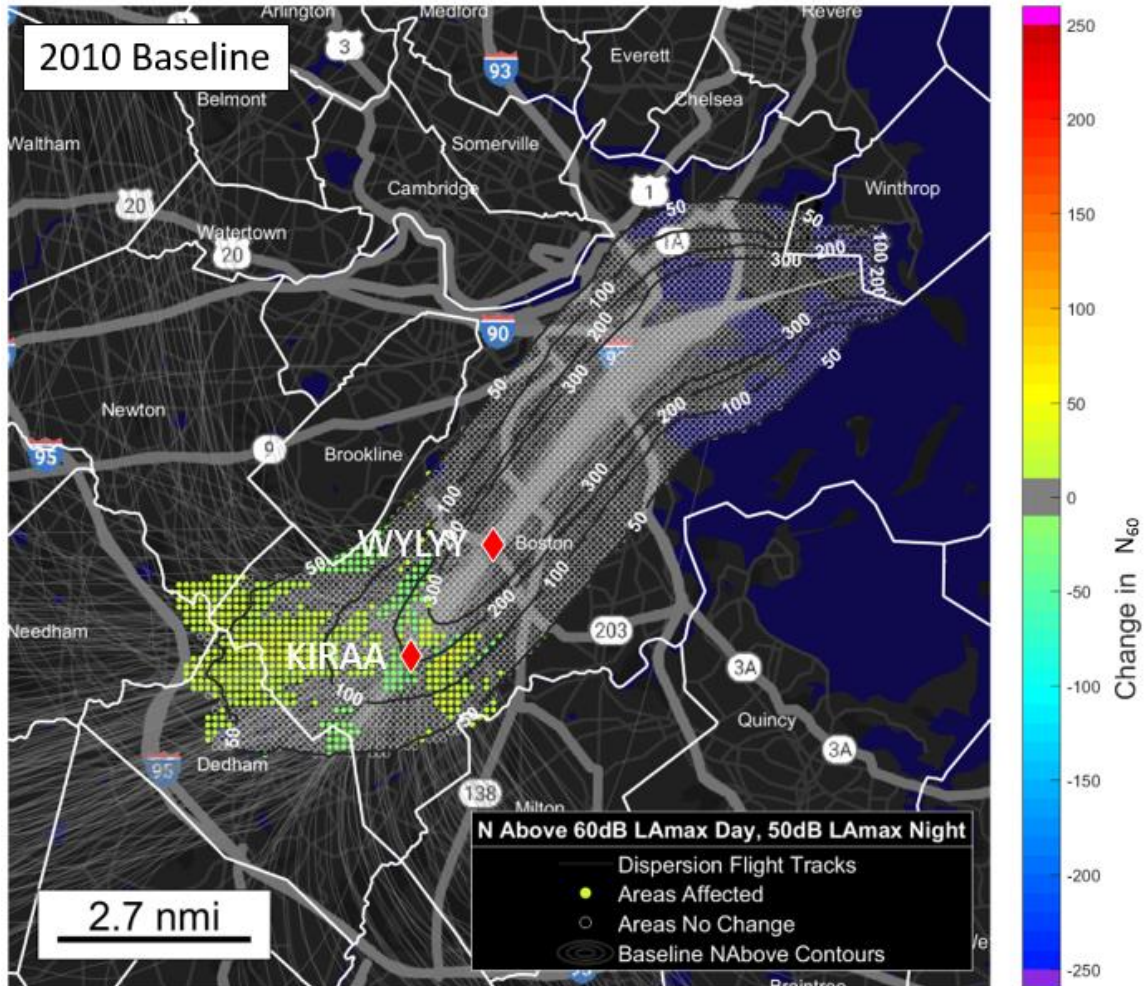
Figure D1. BOS 27 Departures Record of Decision Corridor [28]

Pre-RNAV to RNAV Comparison

The pre-RNAV to RNAV comparison for 27 departures at BOS indicates an increase in 356 people to the impact threshold level of N_{60} with 50 overflights on a peak day, as shown in Table D1. This is a result of the concentration of flight tracks from RNAV which slightly extends the 50 overflight contour for N_{60} on a peak day, as shown in Figure D2. In general, the pre-RNAV to RNAV comparison for 27 departures at BOS indicates relatively little change of an increase or reduction of fewer than 50 overflights at the N_{60} level.

Table D1. BOS 27 Departures Pre-RNAV to RNAV Comparison Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Dispersion	407,001
RNAV	407,357
RNAV Benefit	-356



Analysis based on peak day operations; only includes 27 departures

Figure D2. BOS 27 Departures Pre-RNAV to RNAV Comparison Change in N₆₀ Overflights on a Peak Day

Altitude-Based Dispersion at 3000ft

The flight tracks for altitude-based dispersion at 3000ft for 27 departures at BOS are shown in Figure D3. This dispersion concept would violate the record of decision. This dispersion concept would overfly less population dense areas compared to the current RNAV tracks, and thus results in a decrease in 23,000 people exposed to the threshold level of 50 overflights at the N₆₀ level on a peak day as shown in Table D2. Figure D4 shows the reduction of more than 200 overflights for some of the communities under the current RNAV tracks, and an increase of generally less than 100 overflights for the communities under the dispersed flight tracks.

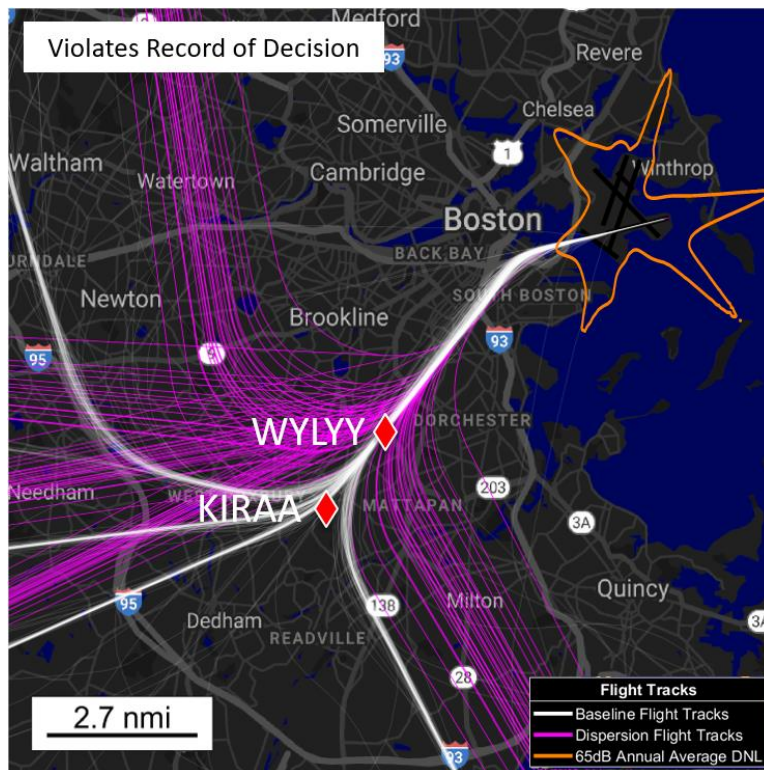
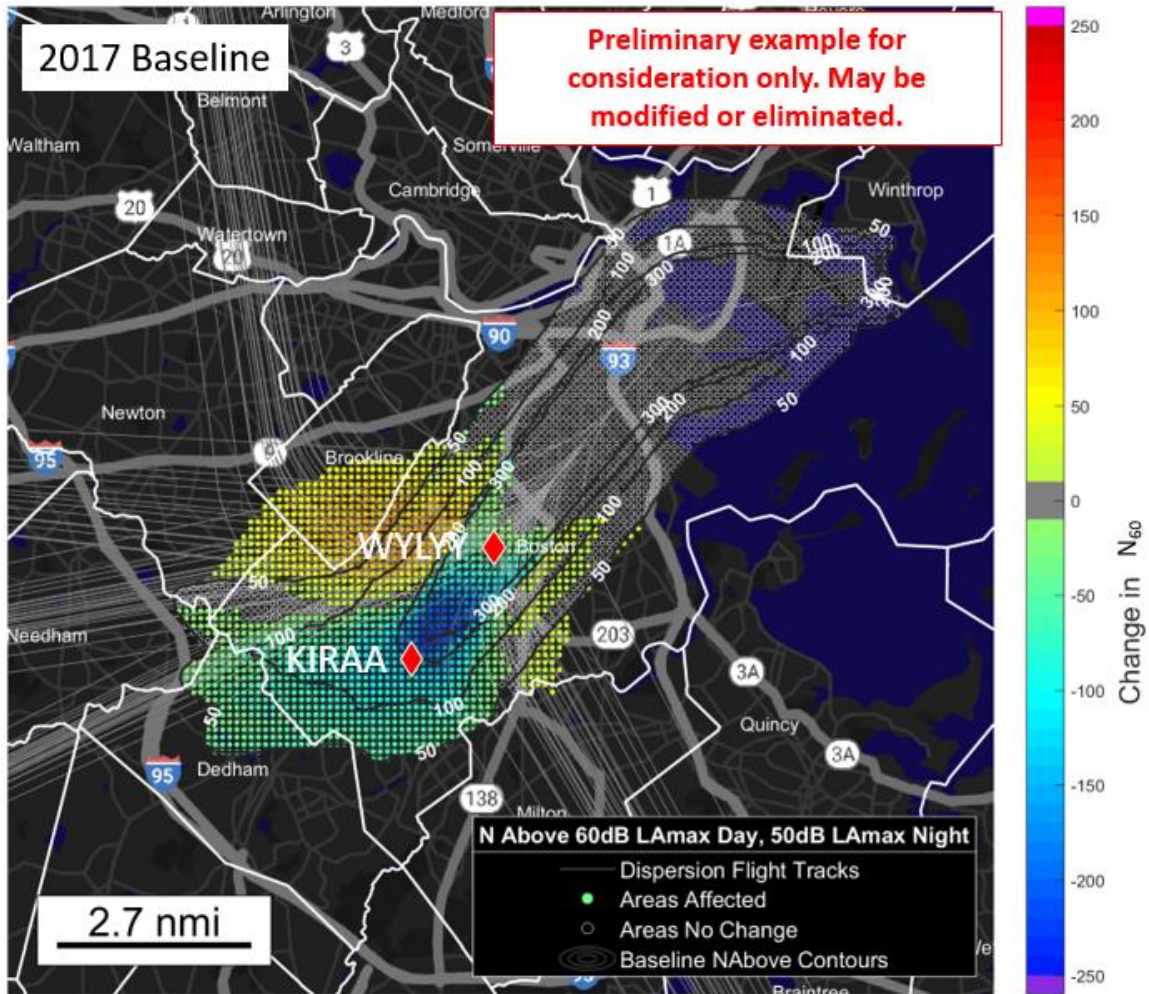


