ANALYSIS OF AIRSPACE TRAFFIC STRUCTURE AND AIR TRAFFIC CONTROL TECHNIQUES

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ABSTRACT

Air traffic controller cognitive processes are a limiting factor in providing safe and efficient flow of traffic. Therefore, there has been work in understanding the factors that drive controllers decision-making processes. Prior work has identified that the airspace structure, defined by the reference elements, procedural elements and pattern elements of the traffic, is important for abstraction and management of the traffic. This work explores in more detail this relationship between airspace structure and air traffic controller management techniques.

This work looks at the current National Airspace System (NAS) and identifies different types of high altitude sectors, based on metrics that are likely to correlate with tasks that controllers have to perform. Variations of structural patterns, such as flows and critical points were also observed. These patterns were then related to groupings by origins and destinations of the traffic. Deeper pilot-controller voice communication analysis indicated that groupings by flight plan received consistent and repeatable sequences of commands, which were identified as techniques. These repeated modifications generated patterns in the traffic, which were naturally associated with the standard flight plan groupings and their techniques.

The identified relationship between flight plan groupings and management techniques helps to validate the grouping structure-base abstraction introduced by Histon and Hansman (2008). This motivates the adoption of a grouping-focused analysis of traffic structures on the investigation of how new technologies, procedures and concepts of operations will impact the way controllers manage the traffic. Consideration of such mutual effects between structure and controllers' cognitive processes should provide a better foundation for training and for engineering decisions that include a human-centered perspective.

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Chapter 1

Introduction

1.1 Motivation

Air traffic is forecast to grow dramatically in the following years and the current system is already being pushed to the limits. In order to better accommodate this increasing demand, the Federal Aviation Administration (FAA) plans several improvements to the current National Airspace System (NAS). These improvements fit in a major program, the Next Generation Air Traffic Control (NextGen), that anticipates the increase and addition of capabilities that are expected to allow a proper response to the future needs of the United States Air Transportation System.

These modifications include improvements in communications, navigation and surveillance systems. These changes, combined with new technologies and procedural changes are likely to alter the structure of the Air Traffic Control (ATC) System.

For the purposes of this thesis, structure of ATC is defined as the framework elements, procedural elements and pattern elements of the traffic. This definition is based on observations conducted by Histon and Hansman (2008). The current structure of ATC has been mentioned by many as a primary source of inefficiencies, its major drawbacks being narrow guidelines and rigid framework (Nolan, 2011; Chatterji, Zheng, & Kopardekar, 2008; Zelinski & Jastrzebski, 2010; Kopardekar & Magyarits, 2003; Howell, Bennett, Bonn, & Knorr, 2003). It is inevitable, however, that the structure in ATC impacts the tasks, the dynamics of the air traffic situations

and the commands available to the controller (Histon & Hansman, 2008). Indeed, structure ultimately affects the cognitive processes that controllers use, generating factors that impact the mental models and abstractions.

Therefore, the transition to new concepts of operation or improvements in the NAS will be better achieved with a well-grounded understanding of what aspects of the ATC structure impact the cognitive processes of controllers. Consideration of such impacts of structure should provide a better foundation for engineering decisions that include a human-centered perspective.

1.2   Structure in the Air Traffic Control System

Histon and Hansman (2008) observed components of the ATC system and characteristics of the airspace, thereby identifying three distinct levels of the structure of ATC. These levels or layers of structure were then incorporated into a hierarchical framework, as presented in Figure 1-1.

At the base of this hierarchy is the framework layer of the structure, which is sub-divided in physical elements, reference elements and airspace boundaries. These elements (illustrated in Figure 1-2) establish the foundation and context of an air traffic situation (Histon & Hansman, 2008).

Built on the context of the framework layer is the procedure layer, which is sub-divided in published procedures and ATC procedures. Published procedures are the regulations that govern any air traffic activity. Other examples of published procedures are trajectory procedures for arrivals and departures and communication protocols. The ATC procedures, including formal and informal operating procedures. Formal procedures include the Standard Operating Procedures (SOPs) and Letters of Agreement (LOAs) that dictate how the interface between sectors should occur. During field studies, Histon and Hansman (2008) observed controllers following undocumented, or informal, procedures that imposed structure in the air traffic situation.

The elements within the framework and procedure layers are a core source of
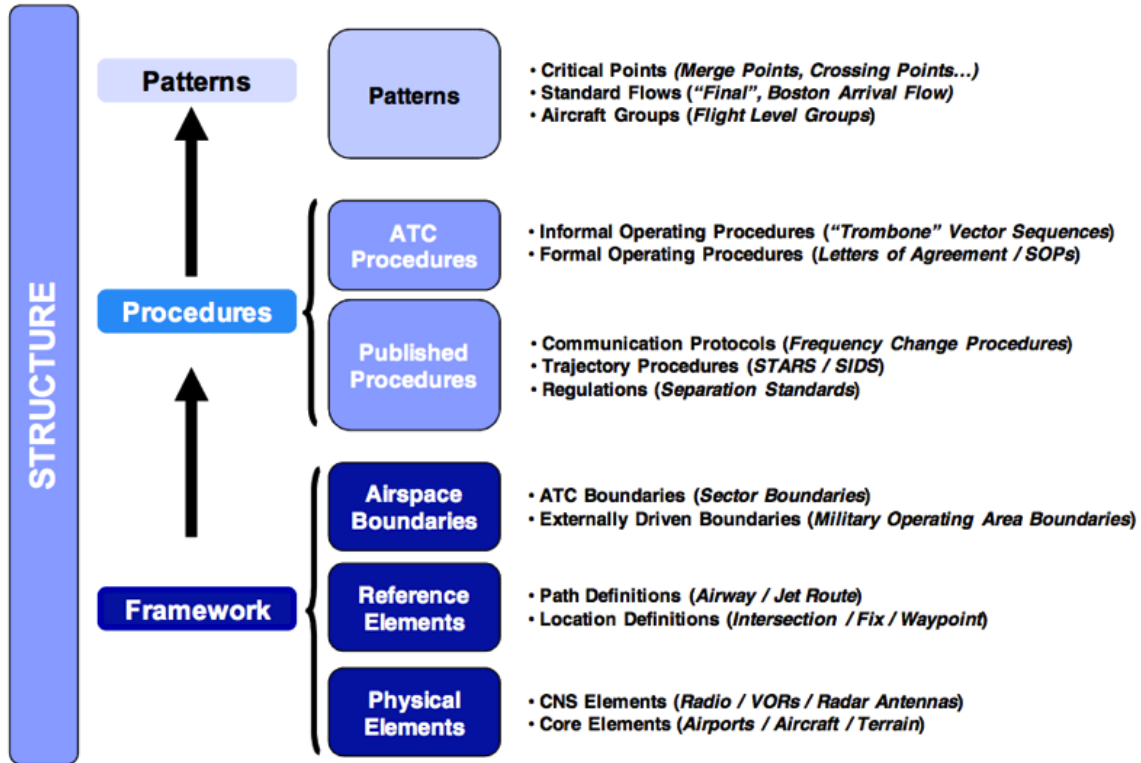
Figure 1-1: Structure hierarchy (Histon & Hansman, 2008).

the top-most layer of the structure: the patterns within the structure (Histon & Hansman, 2008). From focused interviews and visualizations and reconstruction of traffic, Histon and Hansman (2008) identified three key traffic patterns: standard flows, critical points, and groupings.

The ATC structure evolved over time in order to accommodate the increase in air traffic. For instance, in order to assist an increasing body of air traffic controllers, there was a continuous introduction of new procedures and automated systems. Hence, the current structure of the NAS is the result of engineering decisions on the design of a human-centered separation assurance system (Nolan, 2011).

An example of characterization of structure is how responsibility over the airspace is distributed. Due to the continental dimensions of the american airspace, FAA has given the responsibility of separation to Air Route Traffic Control Centers (ARTCCs) or "Centers". The Centers, in turn, are further partitioned into sectors, taking in consideration the resultant workload for managing the traffic flows. Moreover, several

elements of the framework of the structure become evident when looking to a cartographic chart of an airspace sector. Figure 1-2 presents such a chart describing Brewton High sector, Jacksonville 11 (ZJX11). For instance, in this Figure, the following elements can be noticed:

- Minimum and maximum altitudes of the sector and its surrounding sectors;

- Lateral boundaries of the sector;

- Lateral boundaries of the Center that the sector pertains to;

- Jet routes;

- Navigational fixes; and

- Different sorts of airspaces (e.g. special use, military)
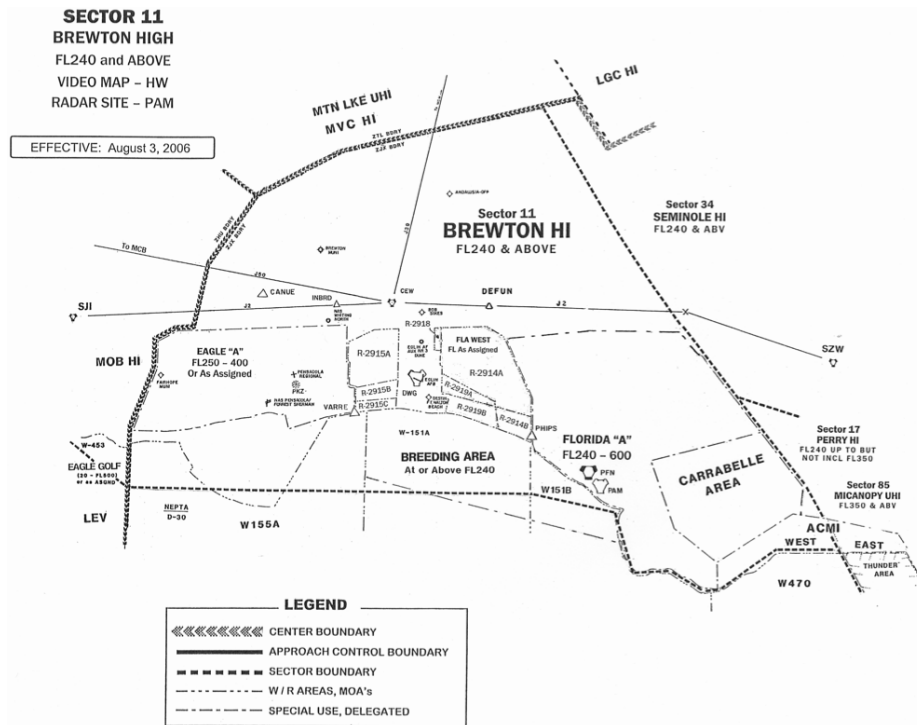
Figure 1-2: Example of structure: cartographic chart describing Brewton High sector, Jacksonville 11 (ZJX11).

1.3 Focus of Research

1.3.1 Focus: Patterns in the Structure

This thesis is primarily about how the patterns in the structure in the NAS are used by the air traffic controllers. One can refer to patterns in the structure and in the traffic in different ways. For the sake of coherence, the following convention is going to be adopted throughout this thesis:

- *Structural features* correspond to the distinct elements or pieces of the overall pattern, such as flows and critical points.

- *Structural patterns* consist on the overall pattern, the arrangement and combination of structural features.

1.3.2 Focus: High and Super High Altitude Airspace

As mentioned before, in the United States, the controlled airspace is typically divided into areas of responsibility known as sectors. A three dimensional airspace sector can be imagined as a complex union of arbitrarily shaped blocks. In this work, sectors entirely above FL340 are considered Super High, sectors with floor below FL340 and ceiling above FL240 are considered High and sectors with ceiling below FL240 are considered Low (Figure 1-3).

There are many different sectors covering the continental US, as well as oceanic airspace, from ground to 60,000 feet. Thus, the air traffic control services are provided in a wide range of operational environments, such as in different classes of airspace, positive controlled versus controlled airspace, continental or oceanic and ramp, ground, terminal and en route airspace (Belobaba, Odoni, & Barnhart, 2009). The airspaces may also feature different characteristics or elements, such as special use airspaces, prohibited areas, mix of traffic performance, local rules or procedures, terrain obstacles and even susceptibility to weather interferences (some of these airspaces can be seen in Figure 1-2). The types of decisions, working mental models, decision
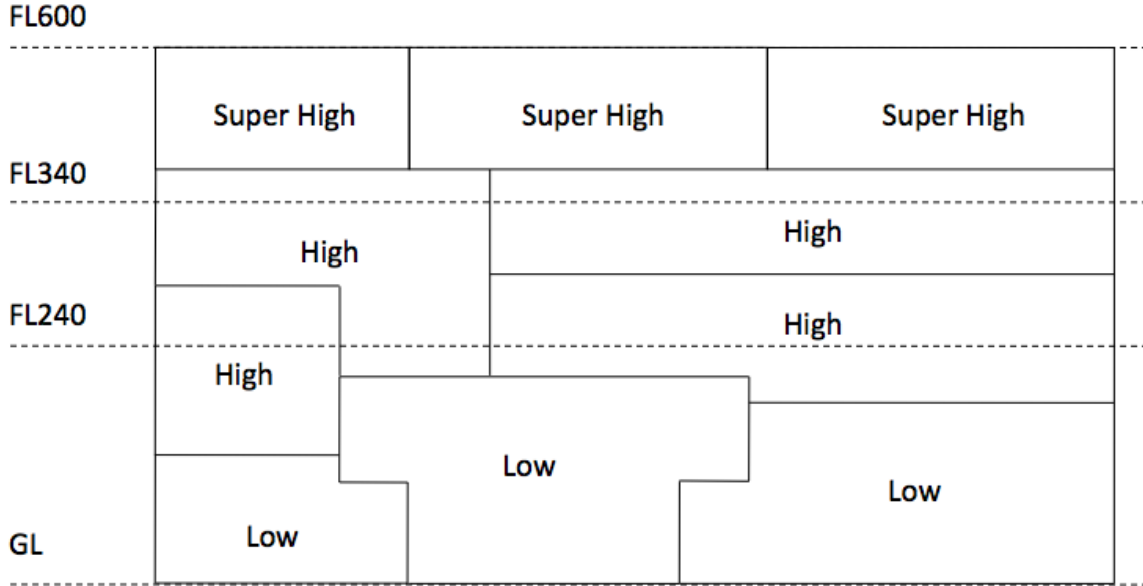
Figure 1-3: Adopted classification of airspace sectors by altitude. Sectors with floor greater or equal to FL340 are considered Super High. Sectors with ceiling greater or equal to FL240 and floor below FL340 are considered High. Sectors with ceiling below FL240 are considered Low.

support systems and tasks related to each of these environments can also vary significantly.

Thus, in order to limit the scope for meaningful conclusions, this thesis only focuses in a subset of these environments. Namely, the scope of the structural analyses in this thesis is on radar surveillance of en route control of High and Super high altitude airspace.

Airspace in the higher stratum of the NAS is also more amenable to implementation of new concepts of operation. The rationale for this greater opportunity is that these sectors are less impacted by local operational constraints and characteristics.

1.4   Objective

The objective of this research is to investigate how distinct structural patterns are used by controllers for managing the traffic.

Figure 1-4 presents a simplified model of the ATC process. In this model, the air traffic controller perceives the states of the air traffic situations and recognizes the

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impact of structure on the tasks that must be performed. Based on the surveilled states, on knowledge stored in the long-term memory and on the perception of tasks from the structure, the controller generates commands that influence the evolution of the air traffic situation.

As proposed by Histon and Hansman (2008) and illustrated in this simplified model, structure is internalized into the long-term memory of the controller's mental model. This internalization process occurs mainly via training (academic studies and on-the-job training) and experience (exercising the profession itself). The result of learning is the development of abstractions and mental models. As an essential part of the developed abstractions and mental models, the learned strategies and techniques account for sector-specific dynamics and structural elements.

An important distinction has to be made, as techniques are commonly associated with strategies. For the purposes of this work, both are distinguished as follows:

- *Technique:* Sequence of actions, way of manipulating the traffic for accomplishing a given task or purpose;

- *Strategy:* Plan of how to use the acquired techniques to achieve safe and efficient
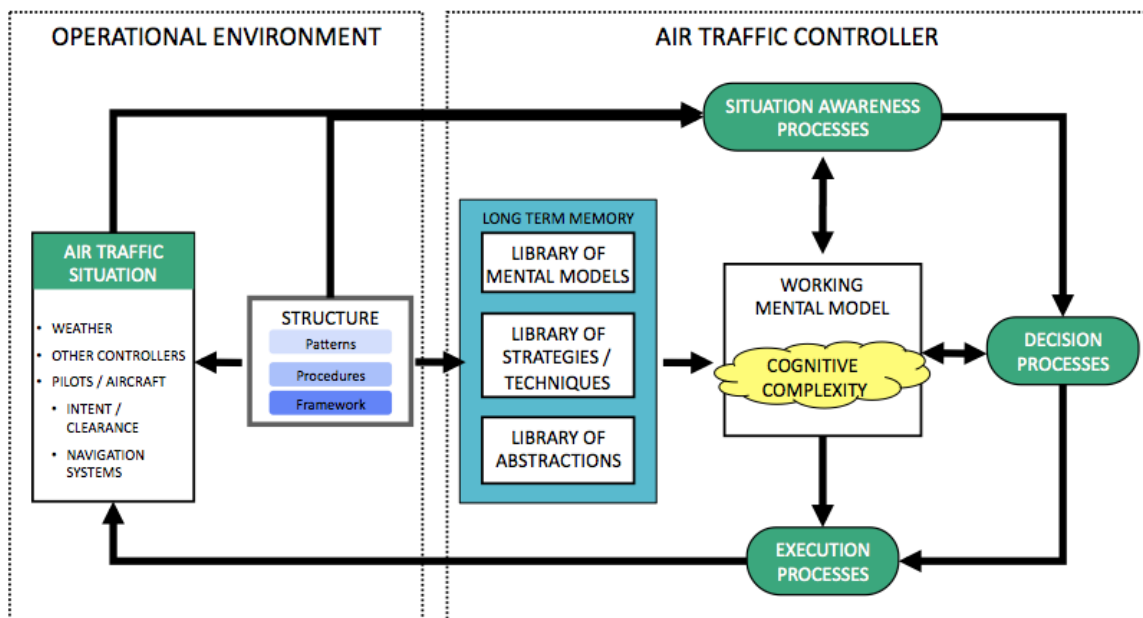
Figure 1-4: Simplified cognitive process model (adapted from Histon and Hansman (2008)).

throughput of traffic.

