An Analysis of Enhanced Traffic Management System Data Using Three Dimensional MATLAB Visualizations

by

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Contents

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ABSTRACT

In this thesis I use MATLAB visualizations to analyze right patterns over major airports. I will analyze capacity constraints on some of the nation's most congested airports, and define flight paths that converge on them using these MATLAB visualizations. I will also analyze the air traffic patterns over a specific number of sites around the United States where a change in plane surveillance technology is scheduled to occur.

2 Motivation

The goal of this thesis is to develop and document air traffic visualization methods in MATLAB. This will be done for two major applications: to analyze the airspace above congested airports, and to get a demographic view of traffic around sites where new air traffic surveillance technology is scheduled to be implemented.

The first application of the visualizations, at congested airports, is necessitated by predicted increases in air travel demand that are larger than predicted growth in capacity. As demand for air travel continues to increase, the number of U.S. flights has and will be constrained by the capacity tolerances of the nation's airports. As a result of this, airports have a large incentive to increase airspace allowances, which raises overall revenues and can help satisfy the increasing demand. One method to increase capacity is to identify parts of the airspace that are underutilized. Another method involves analyzing groups of similar flight tracks as a whole as they make a tube or cone approaching the airport. Isolating and quantifying these flight tubes is critical in determing the capacity potential of a section of unused airspace. Once the tube boundaries are defined and quantified, the tubes can possibly be repositioned in ways that maximize the capacity of that airspace.

The second application is motivated by the FAA's plan to introduce a new plane tracking system to 6 locations across the United States. This new system, called the Automatic Dependant Surveillance–Broadcast (ADS-B) system, is a complete change in surveillance type. Currently, primary and secondary radar installations measure the locations of aircraft with radar sweeps. Radar systems use electromagnetic waves bounced off the target to determine position, and recquire multiple data points to determine velocity changes. The antenna beam width increases the farther it gets from the antenna, resulting in less accurate data for planes that are far away [1] Poor calibration or mechanical failures can also result in inaccurate readings, and if a plane is out of range, it will not be identified at all.

The ADS-B system will rely on accurate satellite navigation systems, such as GPS (Global Positioning System) to give exact readings of a plane's location and velocity. This information, along with flight parameters derived from the aircraft, is compiled by the plane's onboard ADS-B system broadcast once a second and broadcast to ADS-B systems on the ground, or to other aircraft equipped with the technology. Velocity changes can be determined with each broadcast, and are noted in the state

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[1] http://adsb.tc.faa.gov/ADS-B.htm

vector report. [2] This allows for much more accurate plane surveillance.

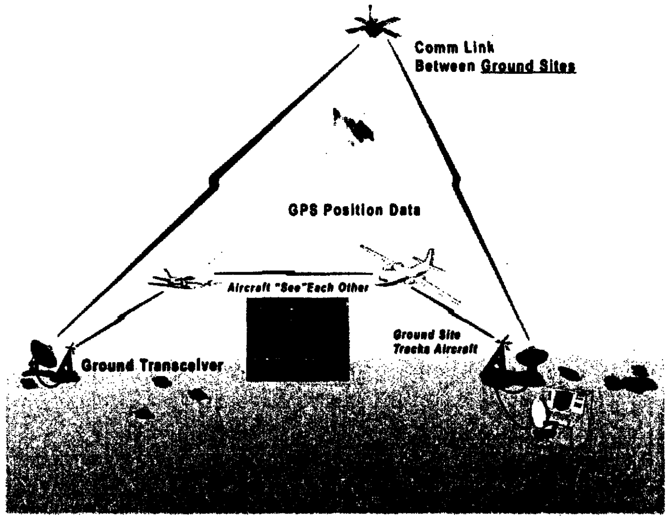

Figure 1: How ADS-B works[3]

The Federal Aviation Administration has determined a number of sites for primary installation of ground ADS-B technologies, called 'Segment 1'. Besides improving communication and surveillance techniques in the service volume of the site, these seven sites will provide the FAA valuable information about the process of installing ground ADS-B technology, and will be used as the cost estimate basis for implementing ADS-B technology on the national level. [4] Once this process is complete, Segment two will begin, which will include installing ADS-B technology at new sites that have yet to be chosen.

In planning the next steps for ADS-B, the FAA must select among numerous potential candidates for Segment two sites. The segment 2 locations will be selected based on their potential enhancement to the existing (i.e. Segment 1) ADS-B infrastructure. In order to determine the benefit of the potential segment 2 sites, the traffic patterns of the Segment 1 sites must be analyzed. Where flights from Segment one sites are going, which airlines run them, what manufacturers equip them, and where (if at all) communications seem to break down are all important questions that have a direct impact on which potential Segment 2 sites will be the most attractive.

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[2] http://adsb.tc.faa.gov/ADS-B.htm

[3] http://www.ads-b.com/home.htm

[4] "Surveillance and Broadcast Services Project Management Plan," Federal Aviation Administraion, January 10, 2007. page 21

3 Objectives

The ultimate objective of this thesis is to develop methodology used to analyze the airspace of two congested airport systems and two sites where ADS-B technology will be installed. These methods will utilize three dimensional MATLAB visualizations. Furthermore, the purpose is to document this process in a concise and understandable manner, in the hopes that it might be performed similarly or improved upon in analysis of new airspaces.

One method used to analyze airspace above congested airports will define and quantify flight tubes using the visualization process. Ultimately, this kind of analysis might serve as a framework upon which to increase the capacity of our nation's major airports.

Another objective is to develop a method for analyzing traffic patterns over two major ADS-B sites, in order to assist the FAA in choosing which sites are right for Segment 2 ADS-B installation,. An extensive demographical view of the historical traffic in these areas will be produced, and this information will be analyzed with the FAA's goal of immediate value generation in mind. Overarching trends will be identified and discussed, and the analysis will take into account each sites unique purpose and demands.