Figure D3. BOS 27 Departures Altitude-Based Dispersion at 3000ft Flight Tracks

Table D2. BOS 27 Departures Altitude-Based Dispersion at 3000ft Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Baseline 2017	407,357
Dispersion	384,114
Baseline - Dispersion	23,243



Analysis based on peak day operations; only includes 27 departures

Figure D4. BOS 27 Departures Altitude-Based Dispersion at 3000ft Change in N₆₀ Overflights on a Peak Day

Altitude-Based Dispersion at 4000ft

The flight tracks for altitude-based dispersion for 27 departures at BOS at 4000ft are shown in Figure D5. Because of the ROD corridor, this concept is similar to the current RNAV tracks; however the dispersion does result in a decrease in almost 2,000 people exposed to the impact threshold of 50 overflights at the N60 level on a peak day, as shown in Table D3. Figure D6 shows that very little change in N₆₀ overflights results from this dispersion concept, and that the change in N₆₀ overflights is usually less than 50 overflights of change.

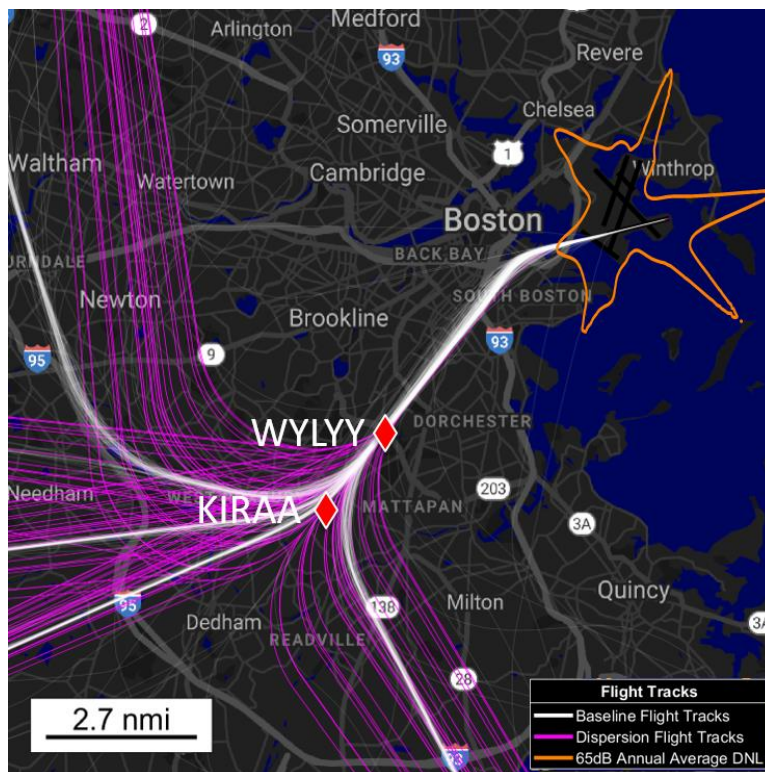
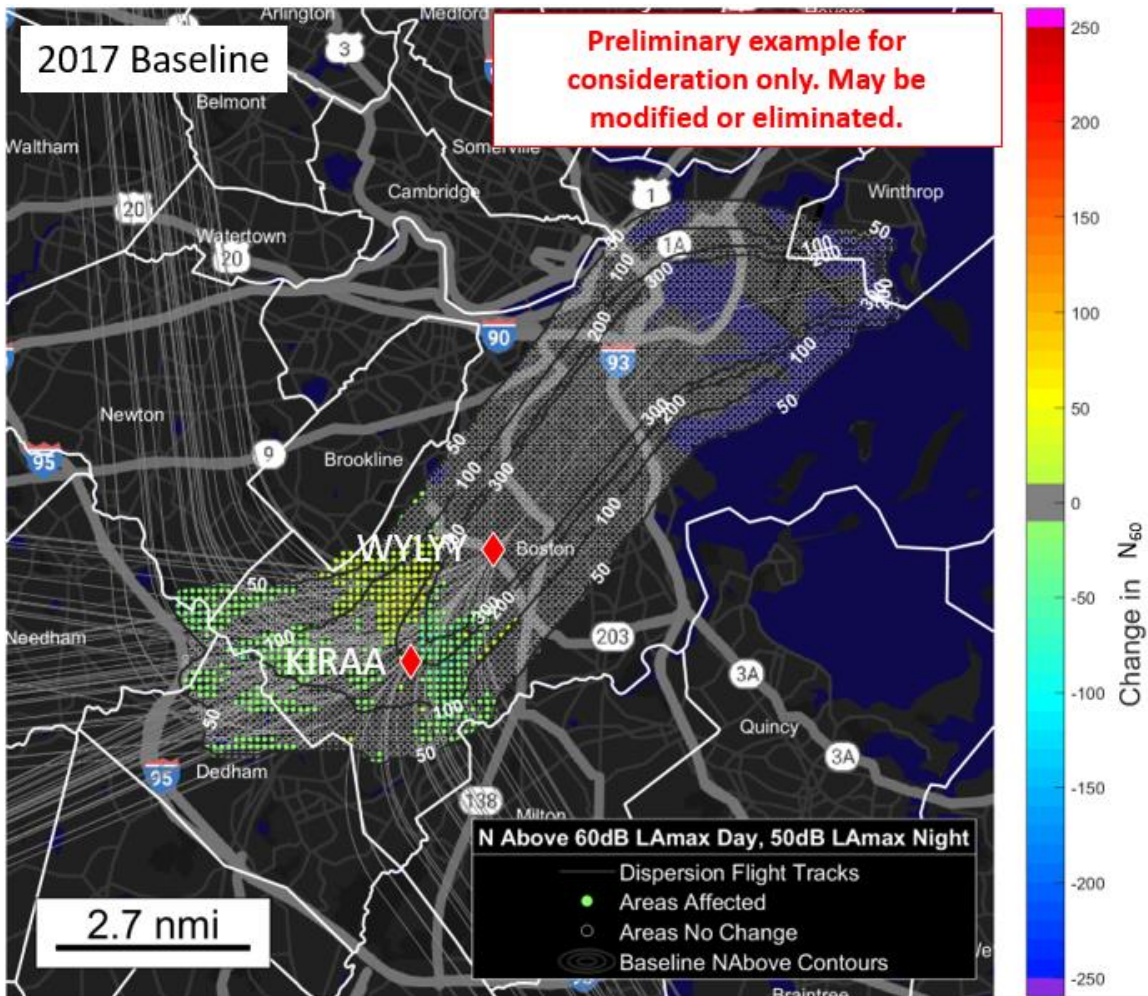


Figure D5. BOS 27 Departures Altitude-Based Dispersion at 4000ft Flight Tracks

Table D3. BOS 27 Departures Altitude-Based Dispersion at 4000ft Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Baseline 2017	407,357
Dispersion	405,385
Baseline - Dispersion	1,972



Analysis based on peak day operations; only includes 27 departures

Figure D6. BOS 27 Departures Altitude-Based Dispersion at 4000ft Change in N₆₀ Overflights on a Peak Day

Controller-Based Dispersion

The flight tracks for controller-based dispersion for 27 departures at BOS are shown in Figure D6. The previous conformance to the ROD corridor can be seen in the magenta flight tracks which are the 2010 peak day radar tracks normalized to the 2017 fleet mix to represent controller-based dispersion. Very little change from this dispersion concept is shown in the population exposure in Table D7 and in Figure D8 due to the previous existing conformance to the ROD corridor.