Thus, in order to accomplish the proposed objective, the approach can be subdivided into two types of analyses:

1. Identify structural patterns in the NAS;

2. Investigate what factors of the structural patterns impact the required techniques.

1.5   Document Overview

Chapter 2 presents relevant literature review for this work. Chapter 3 identifies how structure manifests in the NAS via the investigation of potential structural similarities. It presents a NAS wide analysis of the dynamics of the traffic. This analysis permitted the identification of different types of dynamics that can be found in the NAS and how airspace sectors can be grouped in this matter.

In Chapter 4, the objective is to identify variations of structural features (flows and critical points) and to generate hypotheses about how controllers manage the traffic. Visualizations of the traffic are the main employed technique for this matter.

Chapter 5 aims to understand how techniques that controllers used are related to each structural feature. The analysis is leveraged on insights obtained in Chapter 4. Chapter 5 presents a detailed voice and traffic dynamics analysis for the investigation of how controllers manage the traffic.

Chapter 6 summarizes the main steps that were taken in this work and presents conclusions that are pertinent to the better understanding of use of structure.

Chapter 2

Literature Review

This Chapter reviews pertinent material to the thesis. This review starts by discussing about decision making in the broad context, subsequently moving to specific topics in the ATC domain. These topics are: ATC Cognitive Models and how they relation to the structure in ATC, complexity in ATC and identification of patterns in the structure.

This text assumes that the reader is familiar with the ATC system. Some details about the system can be found in Appendix A.

2.1 Decision Making

As presented in Chapter 1, this work is concerned with the required knowledge for an air traffic controller to operate a given airspace. This work goes beyond procedural knowledge (knowing how to do things) and declarative knowledge (knowing about facts). More specifically, the concern is on identifying the library of techniques (stored in long-term memory) of proficient controllers and understanding how this same library is related to the structure of the airspace under control. It is inevitable that, by eliciting this kind of knowledge, the decision process of proficient controllers must be assessed.

In the context of decision making research, Naturalistic Decision Making (NDM) is of particular importance for this research, because this line of research is concerned

with proficient decision makers. NDM is defined by Lipshitz, Klein, Orasanu, and Salas (2001) as an attempt to understand how people make decisions in real-world contexts that are meaningful and familiar to them.

In order to better characterize NDM, however, it is useful to understand the Classical Decision Making (CDM), which takes a normative or prescriptive approach to decision making. Essentially, it tries to prescribe what choice a rational decision maker should take according to criteria of optimality. Lipshitz et al. (2001) points out major characterizes of CDM that can be found from different authors:

1. Making a choice – Decision making as selecting an optimal solution from an identified set of alternatives (Hogarth, 1987).

2. Input-output orientation – given a set of preferences, there will be a best or a set of best alternatives that the decision maker should choose (Funder, 1987).

3. Comprehensiveness – decision making is an analytical process that requires a relatively thorough information search (Payne, Johnson, Bettman, & Coupey, 1990).

4. Formalism – abstract and context free models susceptible to quantitative testing and experimentation (Coombs, Dawes, & Tversky, 1970).

The gradual transition to NDM occurs as many of these characteristics are questioned as valid representations of the human decision making process. Features of the rational choice mode are then replaced for more descriptive features. For instance, processing the required information entailed by comprehensiveness is potentially exhaustive and futile, thereby leading to systematic deviations from the rational choice (Simon, 1978).

By placing the bounded rational and proficient decision maker at its center of interest, NDM replaces comprehensives by matching, choice and input-output orientation by process orientation and formalism by context-bound informal modeling (Lipshitz et al., 2001).

The Recognition Primed Decision Making (RPD) can serve as the prototypical NDM model (Klein, Orasanu, & Calderwood, 1993). The following section presents the RPD model in the context of expert decision makers.

2.1.1 Recognition-Primed Decision Making

In a field research conducted by Klein, Calderwood, and MacGregor (1989) regarding how firefighters could handle time pressure and uncertainty, data suggested that the commanders were not comparing any options in their decision making process. There was evidence that they were typically carrying out the first identified course of action. The decision maker simply recognized the pattern in a problem from the available cues. This pattern is used to categorize or fit the situation to a given template, which allows the expert to realize what kind of problem is being faced. Also from experience, the expert knows what kind of solution works from every typical situation. Therefore, recognition of a situation leads to a minimization of analytical thinking for understanding and search and choice of a course of action.

RPD works well on situations where there are multiple highly correlated cues, which calls for what Hammond, Hamm, Grassia, and Pearson (1987) referred to as intuitive form of information integration based on pattern recognition. Naturally, it takes experience to know what are the relevant patterns of problems and what are the associated solutions to them. Wickens and Hollands (1999), however, notes that just because experts can make rapid decisions under time pressure and high stake situations, it does not imply that these decisions are optimal or even good, nor that experts will always employ RPD. Hammond et al. (1987) point out that there might be situations that invite for a different, more analytical or even innovative approach for decision making. This might happen when no time pressure exists or when the situation does not fit to any internalized pattern.

On a second variation of RPD, Kaempf, Klein, Thordsen, and Wolf (1996) identified what happens when the situation is not clear. In this case, the decision maker will often rely on simulation of the sequence of events that plausibly led to the current situation, thereby allowing the construction of a mental model that explains what

happened.

A third variation of RPD clarifies how decision makers cope with the constraints and stressors found in the operational environment. The evaluation of a decision is conducted by mentally simulating the course of action, in order to look for its effectiveness and for any unintended consequences. Patel and Groen (1986); Larkin, McDermott, Simon, and Simon (1980) found that people with greater expertise are more likely to use this forward-chained variation of RPD, whereas less experienced decision makers rely more on backward-chained reasoning for understanding the situation. Klein (1998) identified that RPD strategies are most likely to hold when the decision maker has reasonable experience and when the situation is characterized by time pressure, uncertainty and/or ill-defined goals. Also, RPD is less likely to hold with highly combinatorial problems, when justifications for actions are required, and in cases where different stakeholders have to be taken in consideration. These constitute some of the boundary conditions for the RPD model.

2.2 Air Traffic Control Cognitive Process Model

Pawlak et al. (1996) identified major ATC cognitive tasks that must be performed, which can be extended to any type of procedure for ATC. Figure 2-1 illustrates these four major controller activities, combined in one single diagram.

Regarding the controllers cognitive tasks, Pawlak et al. (1996) noticed that three of these processes (namely planning, monitoring, and evaluating) combine to create mental effort for the controller. From these four general tasks that controllers must perform, only implementation can be observed, although Pawlak et al. (1996) observe that some form of implementation can be done without observable action, such as planned co-ordination.

The cognitive process model used in this work is the one developed by Histon and Hansman (2008) and presented in Figure 2-2. This model is an explicit combination of Endsley (1995) model of situation awareness and the decision making processes identified by Pawlak et al. (1996). It also includes the operational environment elements
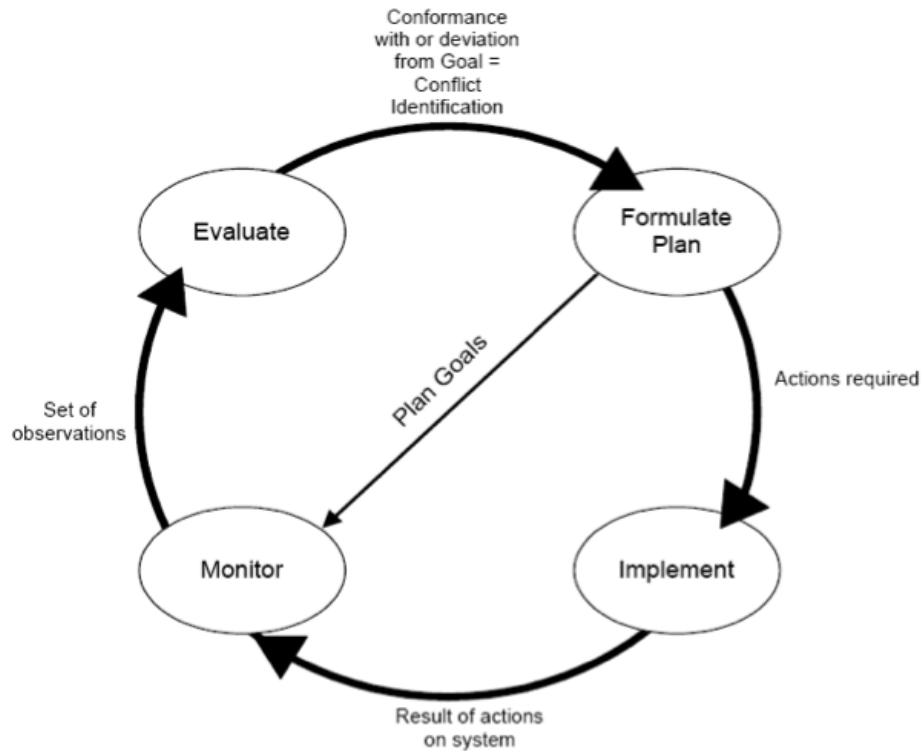
Figure 2-1: A model of the mental and physical processes required in ATC (after Pawlak et al. (1996)).

of the plant or system being controlled. Most importantly, this model incorporates structure as already presented before and its influences on the cognitive processes and its many impacts on the operational environment, such as tasks, air traffic situation and commands and communications.

Three stages or steps represent situation awareness in this model: perception, comprehension and projection. Naturally, perception is related to the observation of the states of the operational environment, mainly through automations, communication systems and tasks that have to be accomplished. Comprehension occurs in the context of these same tasks, which then drives the projection process through knowledge of the status and dynamics of the situation.

Awareness of traffic states and controllers internal states contribute to the decision making process (Kallus, Barbarino, & Damme, 1997). The long-term memory directly impacts the decision processes via the library of strategies and techniques. Long-term memory also indirectly impacts the decision processes, as the working memory
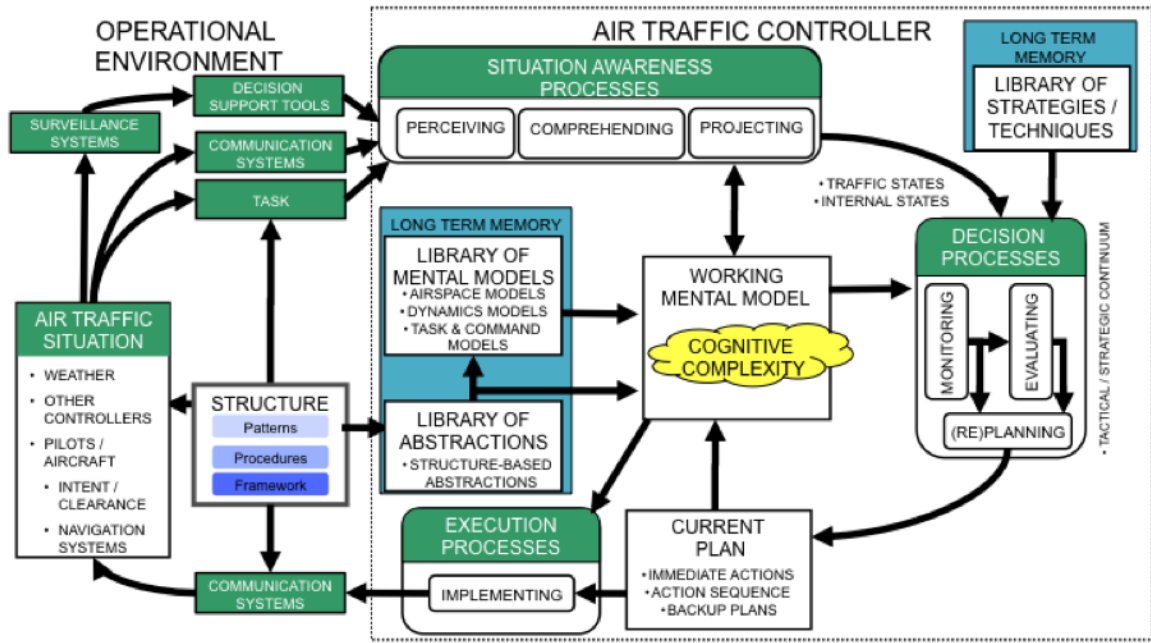
Figure 2-2: Cognitive Process Model (Histon & Hansman, 2008).

accesses information from the libraries of mental models and abstractions.

The library of mental models encompasses general knowledge of air traffic rules, procedures, dynamics of aircraft and weather as well as specific knowledge about the airspace the controller is responsible.

The knowledge requirements also depend on the type of airspace being controlled. Kalbaugh and Levin (2009) identified 102 knowledge elements that were required for controllers to manage and understand the traffic. These elements were then organized by altitude of the airspace, and later validated by subject matter experts. The resulting graphical representation of required knowledge elements per altitude was coined "Sector Knowledge Pyramid" (SKP), which is presented in Figure 2-3.

According to the findings presented in the SKP, approximately 64% less information is required for Super High sectors than for sectors in the lower stratum of the NAS. The difference from the Super High to High is of 36% less information requirements (Kalbaugh & Levin, 2009).

The working memory holds operative information and is the one responsible for all forms of active processing, such as pattern matching, mental arithmetic and support for situation awareness (Cardosi & Murphy, 1995).
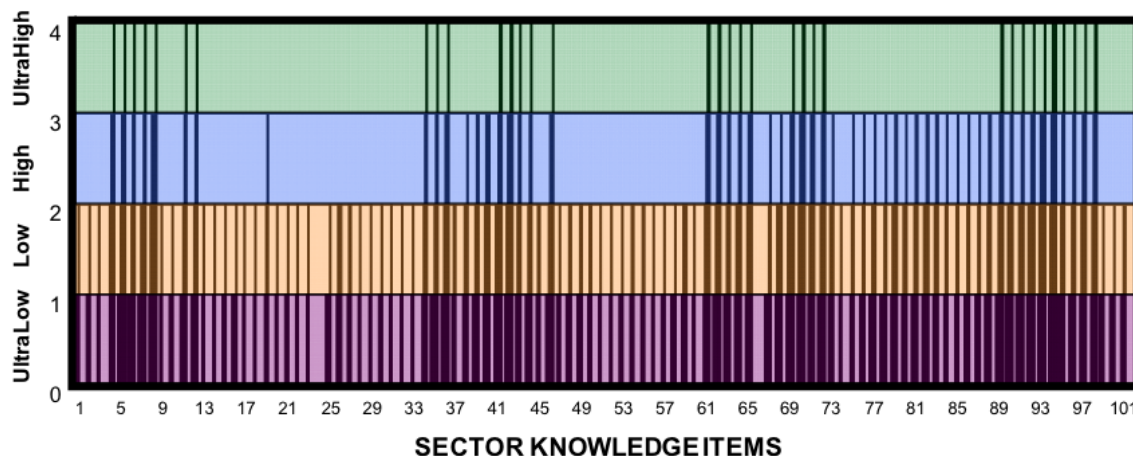
Figure 2-3: Sector Knowledge Pyramid: Illustration of how the amount of information a controller needs to know decreases as the sector altitude stratum increases.
102 identified sector knowledge items were organized by altitude: Ultra-low (below 10K) - 99/102; Low (10K to FL230) - 98/102; High (FL240 to FL340) - 55/02; and Ultra-high (FL350 to FL600) - 35/102 (Kalbaugh & Levin, 2009).

2.2.1 Structure-Based Abstractions

Long-term memory plays a large role in decision making, as the current situation has to be matched to stored patterns. This matching process triggers techniques that are known to solve specific situations (Cardosi & Murphy, 1995). Histon and Hansman (2008) identified structure-based abstractions (Figure 2-4) as "a controllers internalization of the influences of that structure on the dynamics of an air traffic situation, on available commands and the task." Therefore, these abstractions are simplifications of the controllers working mental model, thereby allowing the use of mental models that are less cognitively demanding, but still remarkably effective (Histon & Hansman, 2008).