4 Background

Between 1978 to 2000, the number of plane passengers more than doubled, from 294 million in 1978 to 706 million six years ago, and continues to rise.[5] The number of airports has also increased, as every decade more airports are built to service the same major metropolitan areas. Airports must be continually built to shift demand as our most congested airports near capacity.

Despite having new airports to share the load, the increases in demand have left many major airports struggling to find enough airspace and time to fit necessary additional flights. These capacity constraints have led to increased service to other nearby airports both to defray traffic and to satisfy peripheral demand. The use of these secondary airports has increased greatly in recent years and is expected to continue.

As air traffic controllers monitor flight paths, they must account for all nearby flights to avoid disaster. When two airports are close together, their traffic can greatly affect the other's routing procedures. In most cases, flights headed to or from nearby airports will be a consideration. In extreme cases, flights to adjacent airports severly limit the options of the air traffic controller, and can ascerbate existing congestion problems.

Thus, in order to analyze spatial capacity constraints the flight patterns of both the secondary airports and the major airports must be studied in tandem. From here on they will be referred to as airport 'systems,' which has been defined as a major airport (one of the top 30) and any airport within 50 miles, as shown in figure 2 below. [6]

The 30 largest airports can then be formed into 26 systems, due to the existence of multiple major airports in the NYC (LaGuardia, Newark, JFK) and Washington (Dulles, Reagan, Baltimore) areas . The 26 systems are shown in figure 3 below.

In the next two decades, passenger traffic is projected to increase anywhere from 180 to 240 percent [9], and aircraft operations are expected to double as well. In order to help deal with these demands, the Federal Aviation Administration has created a

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[5] Bonnefoy P. A. Hansman R. J. "Emergence of Secondary Airports and Dynamics of regional Airport Systems in the United States" Report No. ICAT-2005-02, May 2005

[6] Bonnefoy & Hansman, p. 4

[7] Bonnefoy & Hansman, p. 2

[8] Bonnefoy & Hansman, p. 3

[9] FAA p. 4

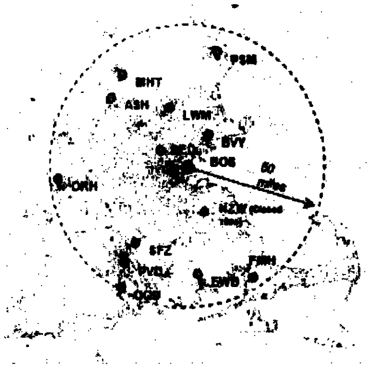

Figure 2: Boston Airport System [7]

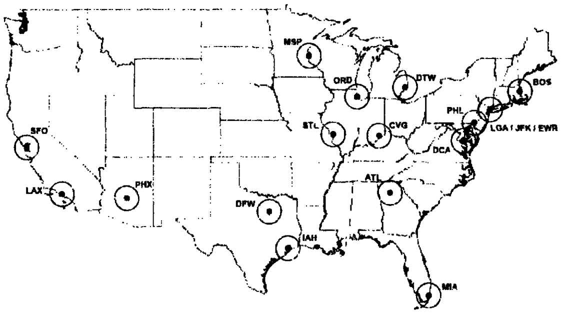

Figure 3: United States Airport Systems [8]

plan for implementation of Automated Dependent Surveillance-Broadcast technology at a number of sites around the country.

ADS-B technology is a simple concept. Instead of measuring the range and bearing with a rotating antenna, an ADS-B system recieves an accurate broadcast from the plane itself, which declares any useful piece of information regarding the plane's structure and exact position.[10] Other planes can recieve the broadcast as well, and may use the information for a variety of purposes. This is all made possible by improvements in communication data links, surveillance techniques, and perhaps most importantly the advent and accuracy of GPS (Global Positioning System) technology.

The proposed sites are Ontario, CA, Garden City, KS, North Platte, NE, Philadelphia, PA, and one site in the Gulf of Mexico. Figure three below shows the locations of each of these sites.

While all of these sites will implement some form of ground ADS-B surveillance

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[10] http://adsb.tc.faa.gov/ADS-B.htm

[11] FAA p. 23

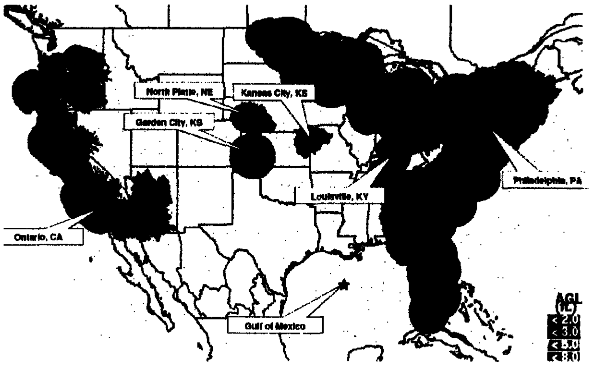

Figure 4: Segment 1 ADS-B locations[11]

technology, varying purposes subdivide the locations into three groups: Loiusville and supporting sites, the Gulf of Mexico, and Ontario/Philadelphia.