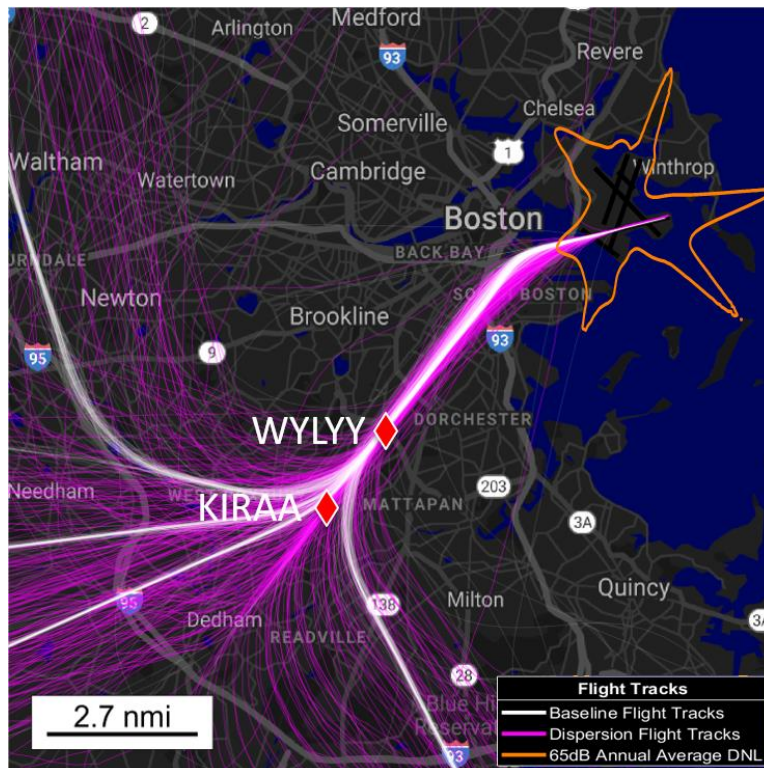
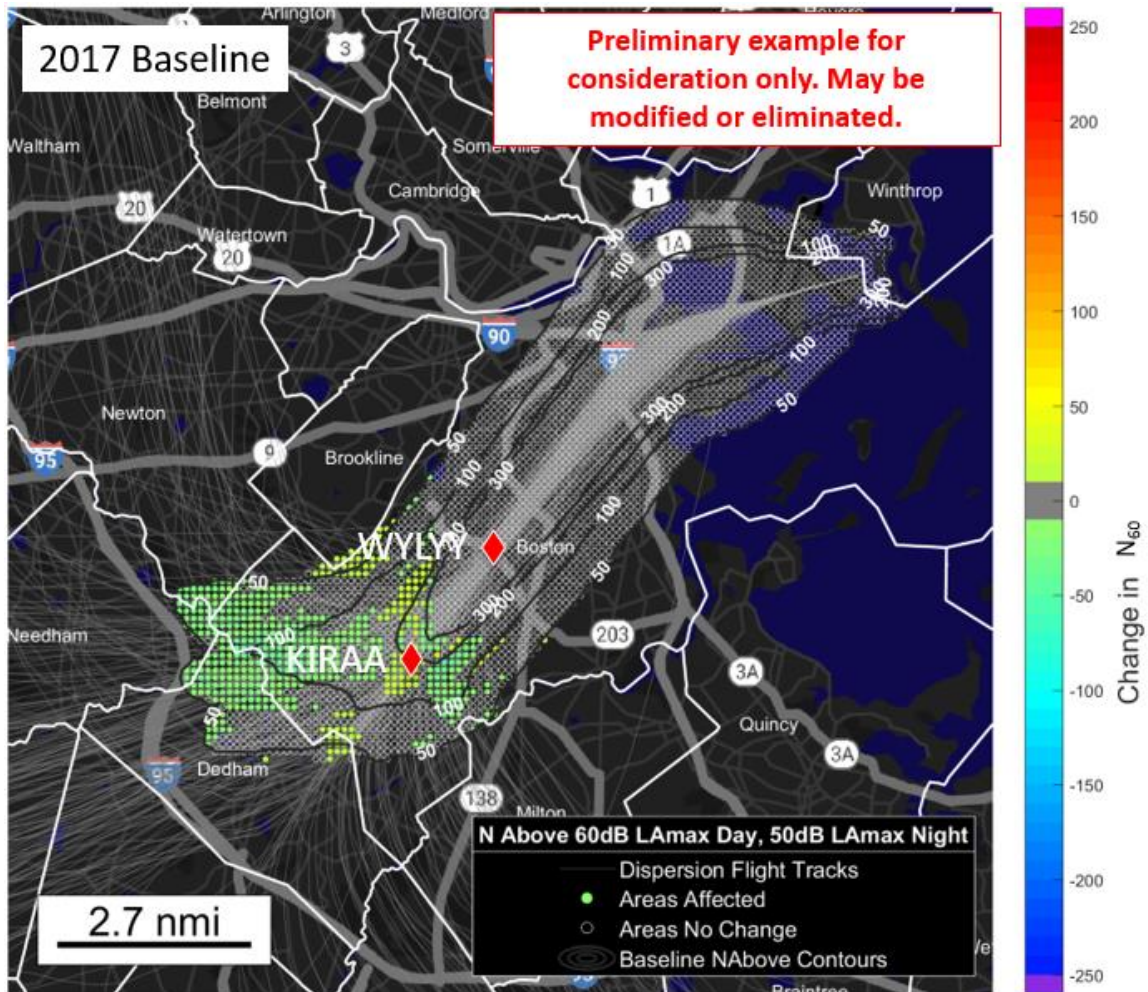


Figure D6. BOS 27 Departures Controller-Based Dispersion Flight Tracks

Table D7. BOS 27 Departures Controller-Based Dispersion Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Baseline 2017	407,357
Dispersion	407,001
Baseline - Dispersion	356



Analysis based on peak day operations; only includes 27 departures

Figure D8. BOS 27 Departures Controller-Based Dispersion Change in N₆₀ Overflights on a Peak Day

Divergent Heading Dispersion

The flight tracks for divergent heading dispersion for 27 departures at BOS are shown in Figure D9. This concept violates the Record of Decision. Due to the population density of the areas under the divergent heading flight tracks, the population exposure to the impact threshold of 50 overflights at the N₆₀ level on a peak day decreases by about 7,000 people. However the divergent heading flight tracks also overfly a highly noise sensitive community. Figure D10 shows the specific communities impacted with the area between the waypoints WYLYY and KIRAA receiving a reduction of more than 250 overflights from this dispersion concept.