Structure-based abstractions pre-solve certain tasks, by segregating parts of the air traffic situation. The ultimate result is task decomposition, since certain independent relationships and comparisons are not relevant. Also by removing unnecessary comparisons, Histon and Hansman (2008) argued that the effective degrees-of-freedom for projection of future air traffic behavior is reduced. By removing dimensions of the search space, the required cognitive resources such as time and effort can be signifi-

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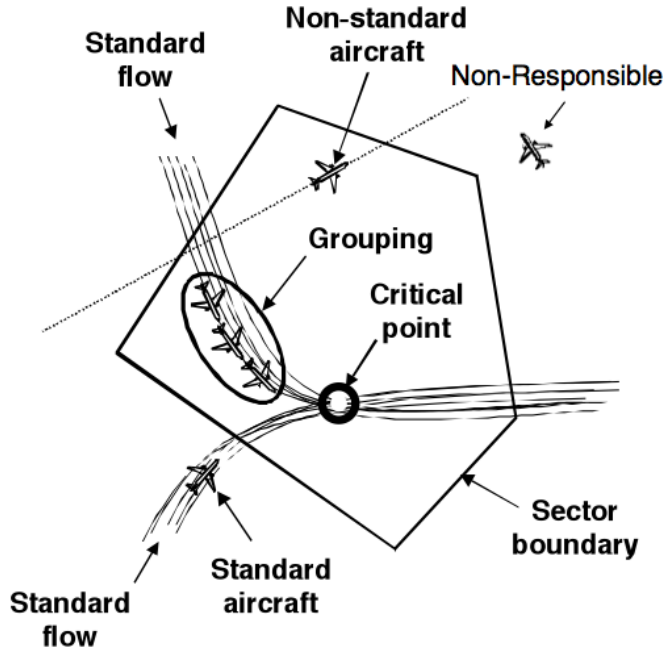
Figure 2-4: Structure-based abstractions identified by Histon and Hansman (2008):
• Standard Flows;
• Critical Points;
• Groupings; and
• Responsibility.
They represent the controller's internalization of the patterns the of structure into simplified and less cognitively demanding mental models.

cantly diminished, albeit a less accurate representation of the real world is used.

Another contribution of structure-based abstraction on the simplification of mental models occurs on the processes of evaluating and (re)planning the situation. Via pattern matching, such abstractions allow task decomposition into standard and non-standard aircraft. This suppresses the need for detailed evaluation and facilitates conformance monitoring to trajectories as complicated as those depicted in standard procedures. Regarding (re)planning, Histon and Hansman (2008) point out that "structure-based abstractions can also be used as the basis of the controllers current plan, reflecting key decision points and implementation points for commands."

Histon and Hansman (2008) also observed strategies and techniques by which controllers took advantage of the structure and of the structure-based abstractions to transform the task. Examples about the use of structure included exploiting established procedures and directing aircraft to reference points to expedite the traffic through airspace. Strategies and techniques related to structure-based abstractions were mainly related to enforcing structure on the situation, as a basis for simplifying abstractions. Examples included constant velocity (Davison & Hansman, 2003) and conformance to patterns by denying shortcuts and forcing adherence to interface procedures (Histon & Hansman, 2008).

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The types of structure-based abstractions identified by Histon and Hansman (2008) were: standard flows, critical points, groupings and responsibility. Each of these abstractions is briefly discussed below.

Standard Flow Abstractions

Histon and Hansman (2008) define standard flows as "recurring patterns of aircraft sharing common lateral paths; typically in-trail of each other." He also acknowledges that a standard flow can be associated with a vertical behavior and it can also interact with other flows, by splitting, merging or crossing. In the current NAS, standard flows are very related to the ground-based navigation system, thereby coinciding most of the times with existing jet routes. Standard flow abstractions correspond to the internalization of these expected flow patterns within and near the sector (Histon & Hansman, 2008).

Critical Point Abstractions

According to Histon and Hansman (2008), critical points are high priority regions in the airspace. Therefore, a critical point can be a location characterized by any recurring problem. Sabhnani et al. (2010) characterize a critical point as an explicit intersection of standard flows. This intersection of flows could then be further characterized as a merge or crossing of two or more flows.

Grouping Abstractions

Histon and Hansman (2008) introduced grouping abstraction as the result of a criterion that collects together parts of the traffic situation. As such, a grouping abstraction can be composed of aircraft, weather objects or restricted airspace. Examples of grouping criteria include aircraft flying the same flight levels, or aircraft that share characteristics in a given time, such as heading, speed, altitude transition or are just in proximity to each other.

Responsibility Abstractions

As noted by Histon and Hansman (2008), responsibility abstractions are an internatization of the delegation of portions of the task to other agents in the system. They are based on elements of the framework (mainly due to airspace boundaries) and the procedural (mainly through ways by which controllers offloads the tasks to other controller and even pilots) layer of the structure.

2.2.2 Strategies and Techniques in ATC Domain

Seamster, Redding, Cannon, Ryder, and Others (1993) argue that, due to intrinsic characteristics of the ATC job, there is a need not only for domain knowledge, but also efficient problem-solving strategies within the time-critical limits of the task. According to them, air traffic control strategies are heuristics that help controllers execute procedures more efficiently. Therefore, strategies may or may not include procedures and they are usually characterized by expertise.

A controller is dependent on these strategies in order to detect and prevent conflicts, while maintaining efficient traffic throughput (Nunes & Mogford, 2003). Sperandio (1978) postulated that strategies are used to moderate the levels of workload, by that means ensuring the picture of the situation. Hopkin (1995) defines the picture as:

> "The controllers picture consists of all that is perceived and is meaningful, interpreted in the context of recalled events preceding the current situation, anticipated events predicted from the current situation, and the professional knowledge and experience used to maintain control over the air traffic through sanctioned rules, practices, procedures and instructions"

A number of studies have been conducted on ATC strategies. In a review of such studies, Nunes and Mogford (2003) focus on strategies for conflict detection that are used to maintain the picture. In their review, trajectory prediction or altitude comparison could be used for conflict detection, depending on the unfolding situation, experience, training and preference.

In a study conducted by EUROCONTROL (2002), 45 controllers in 7 European countries were interviewed to determine their conflict resolutions for various scenarios. Strategies (also mentioned in the document as principles) were identified and categorized in five categories: (1) generic and non-contextual, (2) generic and contextual, (3) country based, (4) airspace based and (5) scenario based. Many of the strategies were only cited once, by a single controller, suggesting either strategic individuality or some degree of tacit knowledge.

In the EUROCONTROL (2002) study, controllers were also asked to elicit factors impacting their resolution strategies. The first cited factor is a combination of highly correlated features: aircraft type, aircraft performance and rate of climb. Noteworthy is the fact that high workload was mentioned by a number of controllers as a driver for simpler resolutions. Authors argue that alternate resolutions would be more optimal for the individual aircraft, but would clearly over-complicate an already busy scenario. Non-nominal aircraft were indicated as a complicating factor, as a source of secondary conflicts that were not internalized or accounted for. Interestingly, aircraft destination was the second most cited factor, incident that did not draw much of the authors attention.

This study also sheds light on techniques that controllers would NOT implement on conflict resolution. These were mainly airspace and conflict scenario specific. There was complete agreement that in one of the scenarios speed maneuver should not be used. The results, however, largely indicate personality biases on control strategies. Some controllers, for instance, would consider it unnecessarily risky to expedite the climb in one of the scenarios, whereas others would indeed adopt such resolution.

In a FAA report, D'Arcy and Rocco (2001) found many trends regarding the decision making and planning of specialists and novices, also differentiating Terminal and ARTCC controllers. They found that more experienced controllers are more likely to act immediately when a conflict is uncertain. Their results also suggest that experienced controllers tend to use the first strategy that they think of. Moreover, the statistical significance for these findings is stronger when looking only at Terminal controllers instead of ARTCC controllers, due to the more time-critical nature of the

job. In this study, careful attention was given to the formulation of backup plans, since participants emphasized its importance. As noted by the authors, this aspect is not explicitly found in previous ATC decision making studies that adopted a recognition-primed decision making perspective (Hutton, Thordsen, & Mogford, 1997; Mogford, Harwood, Murphy, & Roske-Hofstrand, 1994; Mogford, Murphy, Roske-Hofstrand, Yastrop, & Guttman, 1994).

Taking stock of the role of expertise and broadening the spectrum of analyzed strategies, Seamster et al. (1993) conducted a cognitive task analysis and found clear differences between experts and novices. Namely, experts alternated the focus on maintaining separation with managing deviations from standard operating procedures. Experts also spent more effort on organizing the traffic and attending pilot requests. The novices, however, spent most of the initial time focusing only on separation. Experts appeared to maintain a more comprehensive view and to be more global in their analysis of problem solutions. Novices, however, had a sequential approach to problem solving and dedicated almost all of the effort satisfying only separation assurance.

In a broad cognitive task analysis research conducted by Redding et al. (1992), three categories of ATC strategies were identified: display (involving the planning and monitoring of the sector), control (involving the execution of control activities in the sector) and workload reduction strategies (employed to reduce the controllers workload). They found that experts used relatively more workload reduction strategies. Moreover, certain strategies were unique to the expert participants: letting speed take effect, speed up to expedite, tighten separation, slow to intermediate speeds, shortcutting and early pilot notification.

In contrast, some planning strategies were unique to novices. Redding et al. (1992) found key differences in monitoring, planning and decision making, where novices usually got detained on constant monitoring and evaluation, whereas experts tended to adhere to a higher level plan to deal with the overall problem scenario.

The 22 cognitive strategies from Redding et al. (1992) were expanded to 40 strategies by Seamster et al. (1993) and regrouped under planning, monitoring and work-

load reduction management. A number of trends emerged from their study. Experts tended to account for or include more aircraft in their strategies and, even though they used strategies less frequently, they tended to use a greater variety of them. Experts also tended to use workload management strategies more frequently.

The authors also suggested that experts might be using strategies at the event level rather than at the individual aircraft level. By categorizing or grouping aircraft in terms of important sector events, the expert can (a) work with more aircraft, (b) better formulate a sector plan and (c) use fewer control and strategies (Seamster et al., 1993).

From the cognitive process model of Figure 2-2, Histon and Hansman (2008) observe the controllers ability to manipulate the presence of structure supporting his/her own abstractions about the traffic. By analyzing the en route inefficiency using Enhanced Traffic Management System (ETMS) data, Howell et al. (2003) observed dynamic variability in the use of structure as a function of traffic volume. Histon and Hansman (2008) also noticed variations in standard flows and identified operating modes representing broad changes in strategies and practices in response to the evolution of the air traffic situation. These operating modes, notionally shown in Figure 2-5, constitute on a dynamic use of strategies and structure-based abstractions, according to the cognitive demands.
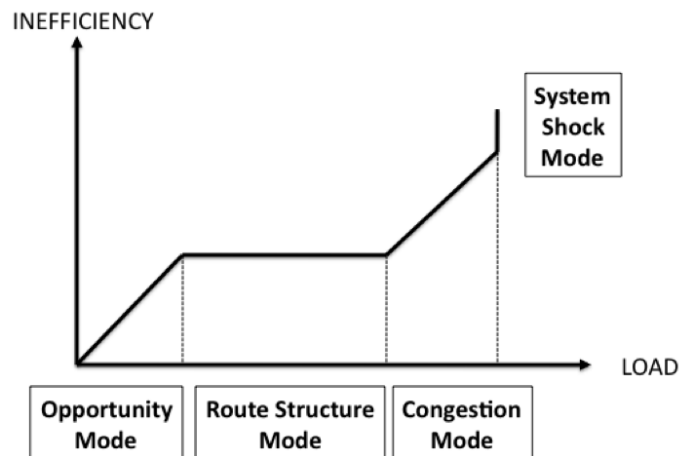
Figure 2-5: Notional air traffic controller operating modes (adapted from Histon and Hansman (2008)).

"Transitioning to a new mode changes the strategies, techniques, and working mental models used by the controller, reducing the perceived complexity" (Histon & Hansman, 2008). In the opportunity mode, difficulty and workload is likely to scale with the number of aircraft, as there is enough free cognitive resources for the controller to optimize each aircrafts trajectory. When in the route structure mode, most aircraft remain in the pre-determined route, allowing the controllers to take advantage of their structure-based abstractions. Resources are allocated to the abstractions themselves, or to non-nominal aircraft, thereby permitting the controller to accommodate higher traffic without significant increase in cognitive demand. In congestion mode, the capacity limits of flows and critical points are reached. This forces the controller to remove some aircraft from the flows and to monitor the interaction between aircraft conforming to the flow structure. Buffers such as path stretching and holding patterns are activated, resulting in increasing inefficiencies. In certain situations of outstanding demand or sudden change in the environment, the pre-existing structure may become unusable or irrelevant, leading to the system shock mode. In this mode, the controller is forced to quickly create contingency plans.

2.3   Complexity in Air Traffic Control

There is a clear consensus among the ATC research and operational communities that complexity drives controller workload, which in turn is thought of ultimately limiting airspace sector capacity (Christien, Benkouar, Chaboud, & Loubieres, 2003; Majumdar & Ochieng, 2002). Histon and Hansman (2008) explain how complexity ends up limiting the airspace capacity and efficiency:

> "In order to protect controllers from situations that are too cognitively complex and, as a result, threaten the safety of the ATC system, constraints are imposed on when and where aircraft can fly. While regulating cognitive complexity, these constraints also limit the capacity and efficiency of the ATC system."

Nevertheless, not all researchers are confident that it will ever be possible to adequately and mathematically express the functional relationship between complexity and perceived workload (Hilburn, 2004). Athènes, Averty, Puechmorel, Delahaye, and Collet (2002) describe complexity as a way to characterize air situations and it is in fact a source of workload, but they also note that the functional relationship between these two is largely unknown. Mogford, Guttman, Morrow, and Kopardekar (1995) define complexity as "a multidimensional concept that includes static sector characteristics and dynamic traffic patterns." (Meckiff, Chone, & Nicolaon, 1998) recognize that the operational procedures and practices as well as the "characteristics and behavior of individual controllers" play a key role.

According to Warfield and Cardenas (1995), complexity is the combination of two components defined by him: situational complexity and cognitive complexity. Cognitive complexity is the dilemma presented to the human mind when it engages with conceptualizations that are beyond its unaided powers. Situational complexity represents those aspects of phenomena that are intercepted by the mind which induce cognitive complexity (Loureiro, 2003). Histon and Hansman (2008) observe:

> "it is not always clear whether complexity is being presumed to be an intrinsic property of the configuration of traffic (situation complexity), a subjective experience of the controller (perceived complexity), or a property of the processes being used to perform the ATC task (cognitive complexity)."

These distinctions made by Histon and Hansman (2008) for different constructs involving complexity are those used in this work. They are illustrated in Figure 2-6.

Interest in defining and developing metrics of mental workload has grown dramatically since the mid 1970s (Hilburn, 2004). Most attempts to define mental workload have grown by way of analogy out of the concept of physical workload (Meshkati, Hancock, & Rahimi, 1989). The lack of a clear definition for complexity and workload is reflected in the disagreement over appropriate metrics (Hilburn, 2004).

Workload can be interpreted as an interaction between task and operator; therefore it varies for different task-operator combinations (Leplat, 1978). In this sense,
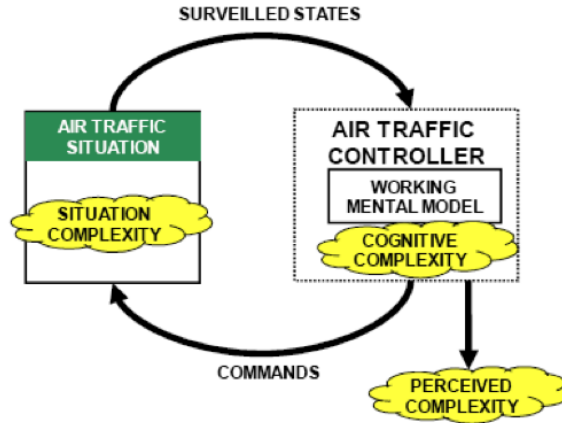
Figure 2-6: Simplified Model of the ATC process and uses of the term complexity (Histon & Hansman, 2008).

many factors can influence the human cost of performing a given task, such as time pressure, noise, stress, and distraction (Hancock, Chignell, & Kerr, 1988; Jorna, 1993). Other factors more related to the controller have also been cited, such as aptitude, skill, experience, operating behaviors, and personality (Bisseret, 1971; Sperandio, 1978). It can be concluded from these studies that the same given task might represent a different workload, depending on the controller (whether he/she is an experienced operator, or a novice, for example). The distinction is generally made between taskload (the objective demands of a task) and workload (the subjective demand experienced in the performance of a task) (Hilburn, 2004).

2.3.1 Estimating Situation Complexity

Among all the complexity factors listed in the literature, traffic density is the most cited and most associated with complexity. Because of its large use and the multiple attempts to improve the complexity metrics upon this basic factor, traffic density has been used with many different definitions and terminologies. Common associated denominations are number of aircraft in a fixed airspace over some defined period of time, number of aircraft per unit of airspace volume, average density encountered by each flight, or simply the number of aircraft in the airspace (Hilburn, 2004). In this work, traffic density, traffic load or traffic count are understood as the same

complexity factor and they are going to be considered as the instantaneous number of aircraft in the sector.

As noted by Hilburn (2004), the body of literature seems at the same time to praise the concept of traffic density (as the best available indicator of complexity), and to criticize it (mainly on the theoretical grounds that it does not capture the richness of what controllers find complex (Kirwan, Scaife, & Kennedy, 2001; Mogford et al., 1995; Athènes et al., 2002)). The critics about the effectiveness of traffic count, as a complexity factor, agree with Edmonds (1999), who observes that, even though the size or number of elements in a system may be a good indicator of complexity, size by itself may not describe its full richness. Therefore, since the early stages of ATC complexity research, significant effort has been placed on identifying drivers of complexity. In a comprehensive literature review, Hilburn (2004) provides a list of such complexity factors.

By aggregating different complexity metrics, researchers have come up with models of Dynamic Density (DD). The weights or contribution of each complexity metric is based on subjective ratings from workload or complexity probes or based on physical activity data (Prandini, Piroddi, Puechmorel, & Brázdilová, 2011). This kind of research has been applied for evaluating the contribution of different factors on the traffic complexity (Chatterji & Sridhar, 2001; Kopardekar, Schwartz, Magyarits, & Rhodes, 2007), as well as for forecasting the complexity for the next minutes (Kopardekar et al., 2007). Complexity is also usually estimated in the context of evaluation of a range of future Concepts of Operations, such as four-dimensional trajectories (L. Li & Hansman, 2009), multisector planner (Flener, Pearson, & Agren, 2007; L. Li, Palacios, & Hansman, 2010) , dynamic airspace configuration (Yousefi & Donohue, 2004; Yousefi, 2005; Masalonis, Callaham, & Wanke, 2003) and, more recently, generic airspace concept (Simmons, 2010; Bloem, Grupta, & Lai, 2010).