The Louisville, KY airport is home to the United Postal Service's (UPS) package processing hub, an is an extremely important part of their service infrastructure. In an effort to improve their efficiency, UPS has begun to install ADS-B technology independently. This offers an oppurtunity to install ADS-B surveillance equipment on the ground without needing an FAA mandate to insure its use. The information gathered by the new technology will be used by UPS to optimize both air and ground operations at the airport. In order to optimize route efficiency and provide accurate arrival predictions, upstream data points are necesary, and will be provided by the Kansas City and North Platte sites.[12]

The Philadephia, PA and Ontario, CA ADS-B installations will also be substantially involved in helping UPS maximize efficiency in both its east and west coast operations respectively. Similarly to Loiusivlle, the ADS-B data will transmitted to the UPS operation center for optimizatoin of ground operations, crew scheduling, and flight routing.[13]

The Gulf of Mexico ADS-B site, however, will be installed for different reasons. The Gulf presently has poor communication, airplane surviellance, and weather reporting. Much of this is due to the remoteness of the flight areas, and the fact that RADAR systems become less and less accurate at large distances from the antenna. As can be seen in figure 4 below, radar coverage almost completely cuts out over the middle of the Gulf. Also, Mexican RADAR systems are sometimes poorly calibrated

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[12] FAA p. 22

[13] FAA p. 23

which leads to the discontinuities in the flight paths from HOU or MSY to Mexico. These communications defficiences severely limit the number of flights over the Gulf due to instrument flight rules. [14]

At high altitudes, a lack of adequate navigation and surveillance ability necessitates route seperation protocols equivalent to those in inter-continental flights (where almost no radar surveillance exists). This results in nmuerous inefficiencies. The Gulf ADS-B implementation will improve communications and result in significant improvement in Gulf high altitude operations, including more direct routing, and robustness to weather disturbances.

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[14] FAA p. 21

5 Methods

Data collected as part of the FAA's Electronic Traffic Management System (ETMS) formed the basis of the analysis. The ETMS is an aircraft tracking system updated in real time that is used by FAA air traffic control systems to manage the air traffic within the National Airspace System (NAS).[15] The data used was historical ETMS data from the date of May 24, 2003. This data is composed of radar hits updated every minute, giving position and altitude of the aircraft in range. Plane characteristics such as altitude, equipment type, origin, destination, and flight number are then combined with the latitude and longitude of the radar hits to create the ETMS data.

In order to analyze this data, code was designed to parse the data[16] and transform it into a form which was compatible with MATLAB plotting and filtering functions. Because flights are similar on a day to day basis, it was only necessary to analyze one twenty four hour period of ETMS data.

This data can be plotted in a number of different ways using MATLAB, including 2-dimensional plots, density plots, and 3 dimensional plots. Below is an example of a three dimenstional plot of all tracks passing through the Denver TRACON sector over a 24 hour period.

Figure 5: All Flights through Denver TRACON

Although two dimensional plots and density plots are useful in analyzing some trends, they do not convey variations in aircraft altitude. In order to determine how traffic patterns vary with both position and altitude, three dimensional visualizations of the traffic data were analyzed. Thus, the majority of the figures used in the analysis

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[15] http://hf.tc.faa.gov/projects/etms.htm

[16] by Jonathon Histon

are 3-D MATLAB generated plots, despite the many overhead views which appear to be two-dimensional.

The ETMS data set used contains the latitude, longitude, altitude, and static characteristics of almost every flight in the US over a 24 hour period. Due to the large size of this data set, it was necessary to filter the data into smaller parts to insure reasonable computation times. In order to accomplish this, the data was filtered first first spatially. The filtering zones used are specific airspace regions defined by the FAA, used for regulating air traffic and referred to as sectors. The sectors of the National Airspcae System (NAS) can be divided into enroute sectors or Terminal Radar Approach Control (TRACON) sectors, the later regulating airtraffic as it approaches major airport systems. The analysis was focused mainly on traffic into and around airports, and thus TRACON sectors were used to filter the data set.

Because the ADS-B installation sites are not necessarily based at an airport, and because ADS-B ground systems receive data differently then a radar-based system, the filtering system to analyze traffic around the Segment 1 ADS-B sites was slightly different. For the site where the Segment one location coordinates were accessible, circular filtering zones were created with the site at the center. These zones were then filtered around as if they were one of the FAA-defined sectors, creating a data set which was both relevant and computationally manageable.

Once the data was broken into these parts, it was further filtered for the purposes of plotting and analysis. Using a MATLAB graphical user interface program, the data could be filtered and plotted for almost any characteristic that can be extrapolated from the ETMS data. The specific filtering methods used in the analysis are included in the results section, and varied based a number of factors. The plots of ADS-B zone data were more often filtered demographically, to show what the benefits of equipping more sites or lines of aircraft might be in Segment 2. The plots of congested TRACON sector flight patterns were filtered based on headings and alitudes, in an effort to define and quantify the flight tubes that consume the airspace.

6 Results and Analysis

6.1 ADS-B Zones

6.1.1 Gulf of Mexico Site

The plots of the ADS-B zones were made first by filtering the data for the particular Segment 1 site, and then by various flight characteristics. To do this the the data was filtered for flights passing through zones around each proposed site that approximated the coverage area of the ADS-B sites and were cylinders with radius of 100 nautical miles. These zones had to be defined, and this process was an important step in the analysis. The process will be described below before the demographic results are shown.

The first step towards creating the filtering zones was to define the cooridinates of the cylinder's center axis. In order to obtain the most relevant results, the filtering zones were placed directly on top of the ADS-B sites, with the cooridinates of the site matching the location of the sector's center. For the Louisville site, the latitude and longitude of the airport was used to center the related filtering zone. The exact location of the Gulf ADS-B site, however, is not yet known, and thus an approximation was necessary.

The possible location was analyzed from the perspective of servicing flights to offshore oil installations, a primary application of the Gulf ADS-B site. To most efficiently help small aircraft or helicopters navigate to and from these oil rigs along the Gulf coast, the ADS-B site would be placed in the center of mass of these oil platforms. In order to determine this location, a map of oil rig locations in the Gulf was reviewed. The map used for this analysis is shown in figure 8 below, with each red dot representing an offshore oil platform, and the large black circle indicating the approximate center of mass as indicated. This location was used as our estimate of the Segment 1 Gulf ADS-B location, and filtering sectors were built around it.