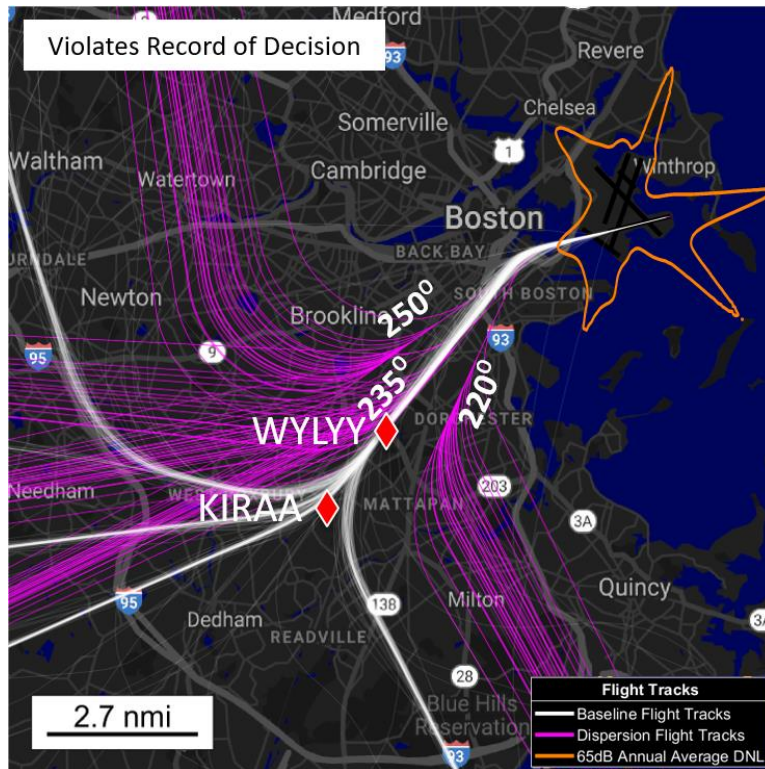
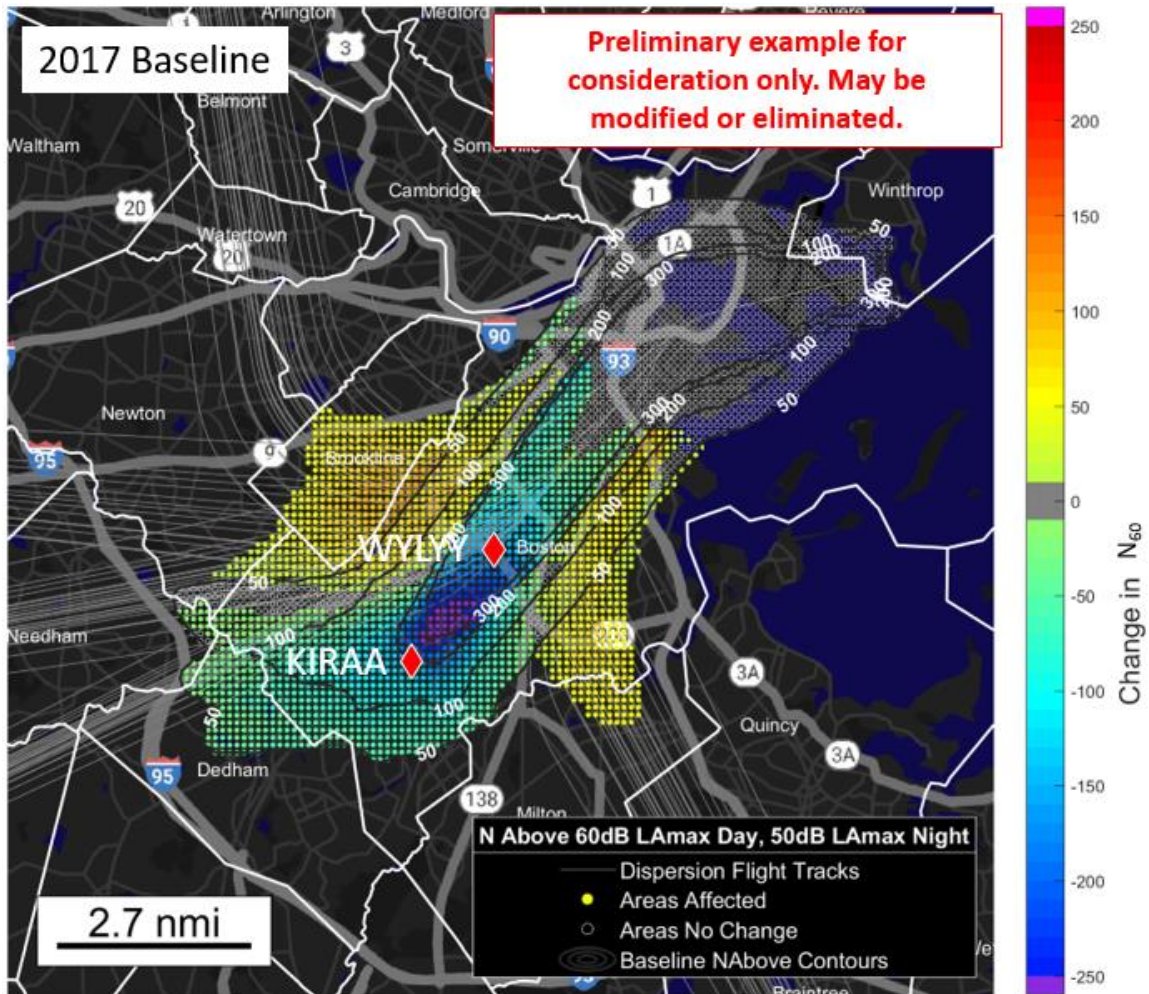


Figure D9. BOS 27 Departures Divergent Heading Dispersion Flight Tracks

Table D5. BOS 27 Departures Divergent Heading Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Baseline 2017	407,357
Dispersion	399,883
Baseline - Dispersion	7,474



Analysis based on peak day operations; only includes 27 departures

Figure D10. BOS 27 Departures Divergent Heading Dispersion Change in N₆₀ Overflights on a Peak Day

RNAV Waypoint Relocation

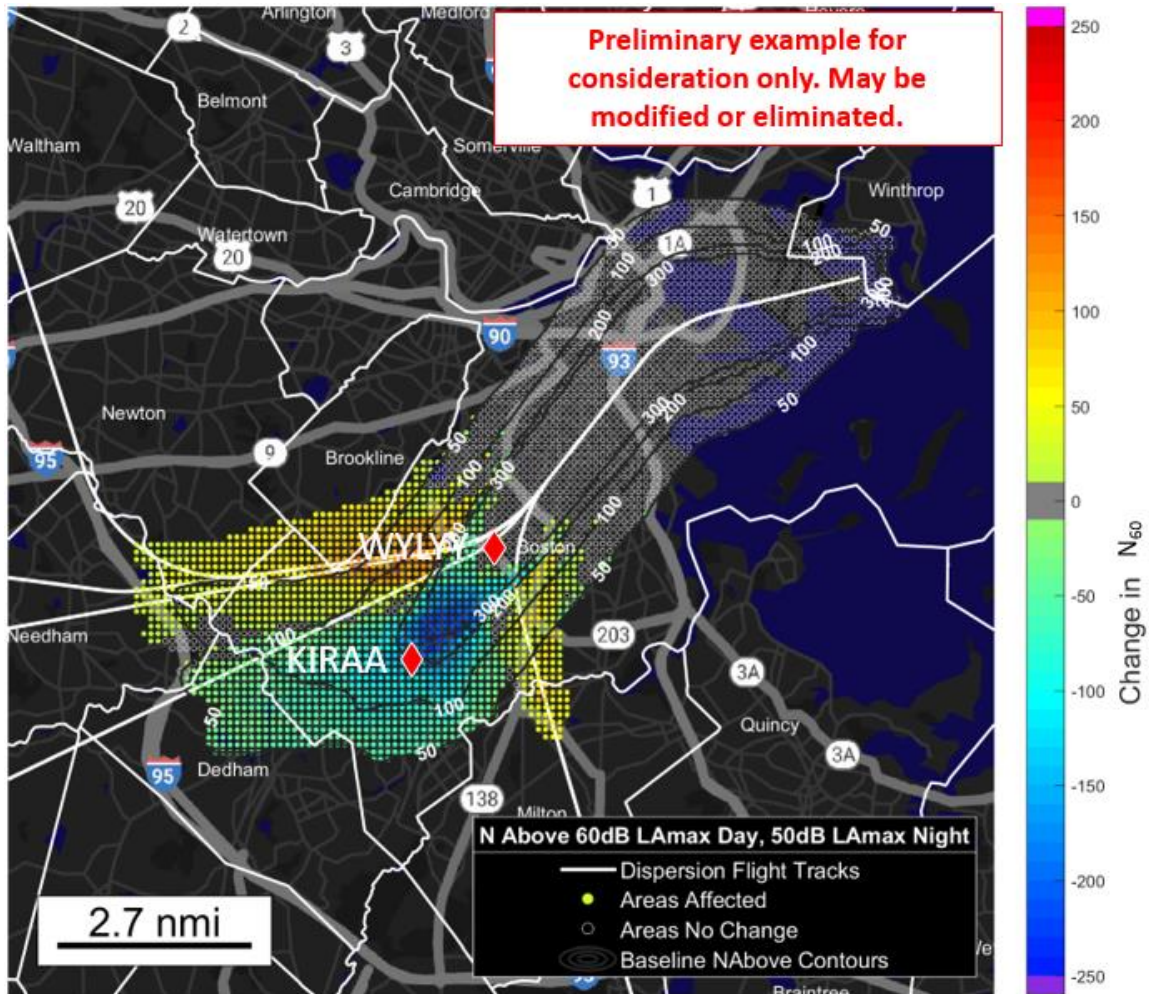
The 27 RNAV departure procedure is designed to overfly the community between the waypoints WYLYY and KIRAA. However previously with dispersed flight tracks, this community would receive some relief. This community is also fairly population dense. This concept of RNAV turning waypoint relocation is the change the flyby waypoint in the RNAV departure procedure from KIRAA back to WYLYY, as shown in the flight tracks in Figure D11. This concept would result in a population exposure decrease of almost 19,000 people to the impact threshold level of 50 overflights at the N_{60} level on a peak day, as shown in Table D6. Figure D12 shows how the community between the waypoints WYLYY and KIRAA would receive a reduction of about 200 overflights from this concept.