DD is analogous to complexity or difficulty of an air traffic situation (Kopardekar & Magyarits, 2003). Kopardekar and Magyarits (2003) considered DD as "the collective effect of all factors, or variables, that contribute to the sector level air traffic control complexity or difficulty at any given time." RTCA Task Force 3 report (1995)

defines DD as "the essential factors affecting conflict rate in both en route and terminal airspace." Laudeman, Shelden, and Branstrom (1998), on the other hand, starts defining DD as a metric of air traffic controller workload. Nonetheless, Laudeman et al. (1998) concurs with other definitions when clarifies that DD is based on air traffic characteristics, what makes it special for the development of both air traffic management automation and air traffic procedures.

Kopardekar and Magyarits (2003) describes in his paper a multi-year, multi-organizational research initiative related to the measurement and prediction of sector level complexity through the use of DD. This research focused on identifying complexity factors and then applying regression equations for properly predicting instantaneous and look-ahead time complexity.

In the conclusion of this multi-organizational work, it was pointed out that DD metrics have promise, most notably as a unified metric with contributing variables of metrics from different parties. Laudeman et al. (1998) and Kopardekar and Magyarits (2003) concluded that the DD metrics, as a combination of effects of traffic characteristics, perform better than the simple aircraft count, which is the basis of the standard complexity gauge. Nonetheless, the performance of the built DD predictor with look-ahead time obtained by Kopardekar and Magyarits (2003) was marginally better than the predicted aircraft count.

In the context of multisector planning, Flener et al. (2007) introduced a time-smoothed version of DD, as an estimate of complexity. Their metric, Interval Complexity (IC), is a 5-10 min average of a linear combination of number of aircraft, number of aircraft on non-level segments and number of aircraft close to the airspace boundary. The weights are sector dependent.

Many researchers recognized that non-linear approaches for DD could yield good results (Kopardekar & Magyarits, 2003; Hilburn, 2004), thereby tentatively resembling the non-linear combination of complexity factors that results on the overall complexity. Chatterji and Sridhar (2001) employed a successful non-linear regression via neural networks, also including several interesting metrics as mathematical representations of the situation complexity.

Ideally, a complexity metric should apply independent of such factors as equipment sophistication, traffic density, or size of the controlled airspace (Chaboud, Hunter, Hustache, Mahlich, & Tullet, 2000). But there seems to be more and more agreement in the literature that complexity is far from being context-free. This is based in a critical aspect of human cognition, namely, that what is complex in one context is not necessarily complex in another (Hilburn, 2004).

Kirwan et al. (2001) have noted that what works well in one setting might not work well in another site, or even at another time of the day. As a parallel to the interactions and connectedness of the elements in complex systems (Hitchins, 2000; Christien et al., 2003; Koros, Rocco, Panjwani, Ingurgio, & D'Arcy, 2003) noted that the interactions between the complexity factors (as a way of determining what is complex) might vary depending on the context.

2.4   Identifying Patterns in the Structure

Before deepening on mathematical representations of the traffic, it is worth mentioning the work of Chatterji et al. (2008). They looked at characteristics of the airspace sectors. In their analysis, traffic and geometric metrics are taken into consideration.

As noted in their paper, "design of sectors has evolved over a long period of time based on incremental addition of new technologies and procedures for air traffic control." Their traffic metrics included seven traffic-count metrics, five separation metrics and three flow metrics, extracted from references such as Pawlak, Goel, Rothenberg, and Brinton (1998); Christien et al. (2003); Yousefi and Donohue (2004). The geometric metrics were three geographical location metrics, four sector dimension metrics, three shape attribute metrics, five route attribute metrics and three neighborhood attribute metrics. Some of the traffic metrics had to be calculated, especially those involving conflicts, since conflicts or near-conflicts are rare in the real operational data.

Chatterji et al. (2008) considered 364 sectors. Some of their traffic findings include: most sectors in the current airspace have fewer than 20 aircraft at any given time and

most sectors have less than five aircraft in climb phase, fifteen in cruise phase and five in descent phase.

Among geometric findings, a wide variation was found in sector volume, area, height and length. Most sectors showed to be aligned with the main traffic flows. A maximum of 17 airways was found in any given sector and 328 sectors had ten or fewer airway intersections. Notably, only 29 sectors were farther than 200 nautical miles from what they considered to be the 74 major U. S. airports.

2.4.1   Identifying Structural Patterns

This section reviews what has been done on identification of features on the pattern layer of the structure (flows and critical points) presented in Figure 1-1

In general, the methods for identification of structural features can be either bottom-up (first critical points then flows are identified) or top-down (first flows and then critical points are identified). Moreover, they can be either grid based (extracting traffic information through two- or three- dimensional partitions of the airspace) or trajectory based (overall trajectory is considered in the analysis). There are also other methods reliant on visualization of traffic density. This text presents some of relevant works done under each methodological approach.

Trajectory clustering has been analyzed in a number of domains, such as video surveillance (Piciarelli, Foresti, & Snidaro, 2005), coastal surveillance (Dahlbom & Niklasson, 2007) and even for hurricane and animal movement data (J.-G. Lee, Han, & Whang, 2007). An interesting review covering different kinds of trajectory clustering problems can be found at (`http://movementpatterns.pbworks.com/Patterns-of-Movement`).

J. Lee and Han (2007) presented a methodology based on partitioning trajectories into segment lines, which are then regrouped based on perpendicular, parallel and angular distances. Other methods are based on longest common subsequences, such as the one presented by Vlachos, Kollios, and Gunopulos (2002). Evaluating benefits from performance-based navigation, Eckstein (2009) presents an automated flight track taxonomy. Trajectories are resampled, and then clustered using k-means.

Combining characteristics of these methods, Gariel, Srivastava, and Feron (2010) propose two separate and successful trajectory clustering algorithms for airspace monitoring. One of these methods is called "waypoint-based clustering", as turning points are first identified and then clustered in order to generate waypoints. Trajectories are then represented as a sequence of these waypoints, which in turn are clustered in order to generate meaningful flows within the traffic.

In the second and most promising method, Gariel et al. (2010) propose improvements over the method introduced by Eckstein (2009). The algorithm is called "trajectory-based clustering". They include an intermediate step where the data is augmented by calculating several statistics from the radar track data, such as angular position, distance to the center, heading, among others. The augmented data is then reduced via a principal component analysis and the final vectors for each flight are clustered via a density based clustering algorithm.

Most of the recent work on air traffic pattern identification has been in the context of dynamic airspace configuration (Martinez, Chatterji, Sun, & Bayen, 2007; Zelinski & Field, 2008; J. Li, Wang, Savai, & Hwang, 2009; Sabhnani, 2009; Xue, 2010; Zelinski & Jastrzebski, 2010). Some of these tried to capture information about the traffic through two-dimensional grid cells. For instance, Xue (2010) determined if a two-dimensional grid cell was either a member of a major traffic flow or an intersection point based on the heading variance of flights. Martinez et al. (2007) used light occupancy counts within each grid cells to create abstract network flow graph of the traffic.

Other methods spent effort on characterizing structure as connections between flows and critical points (Zelinski & Field, 2008; Sabhnani et al., 2010; Zelinski & Jastrzebski, 2010). Sabhnani et al. (2010) proposed different trajectory based greedy algorithms, as well as a grid based method that is less dependent on the variability of individual tracks. These methods output standard flows, from which intersections are identified and, once clustered, critical points are obtained. Tackling the pattern identification from a different perspective, Zelinski and Field (2008) first identified critical points from flight tracks. The method first finds intersection points that are

then differentiated into merging and crossing points. Intersection points are then clustered into critical points, in a process that showed that the number of crossing critical points was far higher than the number of merging critical points. Most of these critical points could be paired with airway intersections, revealing the relevance of the Structure in the current system.

Zelinski and Jastrzebski (2010) extended the methodology of Zelinski and Field (2008) by adding an altitude component and linking the critical points to form the flows. The dynamic change of these structural patterns was analyzed over the course of a day and under the influence of weather. They showed that more and more unpublished links began to appear as airways started to saturate with increasing traffic. The influence of structure was evident when great circle routes presented much more intersecting links than the flight plan routes.

Another class of research on identification of structural features relies on visualization of traffic densities. Histon and Hansman (2008) presented several examples of flows and critical points based on such visualizations. Naturally, such visualizations are still dependent on the airspace grids or transparency levels for the radar tracks. Such methodologies tend to be subjective and to rely on the analysts understanding of traffic behavior, existing procedures and the airspace structure itself. In this process, the identification of critical points, flows, holding patterns and path-shortening features occur concomitantly, which makes the differentiation between top-down and bottom-up approaches less important. The finding of these features usually comes with insights about possible traffic bottlenecks and controllers tasks. Evaluating the opportunity of generic airspace, Cho and Histon (2010) apply this methodology on high altitude sectors with ceiling above FL350, thereby identifying several patterns across the NAS

2.5 Summary

This Chapter started by reviewing the role of expertise on decision making and then how controllers abstract and manage the traffic. Human Factors in ATC was reviewed

by presenting some of the cognitive process models in the literature, giving more attention to the cognitive process model introduced by Histon and Hansman (2008), whereupon this work is leveraged. From Histon and Hansman (2008), it is known that complexity is an intrinsic property of the controllers working mental model, which is also related to the use of structure-based abstractions. Such abstractions are internalizations of the patterns of the traffic in the controller's long-term memory, which, in turn, is a genuine fruit of training and expertise.

Moreover, there has been work on identification of strategies and techniques that controllers use in order to manage the traffic. To the knowledge of the authors of this work, these studies have mainly focused on specific de-conflicting tasks or overall differences between experts and novices. The role of structural patterns in strategies and techniques was identified by Histon and Hansman (2008), but not evaluated in great detail.

Many strategies have been associated with "workload management" and mental models used by controllers were characterized by the complexity of these models. As such, in the ATC domain, the evaluation of the nature of a problem can hardly be disassociated from the notion of cognitive complexity and workload, which was also briefly reviewed. These studies indicated several metrics that probe the dynamics of the traffic and are likely to correlate with the tasks that controllers must perform.

Literature on identification of structural patterns was then surveyed, due to evidence these that structural patterns are intrinsically related to how experts make decisions. It was found that many algorithmic studies on identification of flows and critical points have been done. However, little effort has been focused on evaluating in more detail the relevance of these patterns on how controllers manage the traffic. Moreover, these studies usually force a model to which the traffic has to fit, ignoring possible variations of patterns.

This thesis fits in the broader literature by examining alternative approaches for structural pattern identification, as well as by exploring how these patterns are managed by the controller.

Chapter 3

Analysis of NAS-wide Traffic Patterns

As presented in Chapter 2, literature on decision making has found that experts internalize the patterns in their workspace and often have techniques that respond to these patterns. Based on this literature review, the objective of this Chapter is to identify different types of sectors, which may be an indicative of different mental models.

The types of sectors were identified by evaluating and comparing their traffic structure. This evaluation was conducted by considering metrics for the dynamics of the traffic. In order to identify appropriate metrics for traffic dynamics, the approach was to look metrics that had been used in prior studies to determine complexity and workload for air traffic controllers. The assumption is that these factors are important for the tasks that controllers must perform (Chatterji & Sridhar, 2001; Hilburn, 2004; Kopardekar et al., 2007) and, therefore, would be relevant for traffic pattern identification (Christien et al., 2003).

Four groups or classes of such traffic metrics were selected and calculated for each high altitude sector (aircraft count, altitude transition, concentration of traffic between origins and destinations and directional variability). Based on these metrics, this Chapter investigates whether there are high altitude sectors in the NAS with similar traffic dynamics.

3.1 Methodology

Figure 3-1 illustrates the overall methodology for identification of traffic patterns. The approach started by parsing data sources in order to identify flights that passed through High and Super High altitude sectors (Section 3.1.1). The selected metrics, presented in Section 3.1.2, were then calculated. Clustering, a data mining technique, was employed in order to identify groups of sectors with similar characteristics (Section 3.1.3. Observations from the calculated metrics and results of the clustering analysis are presented in Section 3.2.
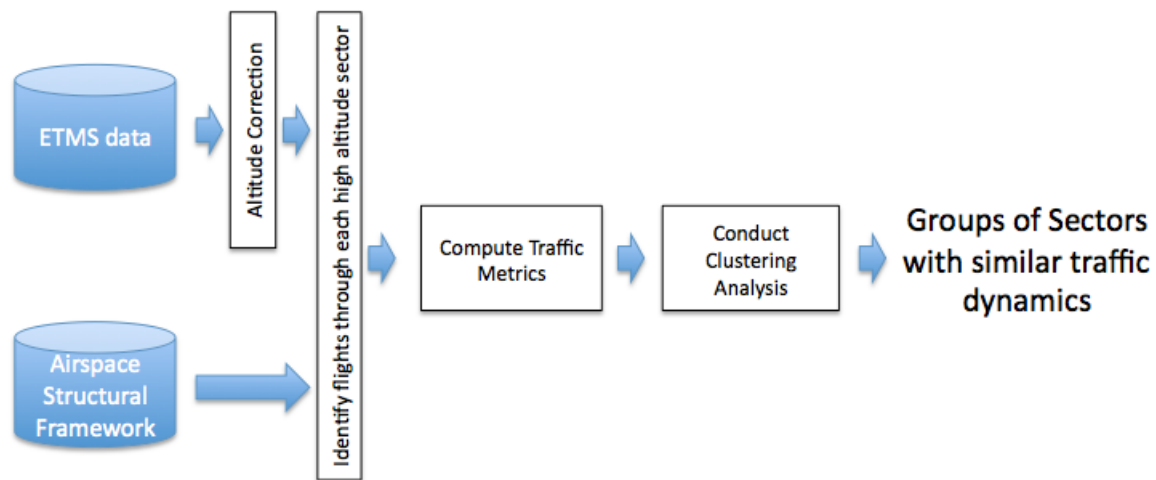
Figure 3-1: Analysis Methodology.

3.1.1 Evaluation Data

Enhanced traffic management system (ETMS) collects information from aircraft flying in the US airspace. The aircraft situation data describes the state of the airborne flights at a given moment, including the 3D trajectory (latitude, longitude, elevation and timestamp), flight plans, flight plan amendments, arrivals, departures, ARTCC boundary crossings, cancelations, among others (Volpe, 1995).

The ETMS data in possession[1] included only origin airport, destination airport and radar track data for the continental US from 07/13/2009 to 07/19/2009 and

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[1]ETMS and structural framework data obtained from personal communication with FAA

09/21/2009 to 09/27/2009. However, because of data recording issues, unphysical changes on the radar track data were often observed. Therefore, a smoothing algorithm developed at MIT by Palacios and Hansman (2010) was used to remove noise in the data.

The available sector boundary data is from 08/27/09. SUAs, MOAs and Warning Airspace were not available in this data. As mentioned in Section 1.3.2, this analysis focuses in High and Super High sectors located in the 20 Centers in the continental US. According to the definition adopted in this work, both High and Super High sectors have ceiling above FL240 (see Figure 1-3). After correcting and cleaning the data, the final number of analyzed sectors was 452. The final range of traffic volume was from 400 to 5073 in two weeks of data. Assuming that most of the traffic occurs for 16 hours of the day (between 6:00 AM and 10:00 PM), this range is between 2 and 23 flights per hour.

3.1.2   Selected traffic metrics

Based on the literature review of traffic metrics, four groups of metrics were chosen for analysis of similarity in the NAS (Table 3.1). Traffic count was defined in terms of the total number of aircraft (NAC) that was observed for the entire span of data. A detailed description of the other types of metrics is provided below.

Altitude Transition Metrics

A flight is characterized as transitioning if the altitude difference from entrance to exit of the sector is equal or greater than 1000ft. The metrics consist on the percentage of climbing, descending and level traffic, compared to the total traffic (NAC). Measures of altitude transition have been incorporated in several studies to account for the dynamics of the traffic (Hilburn, 2004; Christien et al., 2003; Kopardekar et al., 2007; Chatterji & Sridhar, 2001; Laudeman et al., 1998).

Table 3.1: Summary of selected traffic metrics

Type of Metrics	Description	Variable
Aircraft Count	Total number of aircraft	NAC
Altitude Transition	Percentage of climbing traffic	$Climb$
	Percentage of descending traffic	$Desc$
	Percentage of level traffic	$Level$
Origin-Destination Dispersion	Entropy of distribution of traffic from Origin airports	$Orig_{entropy}$
	Entropy of distribution of traffic to Destination airports	$Dest_{entropy}$
	Entropy of distribution of traffic to OD pairs	$OD_{entropy}$
Directional Dispersion	Entropy of directions of the traffic	$Dir_{entropy}$
	Deviation from the main traffic	DMT

Origin-Destination Dispersion Metrics

It was assumed that flights that go to (or come from) specific airports are likely to present similar flight plans and, consequently, similar dynamics inside the sector (that is, similar lateral and vertical trajectories). For instance, if the sector has a high percentage of its traffic associated to the same airport, then the air traffic controller is likely to expect the same behavior and requests from these flights and to exercise similar set of actions to manage this traffic. This assumption is consistent with the grouping abstraction introduced by Histon and Hansman (2008), whereby the controller collects together similar parts of the situation, typically aircraft, within the working mental model. Thus, it was considered that metrics to evaluate the distribution of origin and destination would be relevant for probing the dynamics of the traffic in a sector.