It turned out that this location would also service a majority of high-altitude flights through the gulf to and from South Florida. The oil rig center of mass is located almost directly on the major path between Houston and South Florida, and a filtering zone created at this point would also catch many flights from Dallas-Fort Worth. Flights from HOU and DFW constitute a majority of flights over the Gulf to South Florida. A graph of these flights made by filtering around the oil rig center of mass is shown in the figure below. This location catches many of the flights from

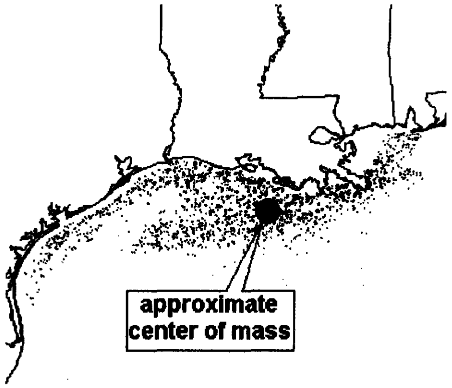


Figure 6: Coastal Oil Rig locations–Gulf of Mexico

MSY or HOU to Mexico, and MSY to South Florida as well.

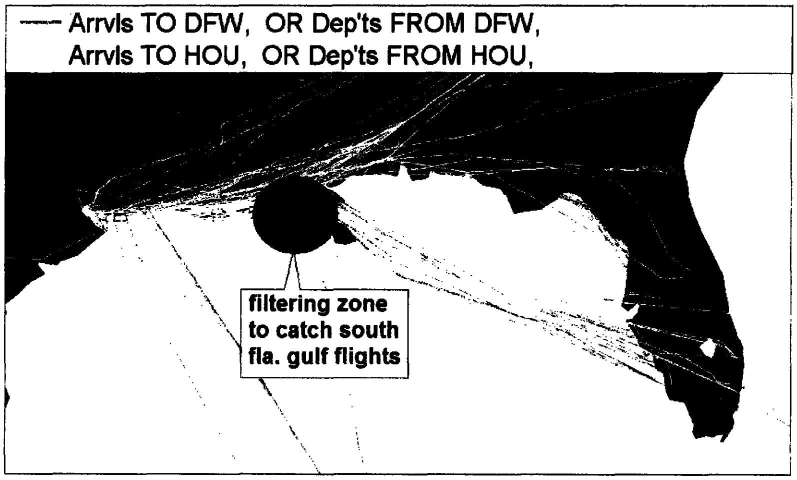


Figure 7: Dallas-Fort Worth and Houston Gulf flights

With the coordinates of the sites determined or estimated, the sectors could be created. The latitude and longitude values for each site were put into a simple excel spreadsheet to create the vertices of a one hundred point polygon approximation of a circle 200 nautical miles in diameter around the site.

Each point was then inserted into a text file which contained the definitions of the sectors. This is the file used to define the sectors boundaries, and is called upon when sector-based data filtering is performed. Each cylindrical ADS-B sector spans zero to 60,000 feet in altitude, in order to capture all flights that pass over the selected area.

Figure 8: Segment 1 ADS-B sites and Phildelphia site zoomed view

The figures above show both an up-close angled view, and overhead view of some of the ADS-B zones. The exact location of the Gulf zone is shown in figure 10 below.

Figure 9: Gulf ADS-B location estimate and resulting sector definition

Once the sectors had been created and the data could be filtered, the traffic patterns at each site were analyzed, starting with the Gulf site. In order to provide information about likely segment 2 locational candidates, and to determine which airlines and manufacturers could benefit from the technology, traffic patterns were visualized and plotted based on various demographical information.

The Gulf ADS-B zone data was first filtered by airport, so that the origins and destinations of the tracks passing over the Gulf could be understood. Flights from/to Houston (denoted IAH) are the most common, followed by flights to south florida from airports not on the Gulf Coast. This can be seen in figure 11.

These flights out of Houston's George Bush's Intercontinental/Houston Airport are the one's of particular interest, because they encompass the highest volume of the flights over the Gulf. As discussed above, most of the flights to the offshore oil rigs are out of Houston, and the higher altitude flights from Houston over the gulf are the prime candidates to install ADS-B technology. Flights from MSY to south florida, and from MSY or HOU to other locations in the US generally do not experience

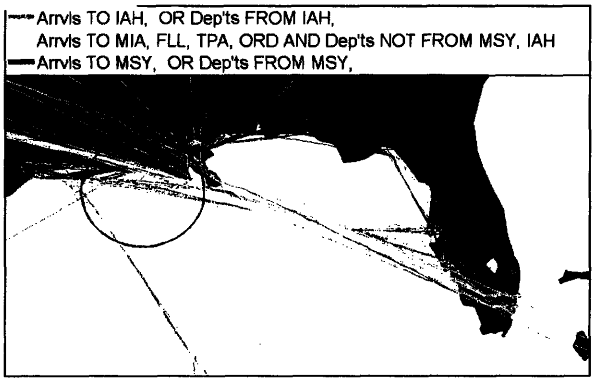


Figure 10: Gulf zone sorted by origin/destination

the communications difficulties of IAH-South FLA flights because they remain over radar-covered areas for the majority of the route. Flights from MYS to South Florida in particular are sometimes routed almost entirely over land, as shown in figure 11. This could be to avoid communications fallouts over the Gulf.