Figure D11. BOS 27 Departures RNAV Turning Waypoint Relocation Flight Tracks

Table D6. BOS 27 Departures RNAV Turning Waypoint Relocation Population Exposure to 50 Overflights at N₆₀ on a Peak Day

N ₆₀	50x
Baseline 2017	407,357
Dispersion	388,449
Baseline - Dispersion	18,908



Analysis based on peak day operations; only includes 27 departures

Figure D12. BOS 27 Departures RNAV Turning Waypoint Relocation Change in N₆₀ Overflights on a Peak Day

Appendix E Dispersion Histograms

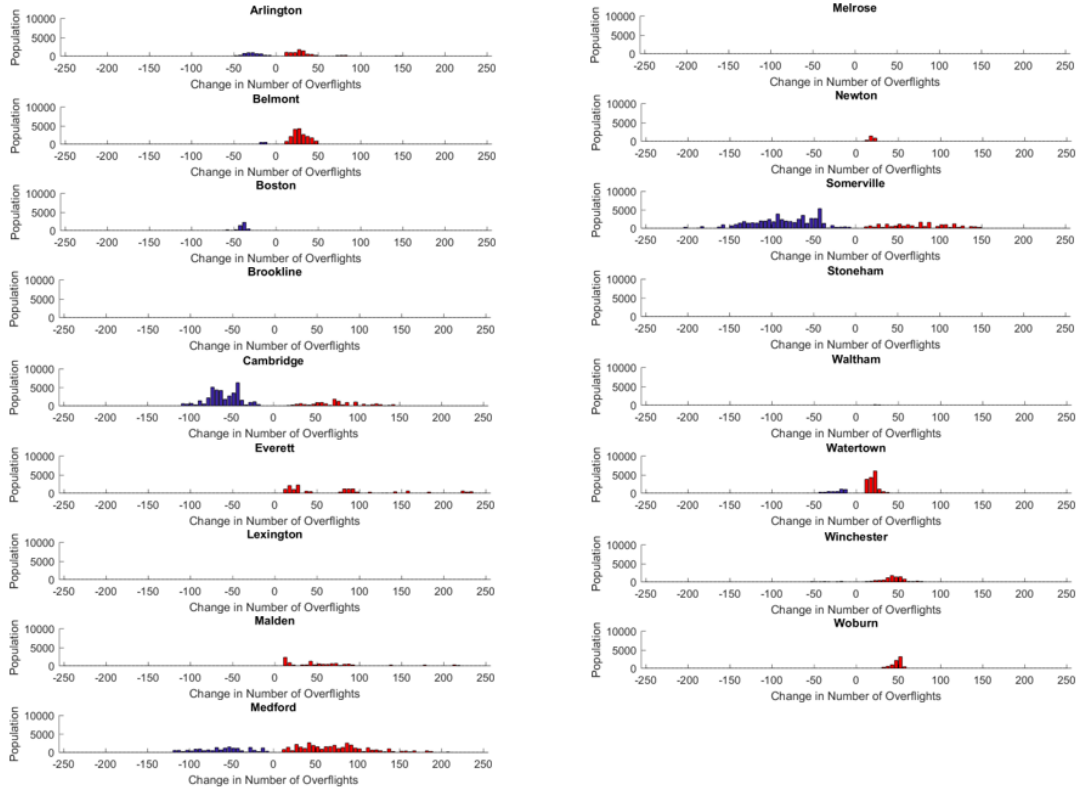