In order to probe the existence of prominent origins or destinations, the percentage

of traffic that is related to specific airports was analyzed. When evaluating the distribution of origins and destination of the traffic, it soon became evident that certain sectors had very concentrated traffic in a few origins or destinations and some others appeared to have a very scattered distribution. Figure 3-2 presents the traffic and distribution of percentage of traffic to specific destinations for Los Angels 26 (ZLA 26) and Kansas City 07 (ZKC07). As such, it appeared that a good characterization of such distributions would be a measure of how disperse these distributions were. The chosen metric for this purpose was entropy of the distribution.

Equation 3.1 presents the formula for the statistical entropy. Let p_i^{dest} be the proportion of traffic associated with the ith destination and $n_{dest}^{(l)}$ the number of unique destinations for the observed traffic in sector l. Then the entropy of the distribution
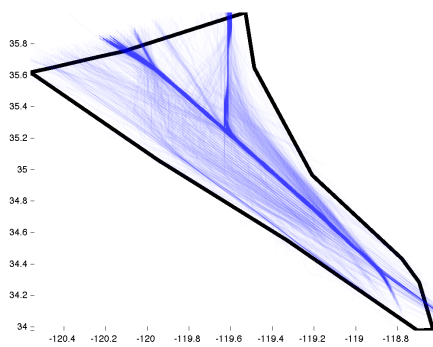
(a) Traffic in ZLA26
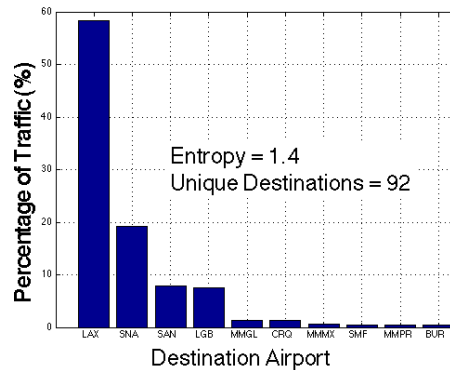
(b) Distribution of Destinations in ZLA26
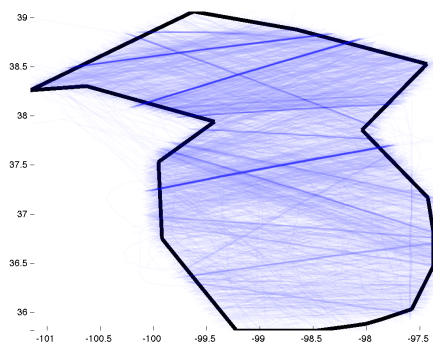
(c) Traffic in ZKC07
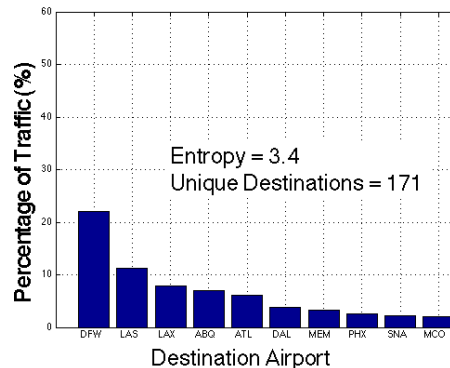
(d) Distribution of Destinations in ZKC07

Figure 3-2: Traffic and distribution of percentage of traffic to specific destinations for Los Angeles 26 (ZLA26) and Kansas City 07 (ZKC07)

of destinations is calculated with the following equation:

$$Dest^{(l)}_{entropy} = -\sum_{i=1}^{n^{(l)}_{dest}} p_i^{dest} \ln p_i^{dest} \tag{3.1}$$

The uniform distribution is known to be the maximum entropy distribution. That is, for a set with n elements, the maximum entropy occurs when each element is equally likely, with probability $1/n$. Moreover, this maximum entropy is $-n\left(\frac{1}{n}ln(\frac{1}{n})\right) = ln(n)$. For instance, if the traffic in a sector had 200 unique destinations, then the maximum entropy for this distribution would be $ln(200) = 5.3$. The opposite extreme case would be if a sector had *all* of its traffic going to a single destination, then the destination entropy would be $-1ln(1) = 0$.

If p_i^{orig} is the proportion of traffic associated with the ith origin and $n^{(l)}_{orig}$ is the number of observed unique origins for sector l, then the origin entropy is calculated by:

$$Orig^{(l)}_{entropy} = -\sum_{i=1}^{n^{(l)}_{orig}} p_i^{orig} \ln p_i^{orig} \tag{3.2}$$

Similarly, if p_i^{od} is the proportion of traffic associated with the ith origin-destination pair and $n^{(l)}_{od}$ is the number of possible origin-destination pairs for sector l, then the OD entropy is calculated by:

$$OD^{(l)}_{entropy} = -\sum_{i=1}^{n^{(l)}_{od}} p_i^{od} \ln p_i^{od} \tag{3.3}$$

Directional Dispersion Metrics

The directionality metrics in this work try to capture how disperse the traffic is in the sector. Intuitively, traffic concentrated around specific directions is likely to be correlated to major flows in the sector. Conversely, if a high directional dispersion is found, then the sector may contain less predominant flows or more background traffic. Christien et al. (2003) also included a measure of disorganization of the traffic, named flow entropy.

The heading is calculated from the point of entrance to the exit of the sector. Figure 3-3 compares Los Angeles 25 (ZLA25) and Denver 32 (ZDV32) in terms of the heading distribution and the integrated image of the traffic. Figures 3-3(b) and 3-3(d) present the percentage of traffic that follows each direction (directions were rounded to the nearest integer). Notice how ZLA25 has a major traffic direction at 315° degrees with a secondary peaks at 120° and 150° degrees. Therefore, this sector presents traffic bidirectionally. For ZDV32, however, it can be seen, from Figure 3-3(c), that the traffic has several directions, which is reflected in Figure 3-3(d) in terms of a more scattered distribution of directions. Two measurements are extracted from directional distributions such as those presented in Figures 3-3(b) and 3-3(d). The first measure of dispersion is the directional entropy:
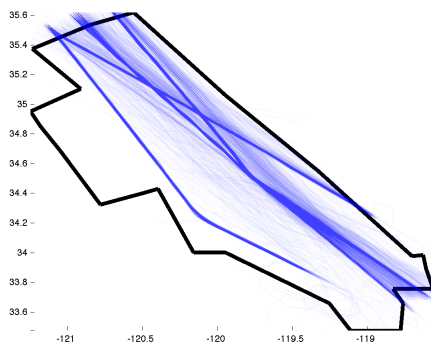
(a) Traffic in ZLA25
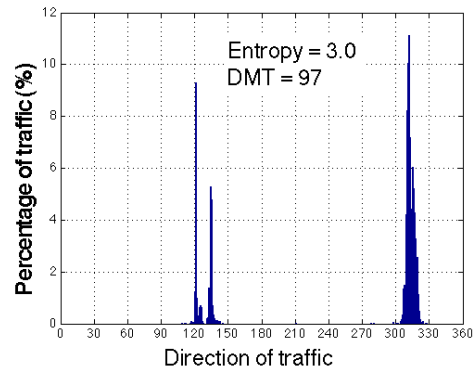
(b) Directions in ZLA25
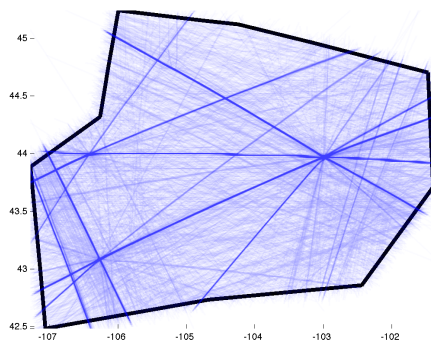
(c) Traffic in ZDV32
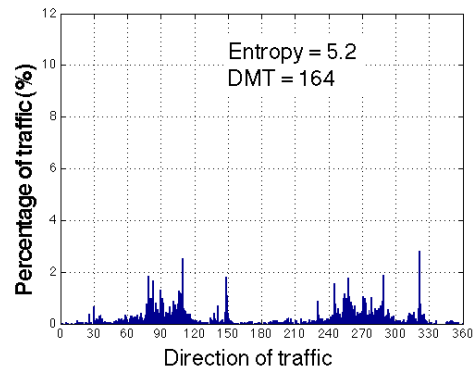
(d) Directions ZDV32

Figure 3-3: Traffic and distribution of directions for Los Angeles 25 (ZLA25) and Denver 32 (ZDV32)

$$Dir_{entropy}^{(l)} = -\sum_{j=1}^{360} p_j^{(l)} \ln p_j^{(l)} \, , \qquad (3.4)$$

where $p_j^{(l)}$ is the proportion of aircraft that follow the jth direction from $1\,^\circ$ to $360\,^\circ$ degrees and N_l is the total traffic in sector l. Therefore, the higher the directional dispersion , the higher the measurement of directional entropy will be. Conversely, low entropy is an indication that the distribution is more peaked or concentrated around certain values. One can see that, indeed, the resultant directional entropy is lower for ZLA25 than for ZDV32. In fact, it can be proven that, for a set with n elements, the entropy is maximum when each element is equally likely (or uniformly distributed). Moreover, this maximum entropy is $-n \left(\frac{1}{n} ln(\frac{1}{n}) \right) = ln(n)$. Thus, for this case where directions are discretized in 360 bins (to the nearest integer), the maximum entropy is $ln(360) = 5.9$.

The other directionality metric is a variation of WASP (Kopardekar & Magyarits, 2003), defined as "the square difference between the heading of each aircraft in a sector and the direction of the major axis of the sector, weighted by the sector aspect ratio." In this work, the main axis of the sector is replaced by the main direction of the traffic, extracted from radar data, and the aspect ratio of the sector is not included in the calculation. As such, the name of the metric is changed to deviation from the main traffic (DMT). Notice that this definition differs from the variance definition, since dispersion is being calculated around the main axis, not around the mean of the headings.

The main direction of the traffic is determined from the mode or the most frequent direction in the directions distribution chart (such as those presented in Figures 3-3(b) and 3-3(d)). Let H_l be this mode, or the main traffic heading. Let α_i be the angle of the arc that spans from the main traffic heading to the ith aircraft heading, thereby assuming values between $0\,^\circ$ and $180\,^\circ$ degrees. The equation for the deviation from the main traffic for sector l, or DMT^l, is then:

$$DMT^l = \sqrt{\frac{1}{N_l} \sum_{i=1}^{N_l} (\alpha_i)^2} \qquad (3.5)$$

where N_l is total traffic for sector l and. The division by N_l aims at reducing distortions of higher DMT simply due to higher traffic (without this correction, high DMT could be obtained for high volume, unidirectional traffic).

Notice that Equation 3.5 tends to assume high values as the amount of traffic not following the main traffic increases. This is particularly true for aircraft flying in opposite (or close to opposite) direction of the main traffic, since each of these aircraft contribute with approximately 180^2 to the summation inside the square root. This constitutes in the main contrast between DMT and directional entropy and the reason why DMT was included in the analysis. Entropy is independent of the ordering of the distribution, whereas DMT is dependent both on the *magnitude* and *ordering* of the headings of each aircraft.

Therefore, if the traffic is concentrated around, say, two flows, the entropy is likely to be very low $(-0.5ln(0.5) - 0.5ln(0.5) = ln(2) = 0.69)$. If the traffic is perfectly divided in two flows, then DMT will assume higher values as the angular difference be zero if these two flows coincide and increase dramatically as the directional offset approaches $180\,°$. Both metrics, however, achieve maximum values under a uniform distribution of headings.

3.1.3   Clustering Method

Each sector was treated as an observation that was characterized by traffic metrics. In order to identify sectors with similar traffic characteristics, a clustering analysis of the metrics for each high altitude sector was conducted. This Section presents the concept of clustering and some details about the chosen clustering method, K-means.

Consider a collection of objects that can be described by a set of measurements. In general, all types of cluster analyses relate to grouping or segmenting this collection of objects into subsets or "clusters". These clusters are formed in such a way that each cluster member is more closely related to one another than to objects assigned

to different clusters. For means of this research, the objects would be high altitude sectors and the measurements would be traffic metrics presented in Section 3.1.2. Thus, clusters of sectors would be groups of sectors with similar traffic dynamics.

Therefore, to objective of different cluster analyses is to create many-to-one mappings where the ith object, $i \in \{1, \ldots, N\}$, is labeled as belonging to the kth cluster, $k \in \{1, \ldots, K\}$, where $K < N$. One approach for such method is to define a loss function to be minimized for each cluster. Let C be a many-to-one mapping that gives a cluster assignment to each object, that is $C(i) = k$. Then a natural within-cluster dissimilarity can be expressed as:

$$W(C) = \frac{1}{2} \sum_{k=1}^{K} \sum_{C(i)=k} \sum_{C(i')=k} d(x_i, x_{i'}) , \tag{3.6}$$

which is calculated with a dissimilarity function $d_{ii'} = d(x_i, x_{i'})$ (Hastie, Tibshirani, & Friedman, 2009). Notice that, based on this dissimilarity or distance function, the total scatter of all objects:

$$T = \frac{1}{2} \sum_{i=1}^{N} \sum_{i'=1}^{N} d_{ii'} \tag{3.7}$$

is independent of the cluster assignment. In other words, given the data, the total scatter is a constant. If there is a cluster assignment, then the invariant total scatter can be broken down into:

$$T = \sum_{k=1}^{K} \sum_{C(i)=k} \left(\sum_{C(i')=k} d_{ii'} + \sum_{C(i')\neq k} d_{ii'} \right) \tag{3.8}$$

or $T = W(C) + B(C)$, that is, the sum of within- and between-cluster dissimilarities. Hence, the clustering method can be formulated either as minimizing $W(C)$ or maximizing $B(C)$.

It should be apparent by now that central to any cluster analysis is the dissimilarity function $d_{ii'}$, or the measure of distance between objects (Hastie et al., 2009). In this work, all the traffic metrics were standardized to have mean 0 and variance 1. Then, the dissimilarity or distance between pairwise sectors was calculated from the squared

Euclidean distance based on the standardized values of traffic metrics. Therefore, the dissimilarities can be expressed as:

$$d_{ii'} = d(x_i, x_{i'}) = \sum_{j=1}^{p} (x_{ij} - x_{i'j})^2 = ||x_i - x_{i'}||^2, \tag{3.9}$$

where p is the number of properties or metrics used to describe each object and x_{ij} is the standardized value of property j for object i. Thereby, Equation 3.6 can be rewritten as:

$$W(C) = \frac{1}{2} \sum_{k=1}^{K} \sum_{C(i)=k} \sum_{C(i')=k} ||x_i - x_{i'}||^2, \tag{3.10}$$

This research used the popular K-means method for solving the clustering problem of minimizing Equation 3.10 for all clusters. By this method, an initial assignment of cluster centroids is randomly selected from the available data. Then, K-means alternates the two following steps until convergence:

1. Identify the closest cluster centroid (Euclidean distance in Equation 3.10) for each object and reassign the cluster membership of each object accordingly

2. Each cluster centroid is replaced by the coordinate-wise average of all objects that are assigned to the respective cluster

Steps 1 and 2 are iterated until the assignments do not change. Each iteration reduces the value of Equation 3.10. However, local minimums can be reached, depending on the initial random assignments of centroids. Therefore, the algorithm was replicated 100 times and the best assignment according to Equation 3.10 was taken as the final clustering.

The choice of K, the number of clusters to be searched for, is a critical input for the K-means algorithm. This is the major shortcoming of applying this method in a research where the final "natural number of clusters" is an important information to be extracted. As a possible (and popular) solution, one could compute and plot the value from Equation 3.10 as a function of K. In such method, typically one

looks for a "kink" in the sum of squares curve when locating for the optimal number of clusters. Unfortunately, there is no widely-accepted mathematical method for determining the optimum number of clusters. Therefore, cluster interpretability and subject matter expert input can play a major role on the choice of K. In this work, cluster interpretability is the criterion for the number of clusters.

3.2   Results

This Section starts by exploring some of the interrelationships between the traffic metrics described in Section 3.1.2. Then, results of the clustering algorithm are presented. These results should be interpreted as a snapshot of the current NAS and limited to the set of traffic metrics that were chosen.

Figure 3-4(a) below presents the scatter plot of Origin Entropy (an extension of Equation 3.1 for origin airports) versus the percentage of climbing traffic. Each circle corresponds to a high altitude sector, or an observation.