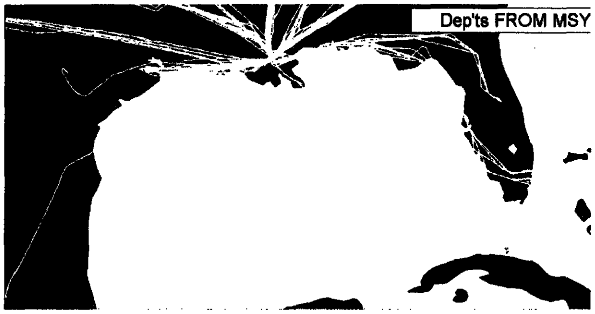


Figure 11: MSY departures

Some of the flights from MSY to Tampa and Orlando are routed in extremely inneficient paths, staying entirely over the coastline. If radar or ADS-B coverage existed in the Gulf, these flights could all fly over the water as desired. Thus, a second ADS-B site off the west coast of Florida could allow these flights to be routed over the gulf and along the shortest possible paths.

A more intensive analysis was performed on the more frequent flights from IAH to South Florida. These flights tend to be routed either ENE or SE directly out of the airport. These tracks have then been plotted against great circle (shortest distance between to points, taking into consideration the earth's curvature) paths to show what the optimal route would be from point to point.

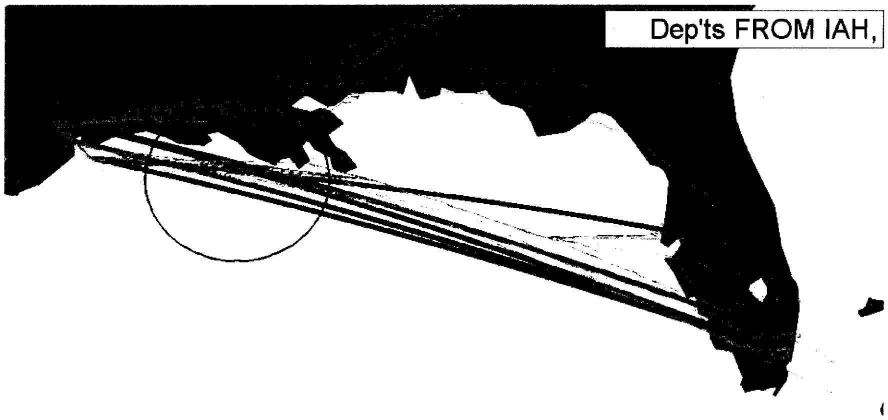


Figure 12: IAH flights versus great circle paths

The blue lines correspond to great circle paths directly from IAH to the airport of destination. The flights leaving IAH to the southeast, however, do not immediately route themselves in an ideal path towards South Fla, but rather travel a significant distance directly southeast before changing course. The red and magenta lines designate great circle paths from these rerouting points to the airport of destination. The flights plotted out of IAH stray far from these paths, traveling north of the great cirlce route regardless of whether they are bound for FLL, MIA, or ORD . There are also a few large distortions in path, possibly due to weather disturbances.

The tracks plotted into Tampa take especially innefficient routes, and seem to travel down the same track as the flights to Fort Lauderdale for approximately 70% of the trip. This results in each flight covering much more distance that would be ideal. A likely reason for this is a lack of radar coverage over the middle of the gulf. While outside of radar range, the flights into Tampa cannot effectively reroute themselves along the ideal path, and must wait for radar contact to change their heading.

These inefficiencies in Gulf air travel demonstrate the need for the sorts of improvements in surveillance and communications that will be provided by the implementation of ADS-B in the area. Almost every flight plotted from MSY and HOU took non-ideal paths, and the flights into Tampa were particularly bad. To improve the routing of these flights, improved surveillance must be installed. A second Gulf ADS-B location near the west coast of Florida would serve this purpose, greatly increasing navigational abilities in the area, and providing the accurate locational data that would enable the flights to take the most efficient path possible. This would decrease those flight times and lower operating costs, benefitting both the airline and the passenger. Thus, somewhere just off the west coast of Florida, along the dominant Gulf routes, would be the most beneficial Segment 2 installation site to the Gulf Area.

Flight tracks in the Gulf region were also analyzed for demographical patterns. The figures below show the airlines with the most flights through the area, Continental Airlines and American Airlines. These airlines which will enjoy the majority of benefits of the Segment 1 installation. These are also the airlines which would stand to benefit the most from the improved efficiencies in routing that could be attained if a second ADS-B site is created along Florida's west coast, as they are the companies which run the flights plotted in figure 12.

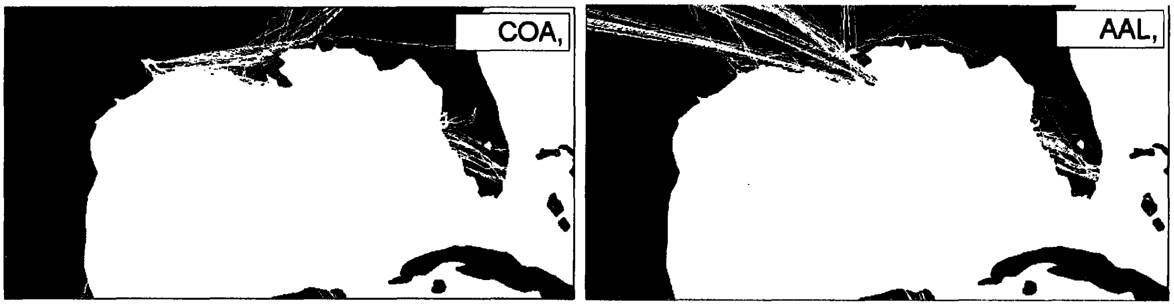
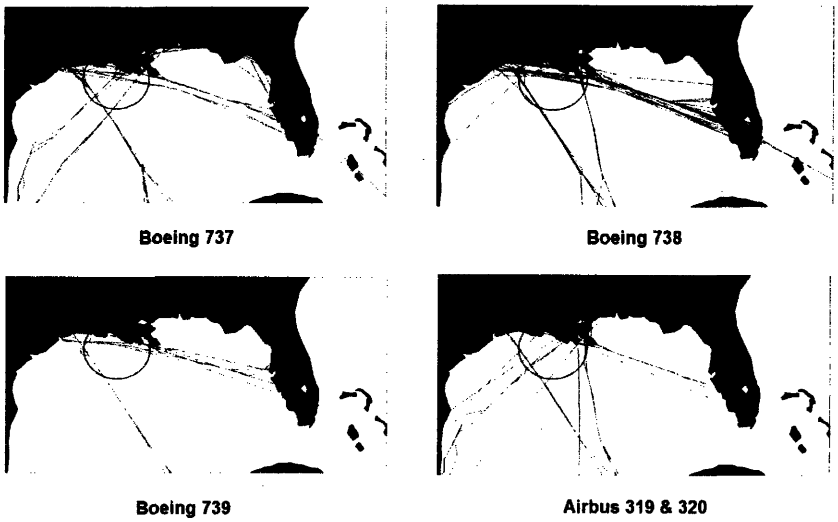