Figure E1. BOS 33L Departures Pre-RNAV to RNAV Comparison Histograms

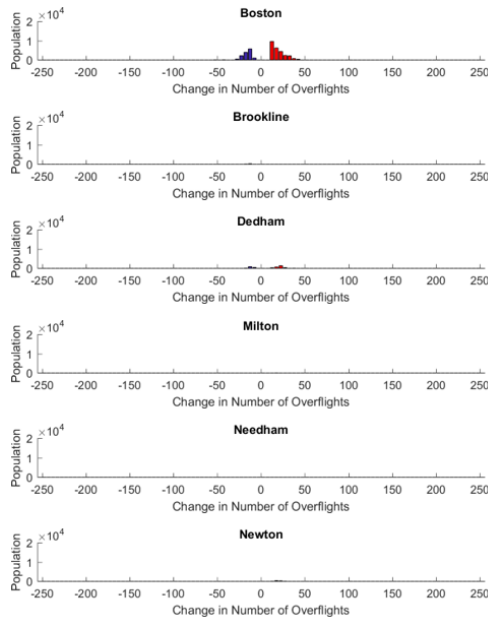


Figure E2. BOS 27 Departures Pre-RNAV to RNAV Comparison Histograms

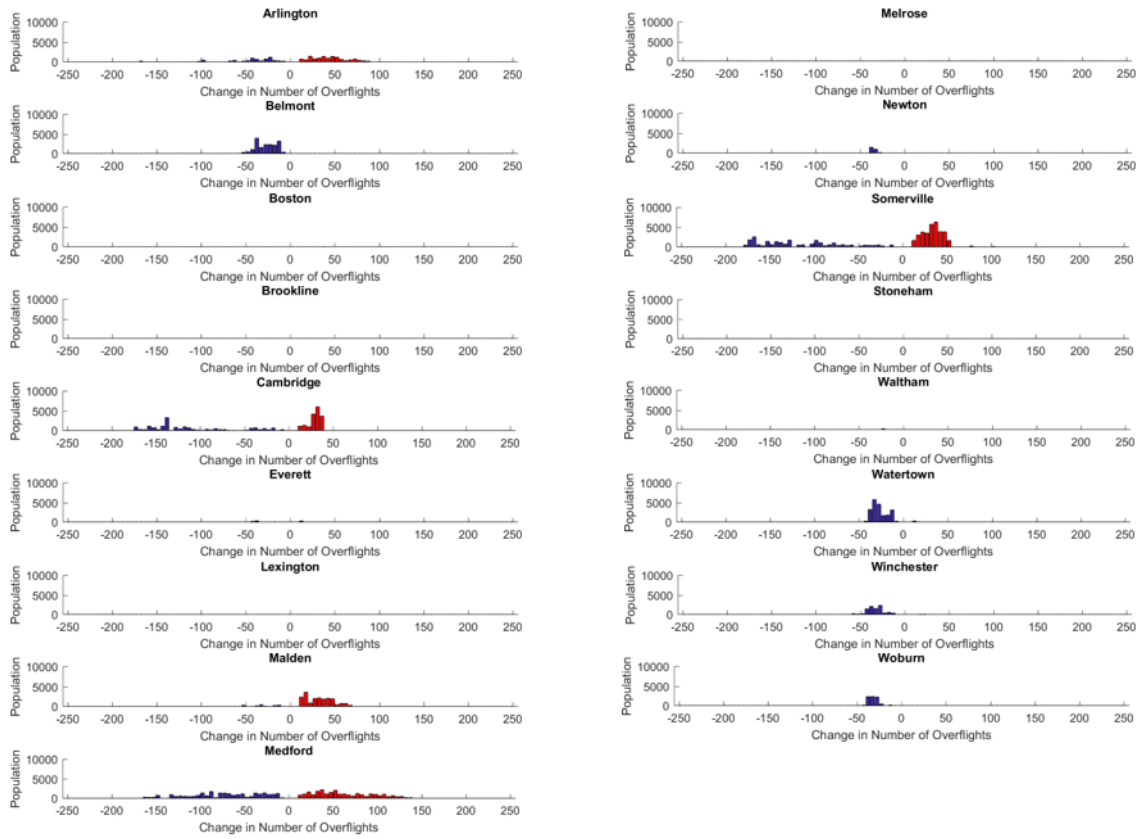


Figure E3. BOS 33L Departures Altitude-Based Dispersion at 3000ft Histograms

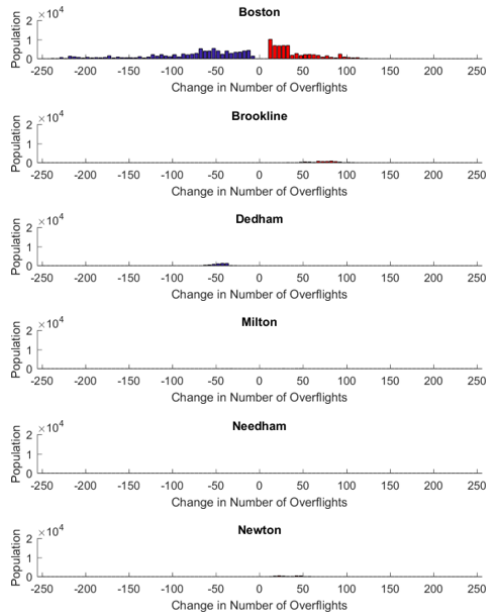


Figure E4. BOS 27 Departures Altitude-Based Dispersion at 3000ft Histograms

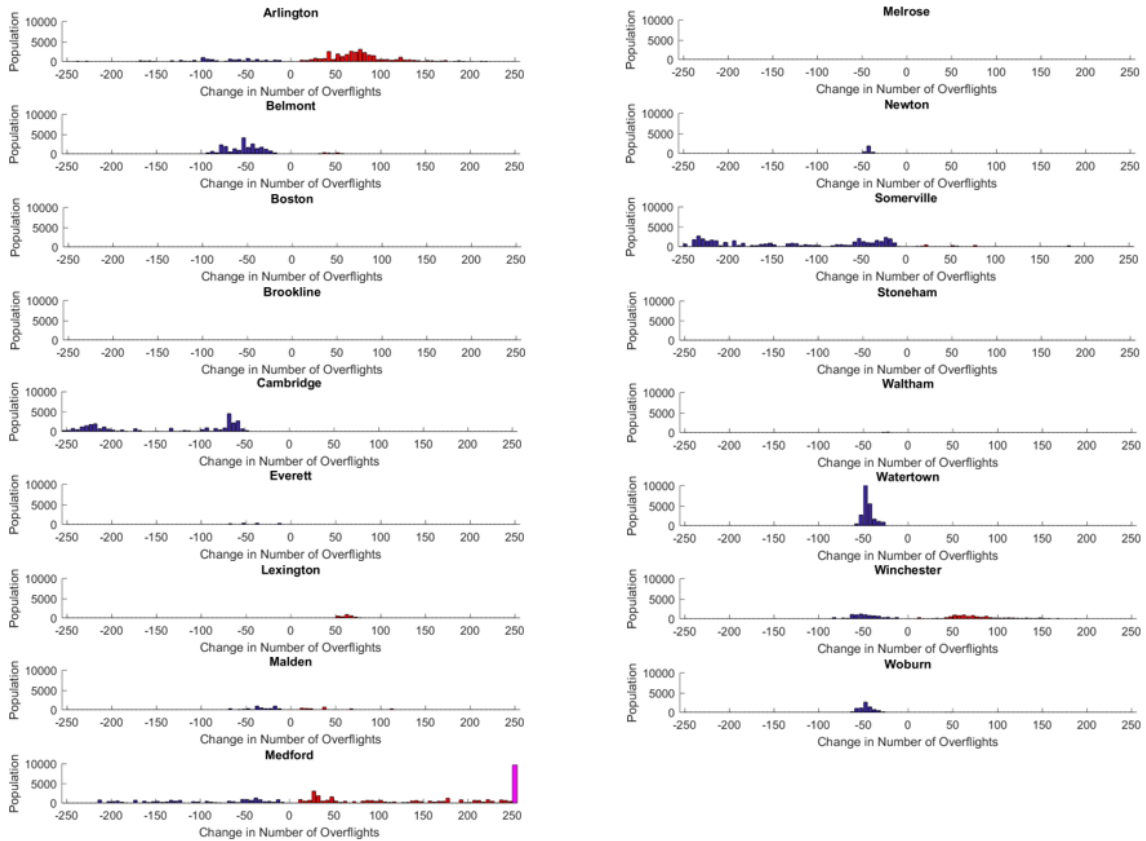


Figure E5. BOS 33L Departures Altitude-Based Dispersion at 4000ft Histograms

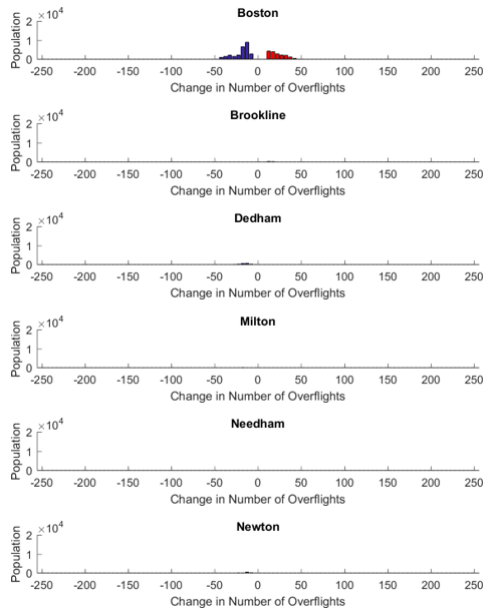