Notice that the origin entropy decreases as the amount of climbing traffic in the sector increases. Recall that lower entropies indicate a concentration of the distribution at few peaks, 0 being the lower bound of entropy for a pure set. Therefore,

(a)   (b)
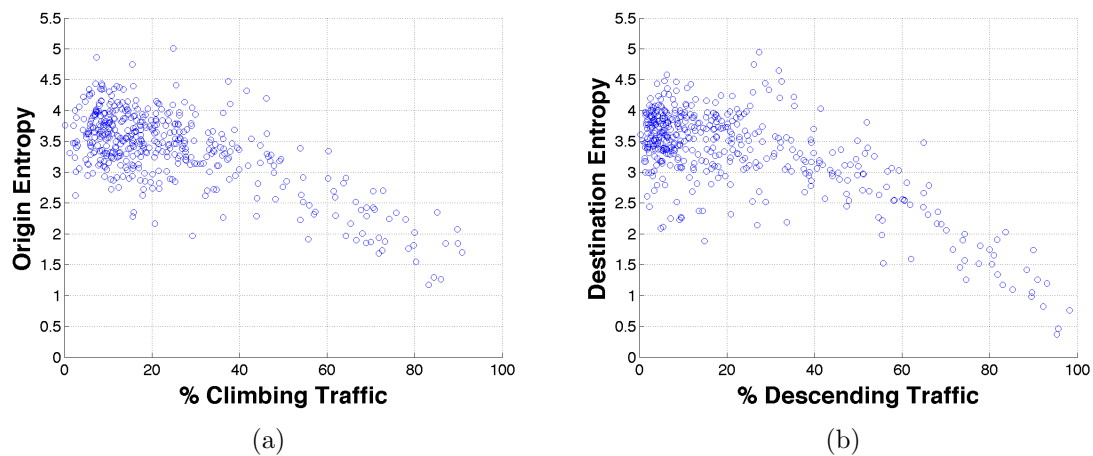
Figure 3-4: Relationship between altitude transition metrics and entropy of the distribution of origin and destination airports

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the information conveyed in Figure 3-4(a) is that sectors with higher percentage of climbing traffic tend to have traffic coming from a concentrated set of airports. These sectors are found mainly nearby major airports, as presented later in this Section. Following the same trend, Figure 3-4(b) shows that sectors with high percentage of descending traffic tend to have traffic going to a concentrated set of airports. These sectors sectors are also found to be located nearby major airports. Note, however, that a significant portion of the observed sectors are on the top left corner of both charts.

Figure 3-5 analyzes the percentages of climbing and descending traffic for all the sectors. Again, each high altitude sector is plotted as a circle in the scatter plot. This
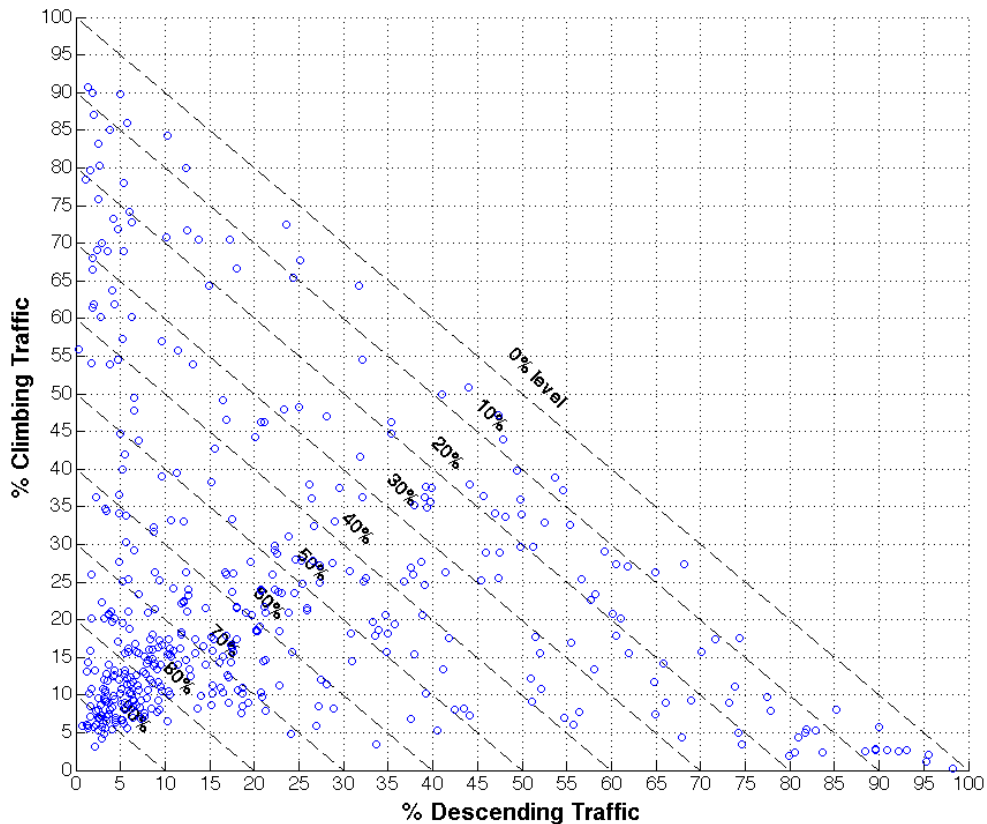
Figure 3-5: Climbing versus Descending traffic per sector. Dashed lines represent same percentage of level traffic. For instance, any sector over the 30% dashed line has 30% of level traffic.
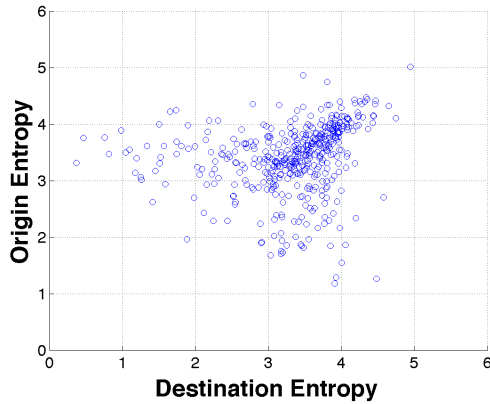
(a) Origin entropy versus Directional entropy
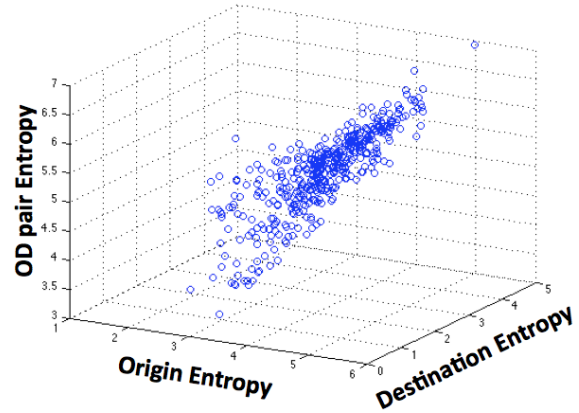
(b) Origin, Destination and OD entropies
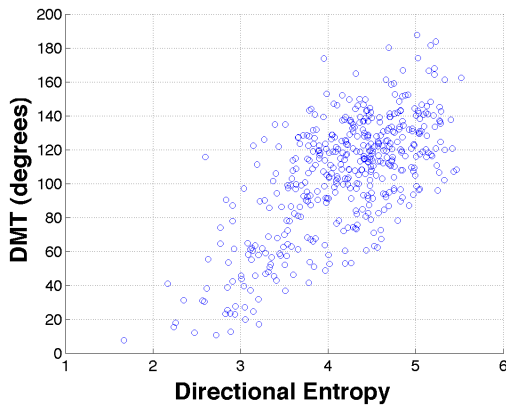
(c) Deviation from the main traffic (DMT) versus directional entropy
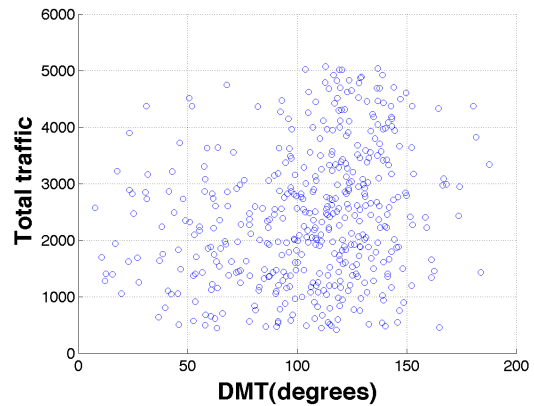
(d) Total traffic versus deviation from the main (DMT)

Figure 3-6: Relationship between other metrics

chart also presents lines with same percentage of level traffic, in 10% increments. Noticeably, a number of the High and Super High sectors are on the bottom left corner of this chart, indicating they have a high proportion of the traffic in level phase of flight.

Figure 3-6 presents the relationship between other variables for each sector. Figure 3-6(a) shows that most of the sectors have high entropies both with respect to origins and destinations and few have traffic concentrated with respect either to origins or destinations. Figure 3-6(b) is a 3-dimensional version of Figure 3-6(a), including OD entropy in the z-axis. One can see that OD entropy increases as the traffic is more scattered in terms of either origins or destinations. Figure 3-6(c) indicates that

both directional metrics are mildly correlated (correlation of 0.68). Deviations from perfect correlation between both metrics are due to the fact that DMT is sensitive to the differences of direction in the traffic. That is, for a given entropy, DMT will vary depending on the distribution of the rest of the traffic relative to the main traffic direction.

Moreover, as presented on the scatter plot of Figure 3-6(d), DMT and total traffic are fairly unrelated (correlation of 0.22). This is due the normalization by N_l in Equation 3.5, in order to avoid bias of higher DMT simply due to more traffic volume.

Clustering Results

The clustering method was used by considering each high and super high altitude sector as an object, and each calculated traffic metric as a property (using the terminology of Section 3.1.3). The final number of clusters was based on the distinct characteristics of each group. The clustering algorithm found five "natural clusters", based primarily on the total traffic volume, altitude transitions and directional variability.

Figure 3-7 presents the characteristics of each cluster, according to the percentage of traffic that had altitude transition, total traffic and deviation from the main traffic direction. Two polygons of same color are drawn for each cluster: the inner (and darker) polygon accounts for 50% of the cluster members, whereas the outer (and lighter) polygon accounts for 90% of the cluster members. One can see that clusters 1 (light blue) and 2 (red wine) were mainly differentiated according to the percentages of climbing and descending traffic, respectively (Figure 3-7(a)). Group 5 (light green) presents a combination of both climbing and descending traffic, resulting in similar percentages of level traffic of clusters 1 and 2. Also in Figure 3-7(a), note that clusters 3 (orange) and 4 (dark blue) overlapped in terms of altitude transitions. These clusters were differentiated (Figure 3-7(b)) as two major regions based on the combined values of total traffic and deviation from main traffic. In Figure 3-7(b), one can see that cluster 5 tended to have medium values of traffic volume and deviation from the main traffic.
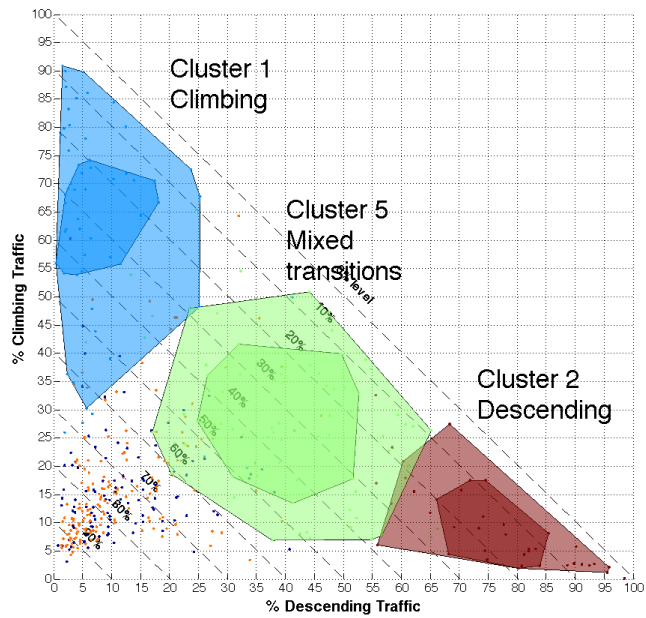
(a) Clusters 1, 2 and 5 distinguished by the percentage of altitude transitions.
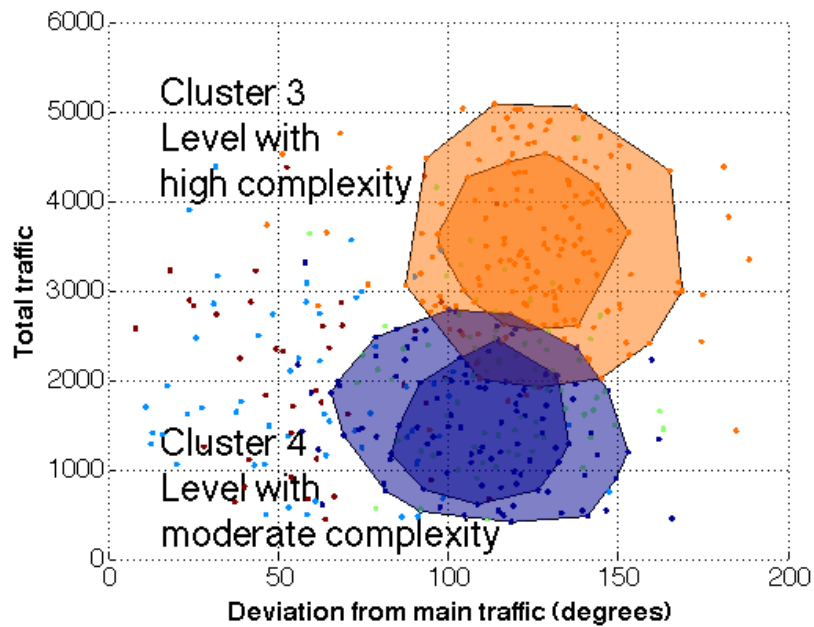
(b) Clusters 3, 4 and 5 distinguished by the combined values of total traffic and deviation from main traffic.

Figure 3-7: Scatter plots for all clusters. Inner (dark) and outer (light) boundaries account for 50% and 90% of the cluster members, respectively.

More details about the distribution of each traffic metric are presented in Figure 3-8. This Figure presents boxplots to convey the statistics for the five clusters identified among the high and super high sectors in the NAS. The standardized value for each metric is presented in the y axis, thereby removing problems of scale in the presentation.

The boxplot for each variable is composed of a box and whiskers. On each box, the central red mark is the median for that group of sectors, the bottom and top edges of the box are the 25th and 75th percentiles. The interquartile range (IQR) is defined as the height of the box, or the distance from the 25th to the 75th percentiles. In the presented charts, the whiskers extend to 1.5 IQR from the edge of the box. Everything beyond the whiskers is considered an outlier and plotted individually as a red cross. Since these charts present the standardized values of the variables, the 0 line presents the mean for the entire population. In addition to these standard elements of a boxplot, the median of each of the variables for the entire population is presented as a dark circle, allowing for a comparison of the distribution of a certain variable in a cluster against the median of all analyzed sectors.

Figure 3-8(a) presents what can be identified as a cluster with mainly climbing traffic (the entire boxplot for percentage of climbing traffic is above the mean and the median for the entire population). The directionality metrics for this cluster (low directional entropy and deviation from main traffic) suggest that these sectors have organized traffic along a main direction. Low entropy of the origin distribution also suggests that the traffic comes from a concentrated set of airports. Conversely, Figure 3-8(b) presents a group of sectors with mainly descending traffic. The traffic for these sectors also appears to be organized with respect to a main direction and a concentrated set of destinations (the values of these respective variables are low). The traffic volume (NAC column) both for climbing and descending sectors also appears to be slightly lower, in average, than the median for the entire population of high altitude sectors.

Figure 3-8(c) presents statistics for sectors in Cluster 3. These sectors have a total number of aircraft, deviation from main traffic and percentage of level traffic higher
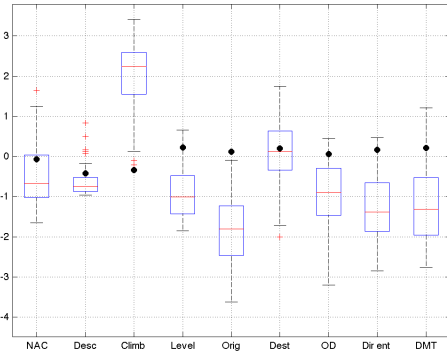
(a) Cluster 1, climbing
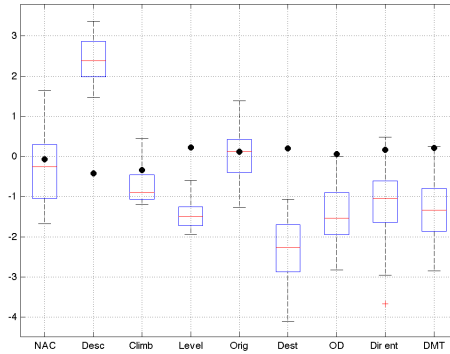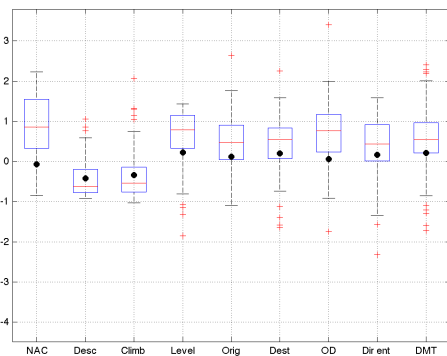
(b) Cluster 2, descending

(c) Cluster 3, level with high complexity
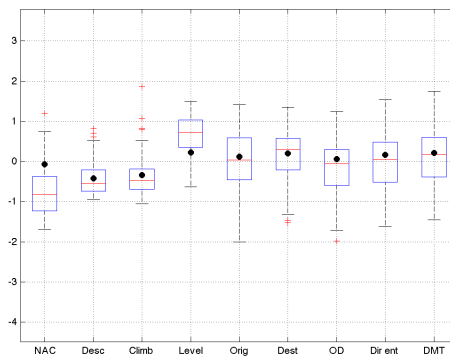
(d) Cluster 4, level with moderate complexity
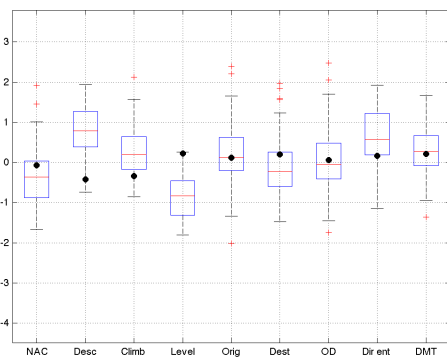
(e) Cluster 5, mixed transitions and low traffic

LEGEND

NAC	Total Number of Aircraft
Desc	Percentage of descending traffic
Climb	Percentage of climbing traffic
Level	Percentage of level traffic
Orig	Entropy of distribution of traffic from origin airports
Dest	Entropy of distribution of traffic to destination airports
OD	Entropy of distribution of traffic to OD pairs
Dir ent	Entropy of directions of traffic
DMT	Deviation from the main traffic
●	Median of the metric for the entire sample of sectors

Figure 3-8: Boxplots for each cluster identified among the High and Super High Altitude Sectors

than average. Moreover, the traffic is scattered across more origins and destinations than the average and median of the entire population, as it can be evidenced by the Orig and Dest columns in Figure 3-8(c). Members of cluster 3 appear to present the highest complexity that one can observe amongst sectors with level traffic.