Figure 13: Continental Airlines and American Airlines flights through the Gulf of Mexico

AAL flights are most frequent from Dallas-Fort Worth to South Florida. Thus, if AAL chooses to equip their planes with the ADS-B technology to improve their flight efficiency, it would make sense for a segment two ground ADS-B location to be at DFW, in order to provide the service to the highest number of already equipped planes.

The Gulf zone flights were then sorted by manufacturer and airplane, to determine which companies would be most likely to equip their planes with ADS-B technology to make them more desirable to the Airlines. Boeing planes run by far the most flights throught the gulf, followed by planes manufactured by Airbus. This can be seen in figure 15 below.

Thus, the best locations for future ADS-B sites in the Gulf Area are off the west coast of Florida, to improve route efficiencies, and at DFW, to service AAL's gulf flights should they choose to equip their planes with ADS-B. COA and AAL are the airlines that stand to benefit the most from this segment 1 installation site, and are


Boeing 737

Boeing 738

Boeing 739

Airbus 319 & 320

Figure 14: Boeing and Airbus plane traffic patterns

most likely to utilize planes with the ADS-B technology.

6.1.2 Louisville Site

In Louisville, as described in the background section, UPS maintains its package handling hub. They have already installed ADS-B on a number of their planes, in an effort to improve the efficiency of their overall operations. To determine which segment two site would best accomodate the already-equipped UPS planes, plots were created filtering out all but the UPS flights.

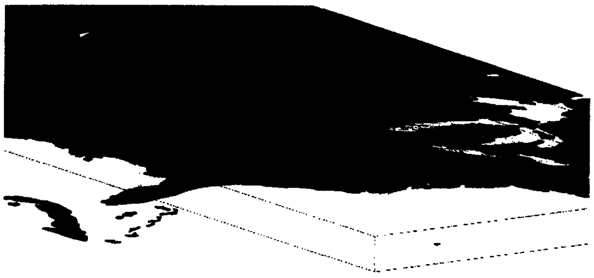


Figure 15: UPS flights

As can be seen from the plots, neither incoming nor outgoing UPS flights take a dominant route. There is not an obvious choices for a segment 2 site that would most benefit UPS in their surveillance of these flights. Many of the flights are either to the northeast, where they can be picked up by the Philadelphia site, or to the west, where the Midwest and Ontario, CA sites should provide additional coverage. There is, however, a number of tracks from Louisville to the southeast, and also to the direct southwest, that would not be picked up by any of the segment one sites (see figure 9). For this reason, possible choices for segment two installation sites is in the middle of these paths, at the Atlanta and Memphis airports. If ground ADS-B surviellance was installed at these locations, the vast majority of UPS flights could be tracked with ADS-B. The locations are shown below.

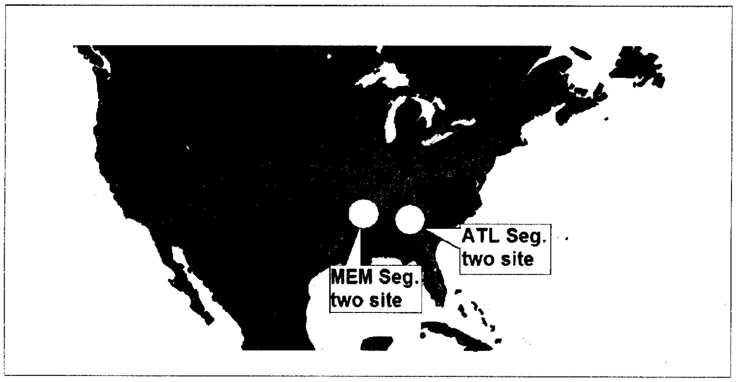


Figure 16: UPS segment 2 candidates

Once the installation at Louisville is completed, the most likely airlines to equip themselves with the technology are (based on volume of flights over the ADS-B site) COM and AAL. A plot of their flight patterns is shown below.

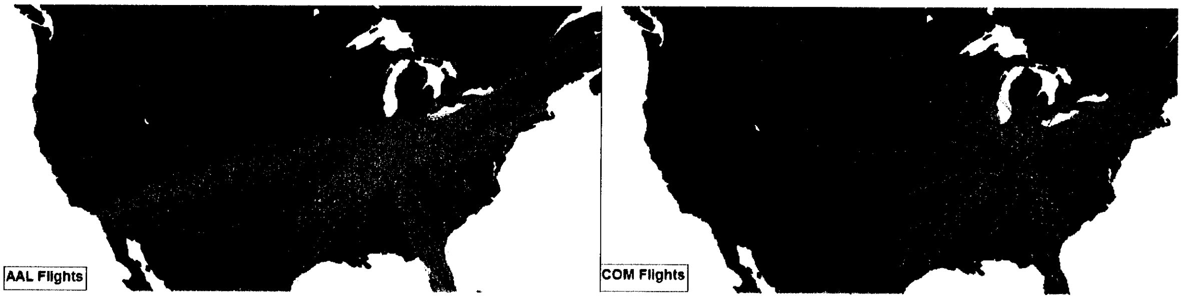


Figure 17: COM

In conclusion, there are four specific sites that would most benefit the overall ADS-B service volume if selected as the locations of Segment two installation sites.