Figure E6. BOS 27 Departures Altitude-Based Dispersion at 4000ft Histograms

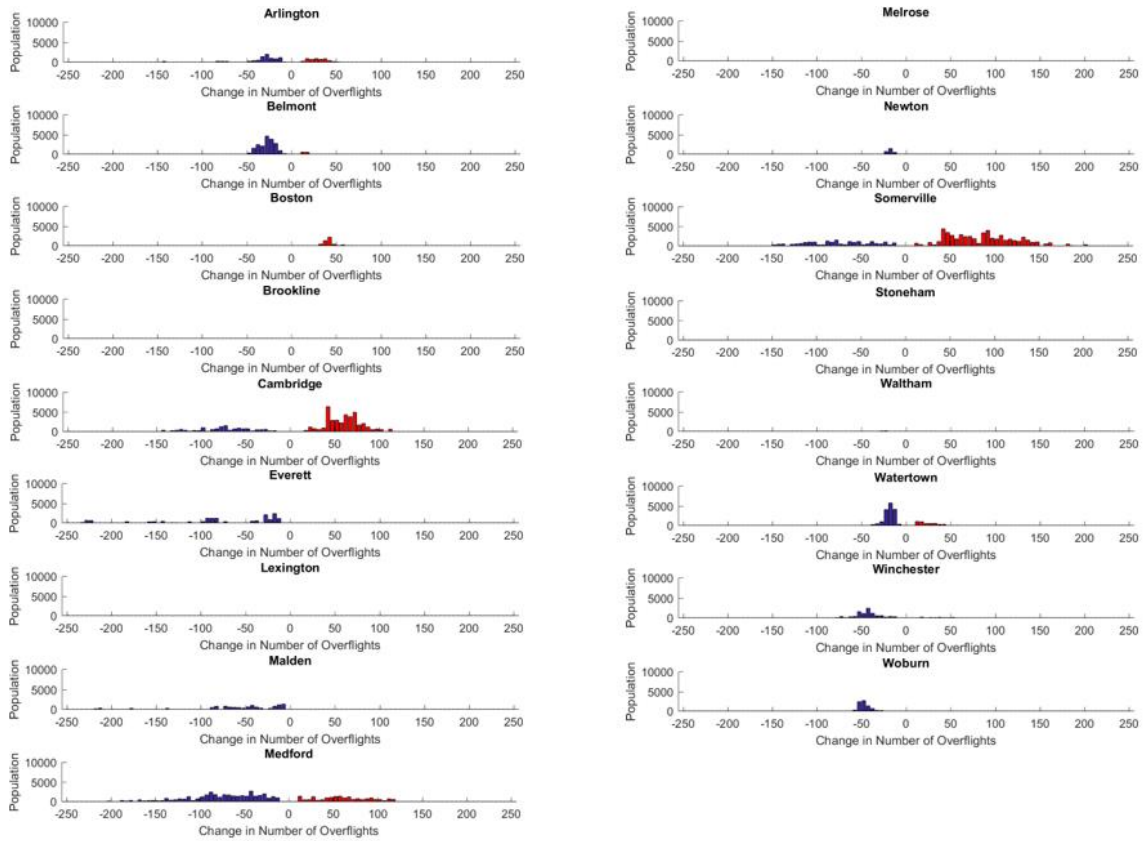


Figure E7. BOS 33L Departures Controller-Based Dispersion Histograms

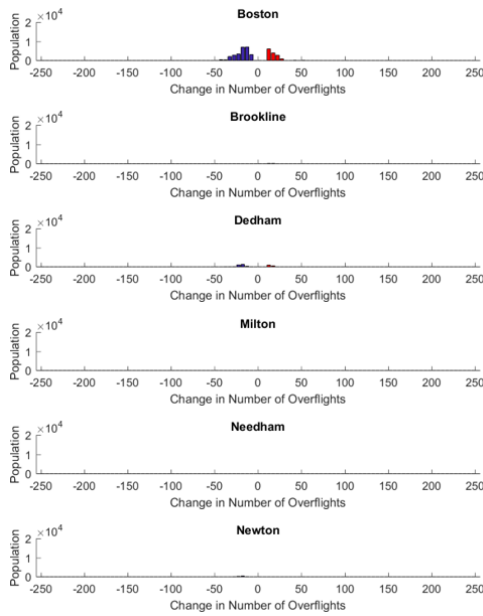


Figure E8. BOS 33L Departures Controller-Based Dispersion Histograms

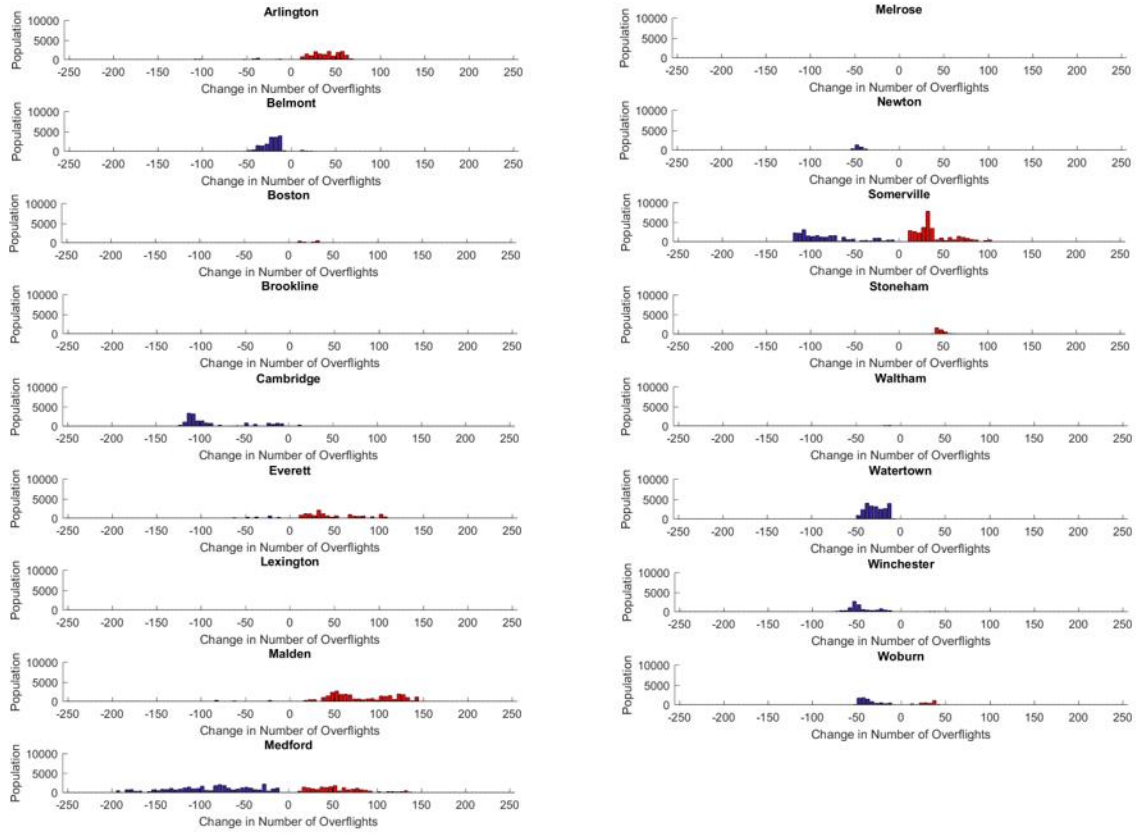


Figure E9. BOS 33L Departures Divergent Heading Dispersion Histograms

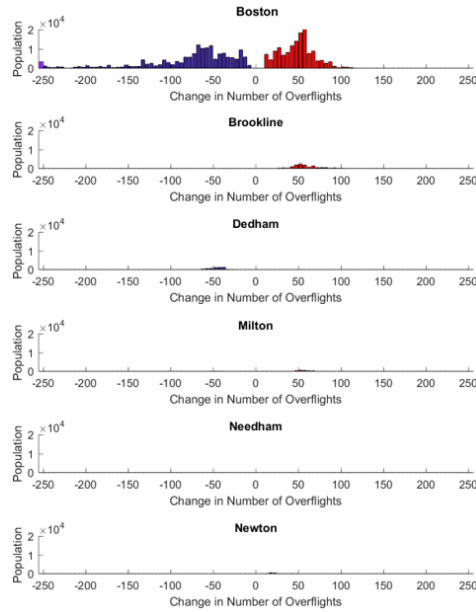


Figure E10. BOS 27 Departures Divergent Heading Dispersion Histograms

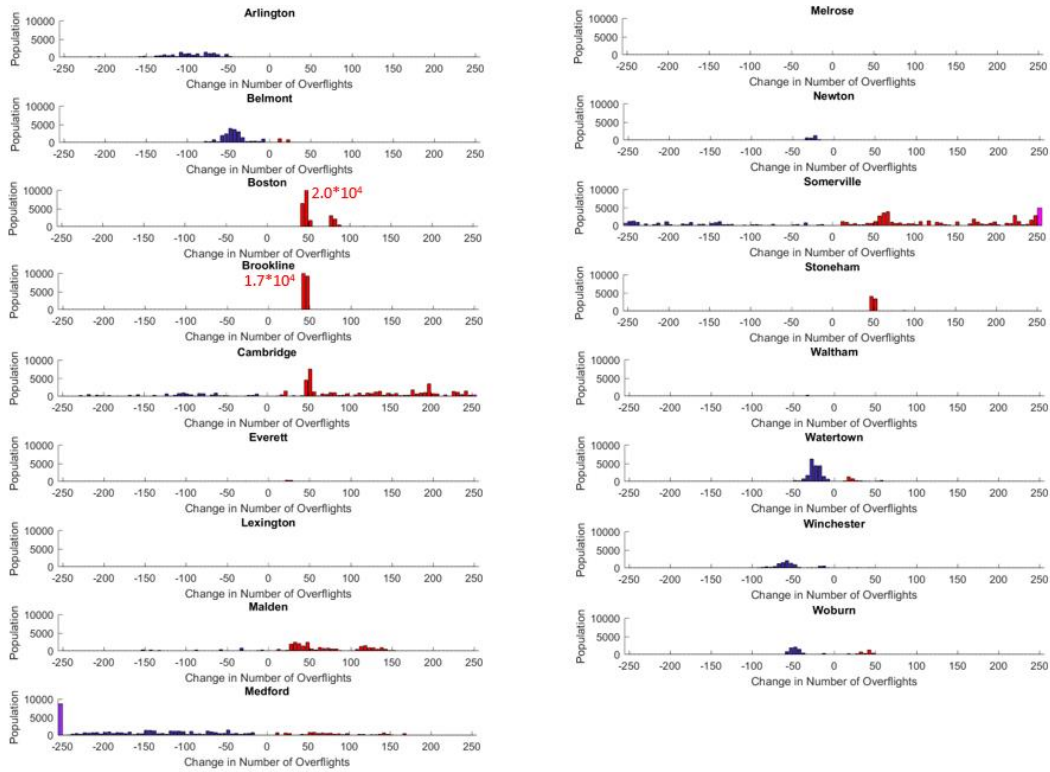