Cluster 4 was found to have low level of traffic (see Figure 3-8(d)). Sectors in this cluster appear to have a higher quantity of level traffic than the median for the entire NAS. Moreover, they present average values of directional and OD dispersion. This observation suggests that these sectors have moderate complexity when compared to the rest of the NAS.

Sectors in cluster 5 (see Figure 3-8(e)) have slightly less aircraft than the average. However, they have percentages of both climbing and descending traffic that is higher than average. This cluster presents the highest directional entropies of all identified clusters. Dispersion of directions may exist in order to accommodate both climbing and descending traffic. Medium DMT and high directional entropy might be a consequence of a strong main direction for the traffic, but still with some dispersion around this main direction.

Figure 3-9 presents the distribution of each cluster in the NAS. The respective sectors for each cluster were plotted with a semi-transparent red face. Thus, a darker red comes out when two sectors overlap in the altitude dimension. Same geographical regions may have different overlapping sectors categorized in different clusters. This suggests how traffic dynamics changes with respect to altitude.

Notice that sectors classified in clusters 1 and 2 are located around major airports. Moreover, they also appear to be thinner, with higher aspect ratio (this is just an observation, no quantitative analysis was done on this matter). Conversely, sectors classified in clusters 3 and 4 tend to be located farther from major airports. Sectors of clusters 3 and 4 that appear close to larger cities (namely Chicago and Dallas Fort Worth) were found to be at higher altitudes, thereby presenting less concentration of traffic with respect to specific airport and higher percentage of level traffic. Members of group 5 appear to be either close to major airports or between climbing/descending and level sectors.
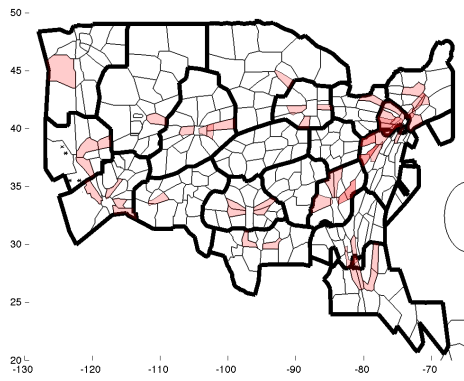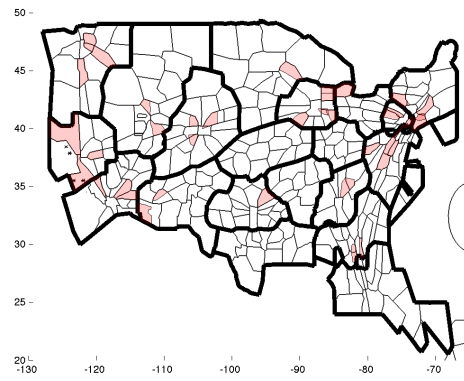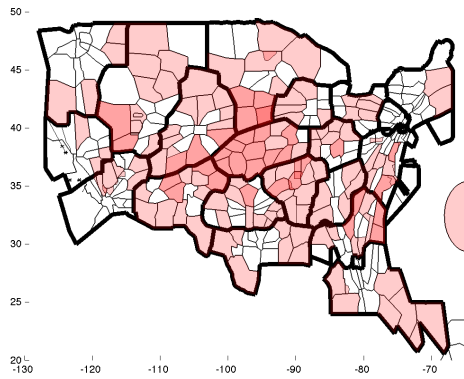
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(a) Cluster 1, climbing

(b) Cluster 2, descending

(c) Cluster 3, level with high complexity
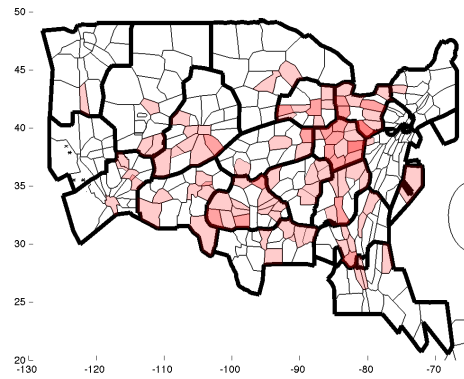
(d) Cluster 4, level with moderate complexity
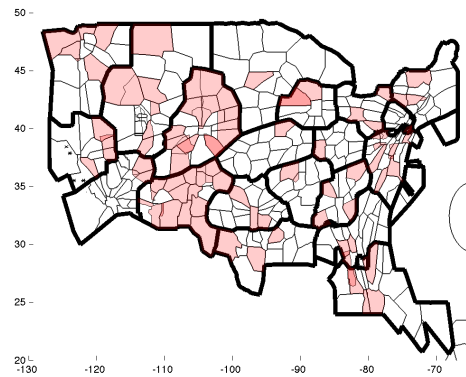
(e) Cluster 5, mixed transitions and low traffic

Figure 3-9: Clusters identified for High and Super High Altitude Sectors

Table 3.2: Summary of clusters for High and Super High sectors

#	Cluster Description	Number of Sectors	Total Traffic	Altitude Transition	Directional Entropy	Deviation main traffic	Origin Entropy	Destination Entropy
1	Climbing	57	Medium-Low	Climbing	Low	Low	Low	Medium
2	Descending	40	Medium-Low	Descending	Low	Low	Medium	Low
3	Level, high complexity	166	High	Level	Medium-High	Medium-High	Medium-High	Medium-High
4	Level, moderate complexity	110	Low	Level	Medium	Medium	Medium	Medium
5	Mixed transitions, low traffic	79	Medium-Low	Mixed	Medium-High	Medium	Medium	Medium-Low

Table 3.2 consolidates the result of the cluster analysis, including the number of sectors in each group. In summary, three groups with significant altitude transitions were found: climbing (cluster 1), descending (cluster 2) and mixed transitions (cluster 5). Among groups with level traffic, cluster 3 appeared to have higher complexity than cluster 4, evidenced by higher averages of traffic volume, directional entropy, OD entropies, and deviation from the main traffic (DMT).

3.3 Summary

This Chapter presented the selected traffic metrics that were identified as relevant for capturing the dynamics of high altitude sectors in the NAS. Natural interrelationships between these variables were found, such as:

- Sectors with high percentage of climbing traffic tend to have their traffic coming from concentrated set of airports (origin concentration, measured by low Origin Entropy).

- Sectors with high percentage of descending traffic tend to have their traffic going to concentrated set of airports (destination concentration, measured by low Destination Entropy).

Results of the clustering algorithm were then presented. The identified clusters highlighted different types of dynamics that could be found in the NAS. It is known

that the current structure of the sectors is a consequence of incremental traffic, procedures and technology (Chatterji et al., 2008). Sectors evolved in order to accommodate the nature of the traffic that had to be monitored and controlled, but in such a way to maintain a certain workload for the controllers (Nolan, 2011). One can see from the devised clusters some of the different combinations of traffic metrics. These phenomena emerge as a wide range of situations to which controllers are exposed.

The analysis presented in this Chapter led to a typology of the sectors in the NAS. This typology should be treated as a snapshot of the current dynamics of the NAS, limited by the selection of traffic metrics and radar track data span. It should be noted that similar dynamics are likely to be associated with common volume, types and sequence of tasks to be performed.

The following Chapters use the identified types of sectors to investigate how common structural patterns and traffic dynamics impact the techniques used by controllers. More specifically, the next Chapter attempts to generate hypotheses about how traffic characteristics can be linked to controller techniques.

Chapter 4

Analysis of Structural Patterns

The previous Chapter looked at overall traffic characteristics in the NAS. This Chapter shifts from this mathematical approach to a more careful observation of structural patterns and how they relate to different aspects of the structure. The objective of this analysis is to generate hypotheses about how controllers manage the traffic.

4.1 Methodology

From Histon and Hansman (2008), two of the identified structure based-abstractions had a high topological implication on the physical setup of the traffic, namely flows and critical points. This Chapter analyzes flows and critical points and what are their variations in the NAS. Some consideration is also given to the intensity and dispersion of the background traffic.

Initial work attempted to derive flows from a density-based analysis, by partitioning the sector's geographical location into a grid, and then counting the traffic volume through each grid cell. From this method, it is usually straightforward to determine the densest trajectories in a sector. However, as the density drops down from the centerline of the flow, it becomes more and more ambiguous to determine whether an aircraft belongs to that flow, to the background traffic or even to another flow. That is, it is difficult to define the threshold for a flow.

As presented in Chapter 2, some researchers focused on the development of math-

ematical models for identification of flows and critical points. The ambiguity of what belongs to flows or not was usually solved in those methods by setting parameters to be met: a maximum "background traffic" (Gariel et al., 2010), or a minimum "coverage threshold" (Sabhnani et al., 2010), or minimum length and width of flows (Simmons, 2010).

In order to conduct a preliminary analysis, this Chapter presents a subjective evaluation of what are the major elements within the system. Thereby, flows and critical points were analyzed via visualizations of the traffic. This subjective investigation looked not only at geometrical or topological similarities of the traffic, but also at what are the variations of such patterns.

Each sector was printed out in one page, including a zoomed in and a zoomed out view. Both views consisted of an integrated, two-dimensional view of all the traffic (from the available data) that went through the sector. The zoomed in view presented only the sector boundary in addition to the overall traffic. The zoomed out view presented the traffic extended 200 nautical miles away from the sector boundary, since most sectors are located within this exact distance from a major US airport (Chatterji et al., 2008). The zoomed out view also included the boundaries of surrounding sectors and nearby airports.

Figure 4-1 illustrates one of those printouts for sector Fort Worth 89 (ZFW89). Notice that by clipping the radar track from entrance to exit of the sector, vertical handoffs within the sector lateral boundaries can be visualized in the zoomed in view. The subjective identification of flows and critical points also allowed to observe a typology of such patterns.

Since all the the available traffic was collapsed in a top view two-dimensional plot, important aspects of the structure were lost, such as altitude transitions, directionality and time variations. Mindful of such oversimplifications of the traffic, these printouts were only used as a first screening for structural variations.

Additional details of the traffic were analyzed in case studies, which are presented in this Chapter. In these case studies, the identified variations of structural features were correlated to origins and destinations (OD) in the traffic. Traffic directionality

Figure 4-1: Fort Worth 89 (ZFW89)

and altitude transitions were also investigated in the context of the OD analysis, since these factors are correlated with the origin and destination of the aircraft. This correlation is evidenced by (1) noting that an origin and destination specify a vector or direction for the aircraft; and (2) altitude transitions are correlated with concentration of traffic to specific airports (Figure 3-4 in Chapter 3).

4.1.1   Evaluation Data

In oder to conduct the aforementioned analyses, the same ETMS data described in Chapter 3 was used (only position, time and origin and destination was available in this data). Two weeks fo data were considered, the days from 07/13/2009 to 07/19/2009 and from 09/21/2009 to 09/27/2009. The analysis focused on 452 High and Super High sectors with ceiling above FL240. The range of traffic volume was between 400 and 5073 aircraft in the two weeks.

Other information used in this analysis was sector binders for Jacksonville ARTCC (ZJX). These sector binders provided charts depicting the main routes and reference points, as well as procedural restrictions. Moreover, location and type of 43,680 airports (balloon port, seaplane base, heliport, closed, small, medium, large) around the world were obtained from a web source: `http://www.ourairports.com/`.

4.2   Observed Variations of Structural Features

From Histon and Hansman (2008), the use of structure-based abstractions appeared to be connected to the physical setup of the traffic (or the structural topology). Thus, this analysis is based on simple and key geometrical elements that could be captured from observation of several sectors..

The goal is to identify variations of two of the structure-based abstractions identified by Histon and Hansman (2008), namely flows and critical points. The method for subjective identification of these patterns consists in overlaying semi-transparent radar track lines for each flight in the sector. As a result, the darker a certain region is, the stronger the evidence of overlapping trajectories. In this method, flows

are identified from darker paths. Critical points are identified from darker spots or, equivalently, from intersections of flows. Due to the subjective attribute of this first screening, definitive thresholds for characterizing flows in terms of width, amount of traffic and length were not devised. Notwithstanding, certain patterns and their variations were evident

Two main types of flows were identified: dense flows and converging/diverging (C/D) flows. Also, two types of critical points were observed: crosses and merges/splits (M/S). It was found that the topology of the traffic could be described as a combination of these basic elements or patterns.

Flows

Figure 4-2 highlights key dense flows subjectively identified in two different sectors. More consistent tracks along a path line were mostly observed in elongated sectors, which were found to be aligned with the traffic directions going from or to nearby airports. Due to local operational constraints, some of these sectors also presented holding patterns associated with the dense flows. Such procedures work as a buffer, thereby increasing the airspace capacity.

Other observed variation of flows is when several tracks converge to or diverge from a single point, most of them not following the same path. This pattern is referred to as a converging or diverging (C/D) flow. An important distinction: when dense flows converging to or diverging from a point can be identified, they are considered as a combination of dense flows, not a C/D pattern. This does not exclude the case where converging or diverging dense flows occur concomitantly with a C/D pattern at the same point.

The C/D flow can be further categorized in terms of the location of its focal point, that is, if it is either internal or external to the sector, as illustrated in Figure 4-3. From a cognitive standpoint, however, the differentiation of a C/D flow as part of the primary structure or as just background traffic demands a deeper analysis of how the controller manages and abstracts this pattern. For instance, if the C/D flow converges to a merging point descending to a destination airport, then most
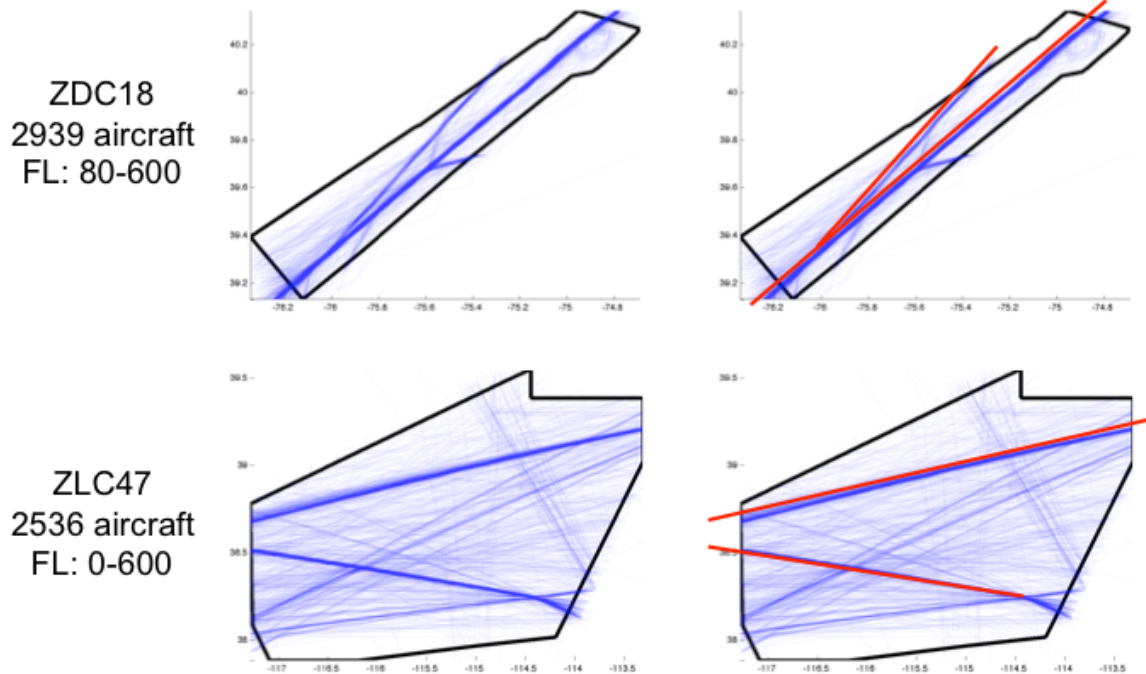
Figure 4-2: Examples of dense flows (highlighted in red)

Fan has an internal Focal Point   Fan has an external Focal Point
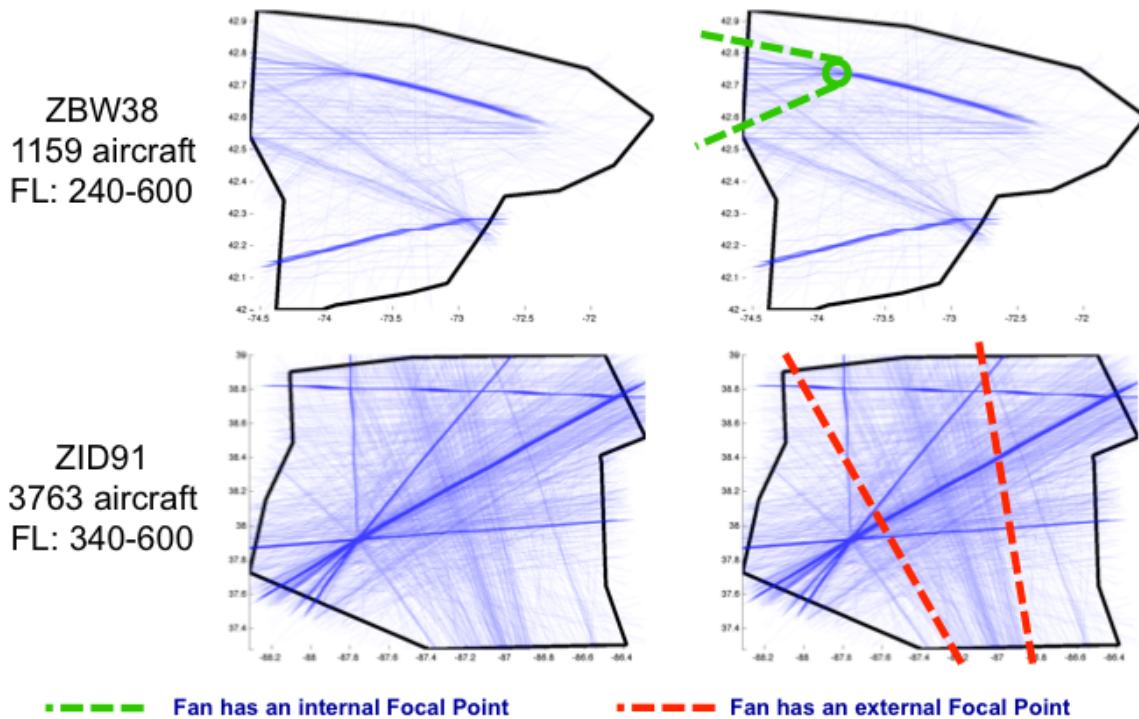
Figure 4-3: Examples of converging/diverging (C/D) flows

likely the controller has to monitor and implement altitude transition, speed and/or longitudinal separation. In this case, the converging flow and the resultant dense flow

may be part of the primary structure.