Locations at Dallas-Fort Worth, Memphis, and Atlanta would most increase the coverage area of ADS-B without having to mandate equippage of planes flying through those areas. An installation off the west coast of Florida would allow for better Gulf navigation, and could significantly improve the route efficiency of all of the flights through that zone. The airlines likely to equip their planes with ADS-B after segment 1 installation are COA and AAL in the Gulf, and COM and AAL in Louisville.

6.2 Superdense Aiport Systems

The analysis of superdense airport systems began with a filtering process that was simpler than that of the ADS-B zone analysis. Certain sectors coincide with the airspace around a major airport system (TRACON), and these sectors were used exclusively. The New York and Chicago TRACONs were chosen for their high level of congestion and for the presence of several of major airports within each. The data was then filtered for flights through these sectors.

The quantification of tube size was done in a two step process. The first step was to distinguish individual flight tubes from one another, and the second was to quantify them. In order to discern these distinct 'tubes' of exit and entry, the flight tracks were plotted in ways that make the tubes easiest to identify and quantify. The most common filtering criteria used for this purpose were airport of origin/departure, initial/final heading, and maximum altitude. A general altitude filter can also used to isolate certain sections of a flight path, in order to visualize only a specific portion of the tube.

To begin the process of tube definition using these techniques it was determined which group(s), among all the tracks, could be considered a flight 'tube.' In order to do this, the entire sector overview had to be studied to and try to discern defineable tubes from jumbles of paths. As one gets close to the airport, tubes almost always begin to form amongst the flight paths, as flights land or take off from nearby runways (or the same runway at a different time). Once the tubes were identified, the process of measuring size as it fluctuates with altitude or ground distance from the airport was started. The New York and Chicago TRACON plots used to identify tubes are shown below. The tracks are only graphed until they reach the boundaries of the sector, to simplify the identification process.

All of the plots were made using a graphical user interface (GUI) developed in MATLAB. Many adjustments to the GUI were made during the research, including additions to aid in the identification and quantification of the flow tubes. One of

Figure 18: New York TRÅCON flights

these was a 'shapes' tab, which provided for the insertion of shapes onto the current figure. The function which made the shaded rectangles utilized MATLAB's 'fill3' command. This command creates a 2-dimiensional filled polygon in a 3-D space from a set of specific X-Y, Y-Z, or X-Z coordinates. The shapes are inserted where they will intersect a group of flight tracks, to provide a high contrast background so that the tracks in front of the shape can be seen more clearly.

When they are inserted, it becomes clear which tracks crossed the slice at that particular altitude or plane, and the size of the tube can be seen more easily. They can also be used to quantify the size of the tubes, by adjusting the size of the square until it fits completely over the entire flow tube and filtering out other altitudes if desired. In this way variance in tube size can be analyzed as they move through space. The figure below gives an example of this sort of shape insertion and altitude filtering used to demonstrate tube size relative to altitude.

To quantify the tube size, they were first separated by airport, and then by heading. Tracks of departing flights with simliar initial headings, and incoming flights with similar final headings are what make up the tubes, especially close to the airport. The size of the tube is then determined by inserting square slices of larger and larger size until approximately all the flight paths pass through it at a given altitude. This was then repeated every 1000 feet to determine the change in area relative to altitude for a given tube.

This process was completed for four tubes, two from each highly congested airport

Figure 19: Chicago TRACON flights

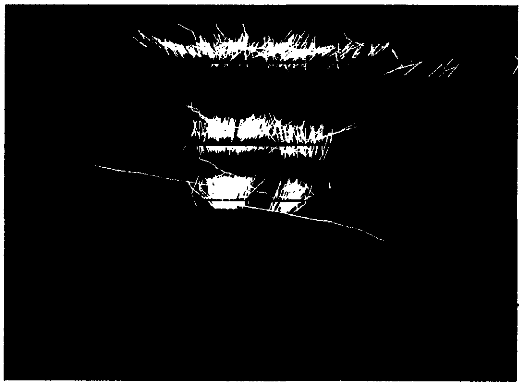


Figure 20: An example of shape insertion and altitude filtering

that was studied. A tube of arrivals and departures was quantified for both Newark and O'hare airports. The figures that resulted from this process is shown below.

The tube's were quantified up to 10,000 feet, which is the level where the tube definition begins to break down for the Newark departures . This maximum level was chosen for the other tubes as well, so that the differences in size between them all could be more easily compared.

The size of the tubes were then plotted against altitude. These graphs are shown below.

As can be seen from figures 21 and 22, the O'hare departures tube was significantly denser than the Newark tube. It was also spanned a larger area at each altitude, as can be seen from the graphs of tube size in the Appendix. This was partially the result

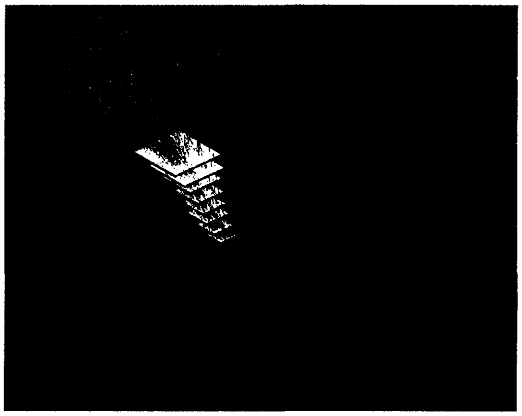


Figure 21: Newark departures tube quantification to 10,000 feet

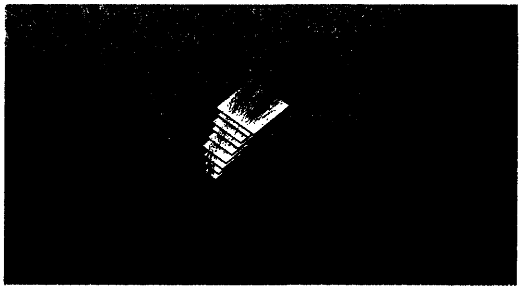


Figure 22: Ohare departures tube quantification to 10,000 feet

of a much higher number of flights plotted, with 437 individual tracks to Newark's 256. The arrivals tubes, on the other hand, were somewhat similar.