Figure E11. BOS 33L Dep. RNAV Turning Waypoint Relocation -1nmi Histograms

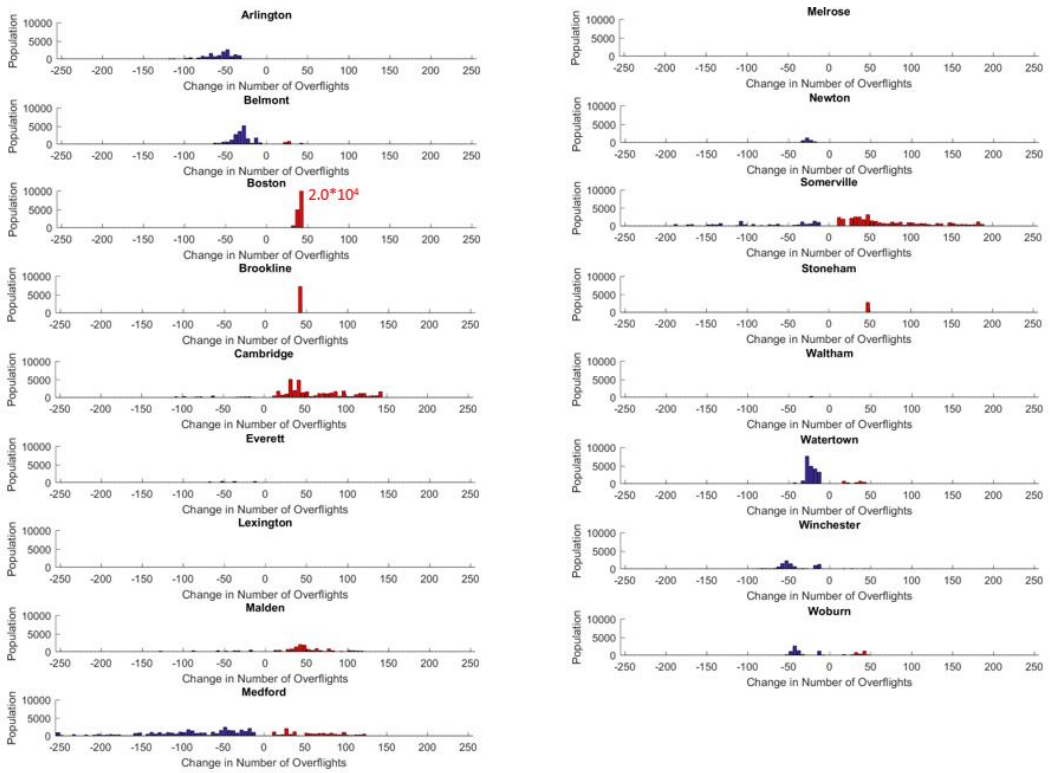


Figure E12. BOS 33L Dep. RNAV Turning Waypoint Relocation -0.5nmi Histograms

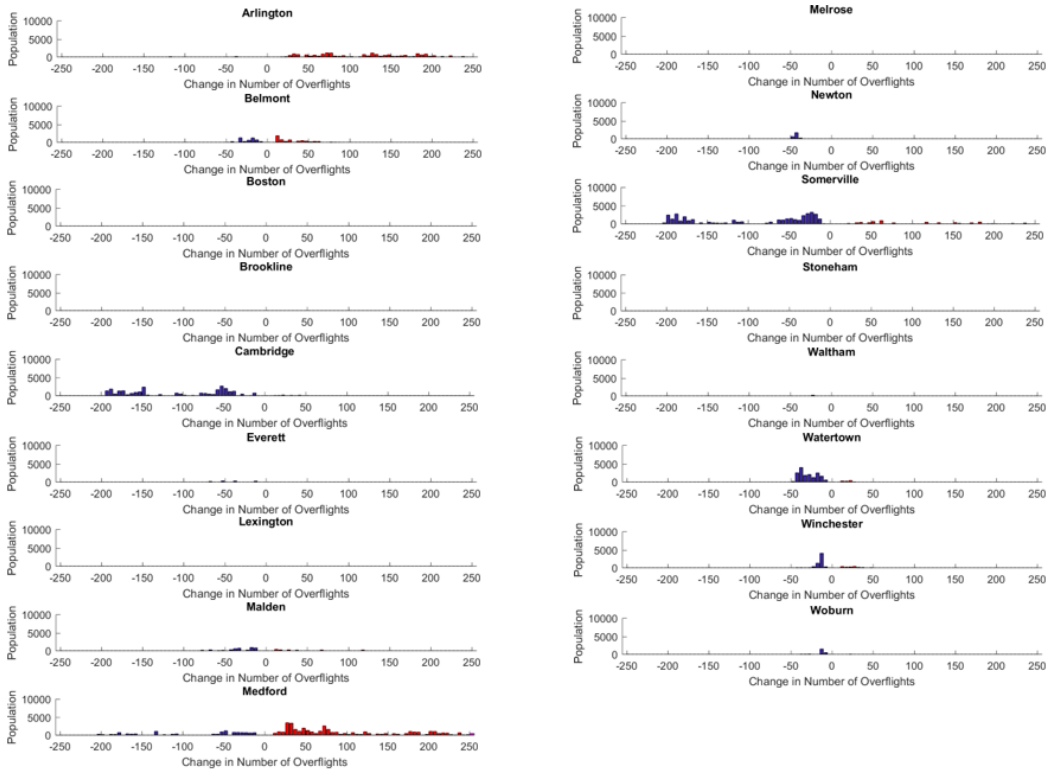


Figure E13. BOS 33L Dep. RNAV Turning Waypoint Relocation +0.5nm Histograms

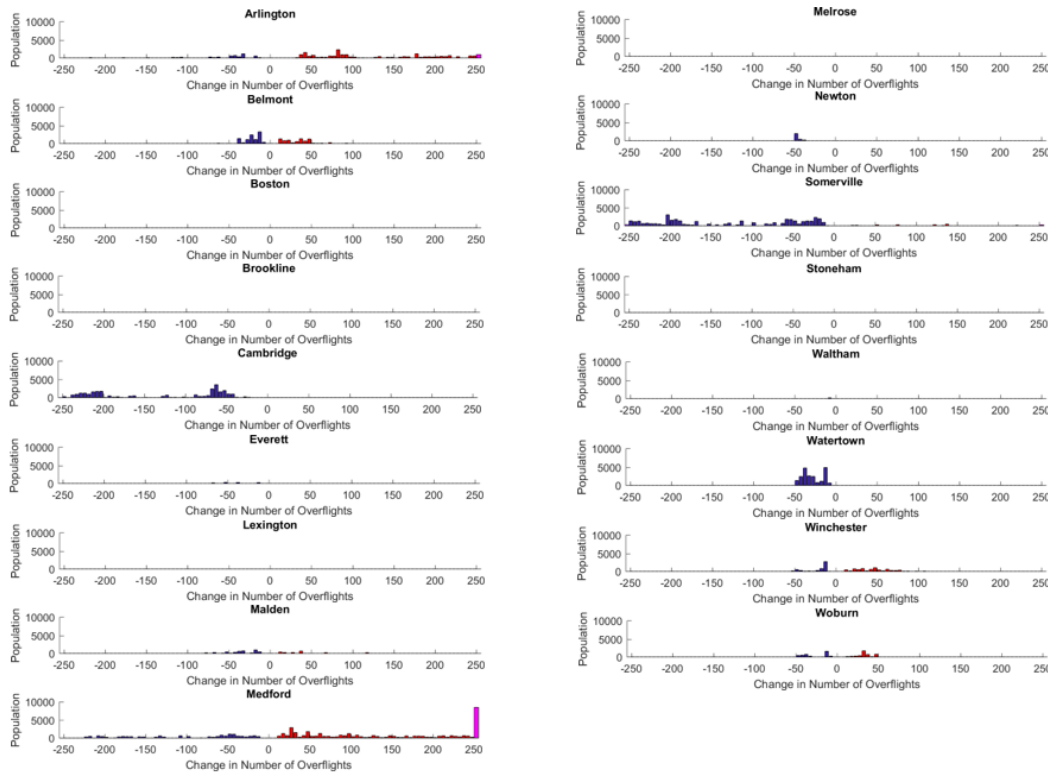


Figure E14. BOS 33L Dep. RNAV Turning Waypoint Relocation +1nm Histograms

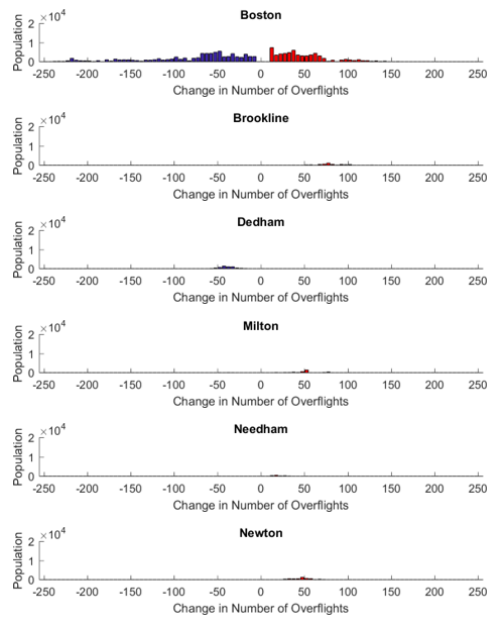


Figure E15. BOS 27 Departures RNAV Turning Waypoint Relocation Histograms