The graphs of the tube size relative to altitude may demonstrate the way in which air traffic above airports is directed. On the examined day, departing flights out of both O'hare and Newark began to be routed to their final destination immediately upon takeoff. The tube size rate of change increased gradualy but consistently, and led to a steady exponential increase in tube area as altitude increased. Incoming flights did not show a steady increase or decrease in tube size except for altitudes less than 4000 feet. For higher altitudes tube sized fluctuated almost sinuisoidally.

Figure 23: Newark arrivals tube quantification to 10,000 feet

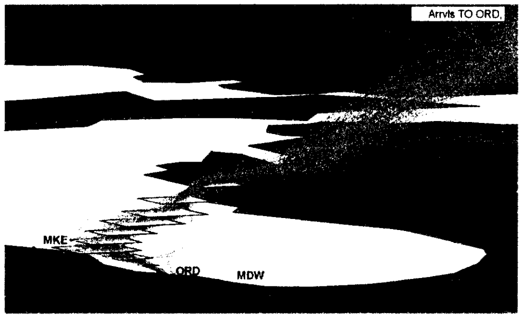


Figure 24: Ohare arrivals tube quantification to 10,000 feet

7 Future Work

The main area for possible future work on the topic would be to extend the analysis to more flight tubes, more congested airports, and all of the Segment 1 ADS-B zones. Just one tube from each airport, and two ADS-B zones were studied. This leaves many flight tubes, even in the New York and Chicago sector alone, that remain to be quantified.

The techniques themselves could also be vastly improved upon. For one, purely horizontal slices are limited to measuring tube size against altitude only. To analyze how tube size varies with latitudinal changes for example, vertical slices would have to be implemented. Ideally, the inserted shapes could be rotated to lie on any plane, and would be inserted perpendicular to the axis of the flight tube which they were intersecting. Tube size could then be measured relative to total distance traveled along the axis. This would allow for quantification of tubes of any size and orientation.

Another problem with the square horizontal slices was that tube size cannot always be well approximated by a square shape. A circle would work better, but is significantly more difficult to define and plot. The best way to define the tubes would be to create a polygon made out of the flight tracks themselves. The outermost tracks at a given altitude would define the points of the polygon, and thus the tube size would be that polygon's area.

These methods could then be applied to each flight tube at each airport system, and could be used to help maximize airspace use efficiency at our nation's airports.

8 Appendix

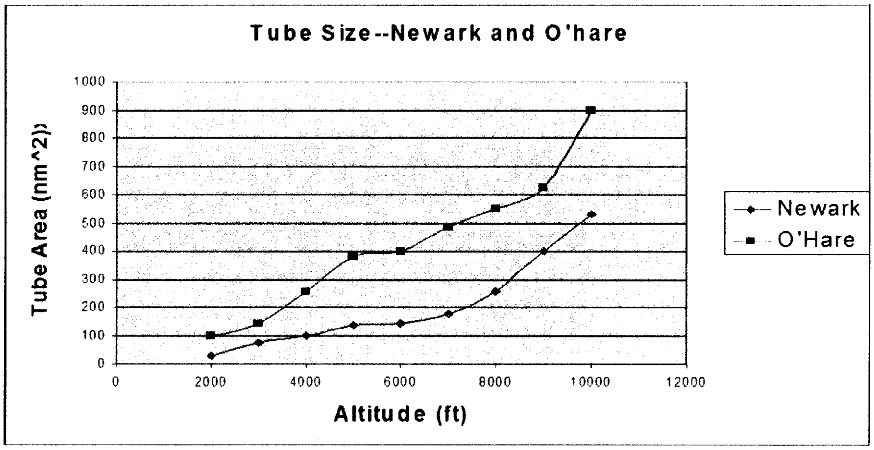


Figure 25: Departure tube areas

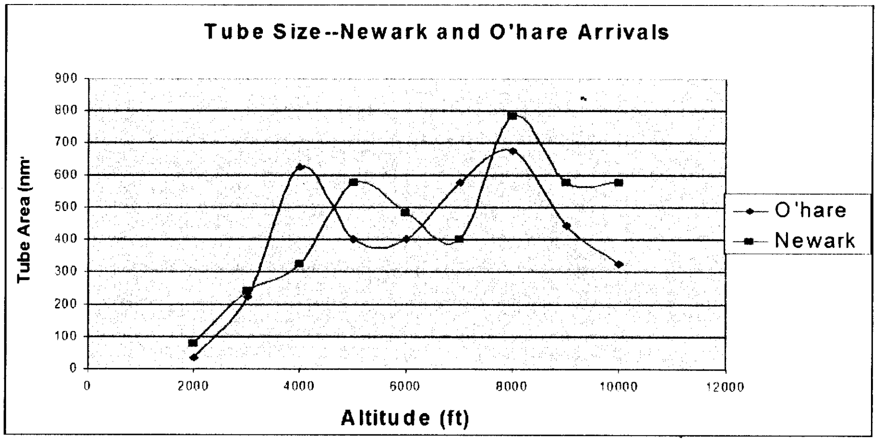


Figure 26: Arrival tube areas

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