Critical Points

In this review of traffic patterns, critical points were analyzed as points with repetitive intersections of traffic, and, as a result, representing points of potential loss of separation. As such, critical points were identified as the intersection of dense flows or the focal point of a C/D flow. Areas of potential conflict (or critical areas) were not explicitly analyzed. Note, however, that a critical point might be located inside a given sector, but it might be critical to a group of other controllers, even in other facilities. One or more upstream controllers might be responsible to deliver aircraft in a given altitude, speed or longitudinal spacing, thereby allowing a feasible workload for the controller that actually oversees the critical point.

Figure 4-4 illustrates an example of crossing of flows as a variation of critical points. Another variation of critical points is merges or splits (M/S) of traffic. Naturally, the focal point of a C/D flow is always a M/S critical point (examples in Figure 4-3). The cases presented in Figure 4-5 are examples of merges or splits involving dense flows.

Many instances of critical points found in the NAS were not related only to two flows, but to many of them. These critical points were generally called stars, as they have more than four segments of traffic going out of them (Figure 4-6). Each star appeared to have its own particularities, featuring combinations of merge, split and crossing traffic behavior across different altitudes. A deeper directionality analysis of dense flows associated to a given star would be required to determine which of
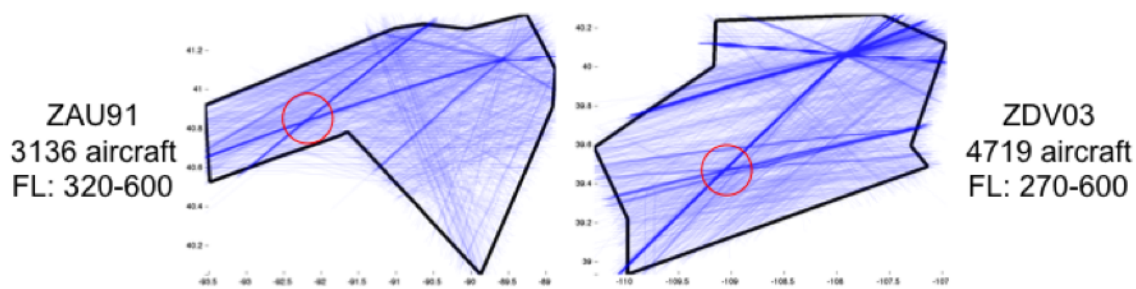
Figure 4-4: Critical Points: crossing
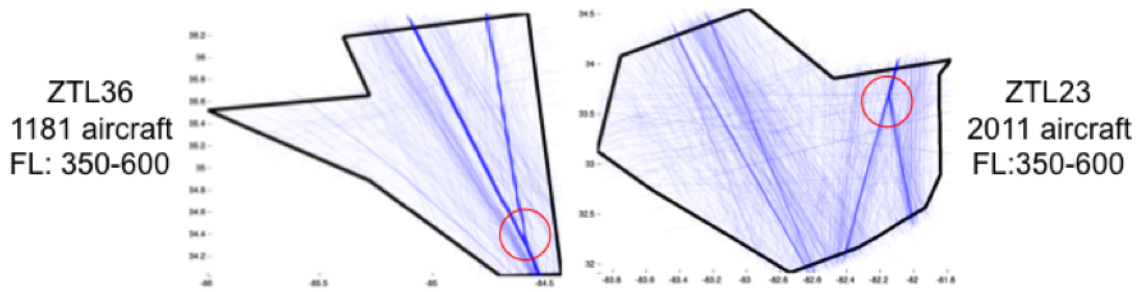
Figure 4-5: Critical Points: merge / split

them are crossing, merging or splitting. Moreover, stars were usually associated with some nearby disperse traffic, as a faded background traffic. It is not straightforward to ascertain if this surrounding traffic is background traffic. For example, as noted by Histon and Hansman (2008) and reviewed in Figure 2-5, controllers operate in different modes according to the number of aircraft. In less busy situations, an opportunity mode allows for shortcuts that might yield the background-like effect on the traffic plots.
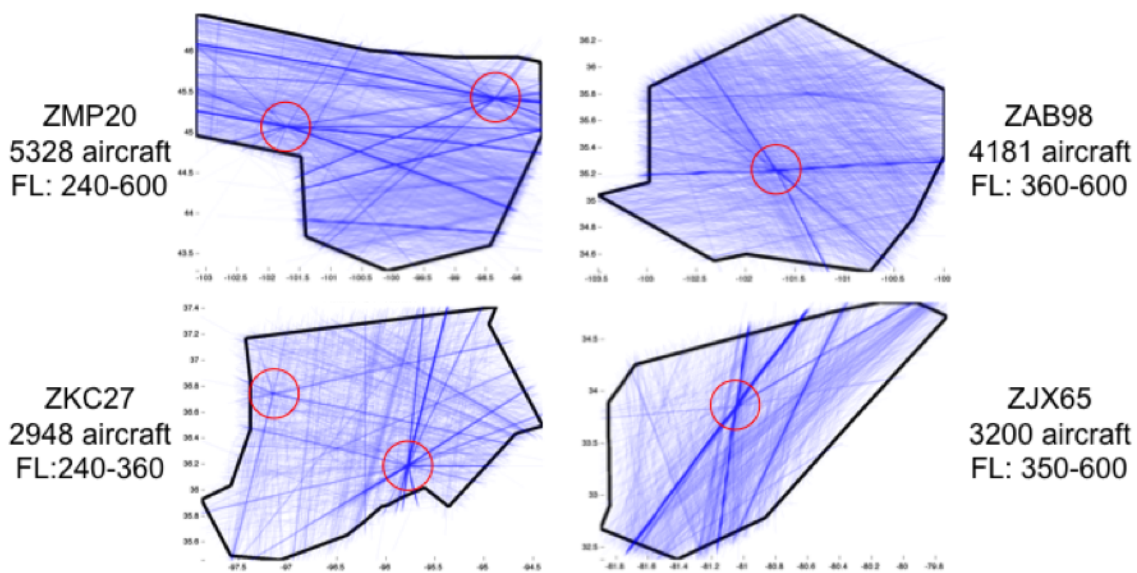
Figure 4-6: Critical Points: Stars

4.3 Analysis of Origins and Destinations

This Section starts presenting the overall linkage between internal and external structure and how this linkage can improve the understanding of the patterns in the traffic. Motivated by this linkage, groupings by origins and destinations (OD) in four OD case studies are identified and investigated in more detail. The objective is to use these groupings to identify the dynamics of the traffic that pertains to certain flows and critical points. These dynamics may provide an indication of the tasks that must be performed, and, therefore, how the traffic is managed.

By looking at the zoomed in or sector's view alone, much of the interrelationships (and, therefore, mutual constraints) of the structural features are not obvious. These interrelationships can be assessed from the analysis of the overall picture of the traffic. The use of the zoomed out view for better understanding of the sector's structural patterns is first exemplified with Oakland 33 (ZOA33) in Figure 4-7.

From this Figure, one can se that the east-west traffic is associated with the San Francisco area (airports OAK, SFO and SJC). More specifically, the upper flow goes to OAK, the mid flow and its associated merging patterns flies to SFO and the bottom flow goes to SJC. There is also a converging flow that goes to OAK and presents a focal point outside the sector. Traffic to SFO is also associated with a converging pattern that starts on upstream sectors and has a focal point at critical point CP1. Moreover, traffic to SFO also presents shortcuts that avoid the CP1 and extend to downstream sectors.

From Figure 4-7, one can also see a northwest-southeast traffic associated with Las Vegas. This traffic flies through two critical points close to the southeast border of ZOA33. One critical point (CP2), composed of traffic to LAS, is associated with a set of internal and external patterns. The third critical point (CP3), composed of traffic from LAS, also presents a set of other associated patterns, both inside and outside the sector. three weaker flows that cross ZOA33 and one stronger flow, outside ZOA33, that is related to LAS. The other critical point is related to two other flows outside ZOA33 that then present a C/D pattern inside ZOA33.
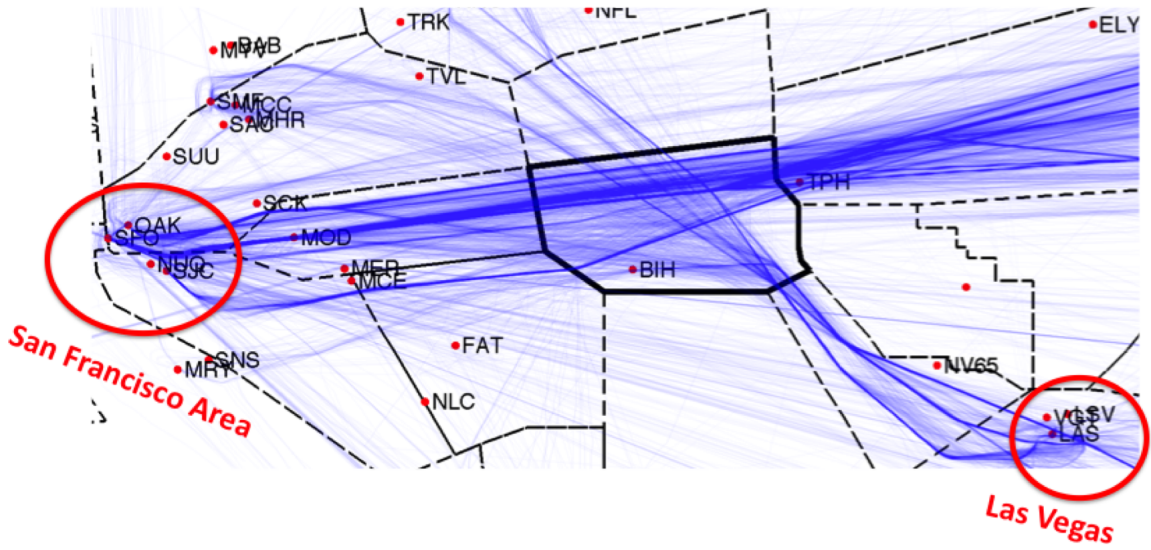
(a) Zoomed out view of ZOA33
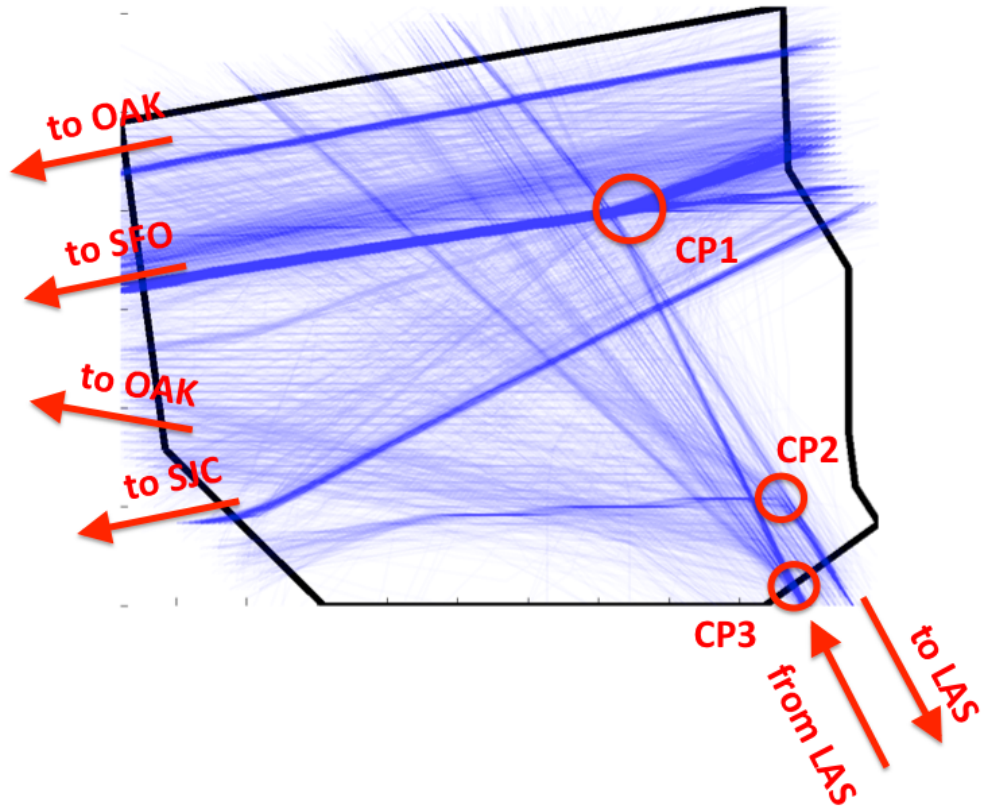
(b) Zoomed in view of ZOA33

Figure 4-7: External structure analysis of ZOA33. Illustration of the connection between internal structure and origins and destinations of the traffic.

This brief analysis of ZOA33 presents how the internal structure is connected to external features, such as airports and other flows.

Analysis of the external structure also allows the understanding of deviation of the traffic from the route structure, or the structural framework of the sector (composed of routes and reference points). Figure 4-8 below illustrates the zoomed in view and the structural framework for Moultrie sector, Jacksonville 49 (ZJX49). Visual inspection indicates that some routes depicted in the sector binder chart can be related to traffic patterns. But there are other flows and even critical points revealed from ETMS data that could not be mapped to published routes. Moreover, the conformance to those routes is not tight, that is, flows are usually associated with some traffic dispersion.

Figure 4-9 presents the zoomed out view of ZJX49. By looking at the external structure, the non-conformance to the structural framework can be seen as a result of (1) shortcuts to avoid a critical point and (2) directs connecting two reference points outside the sector boundaries. Therefore, there is a linkage between the internal structural pattern and the structural features that are external to the sector.

The observed connections between the internal structure and nearby airports im-
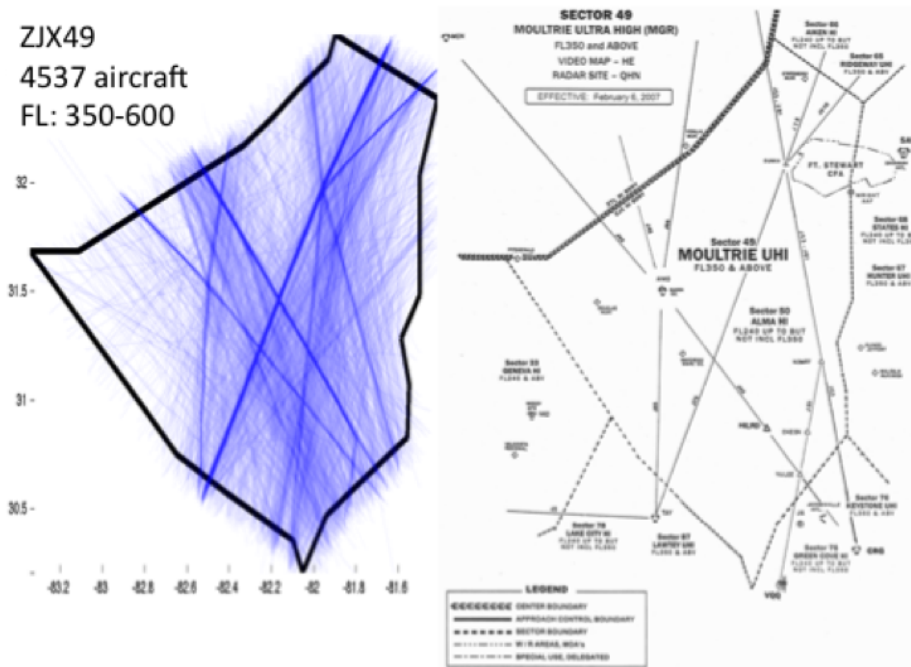
Figure 4-8: Zoomed in view and route structure for ZJX49
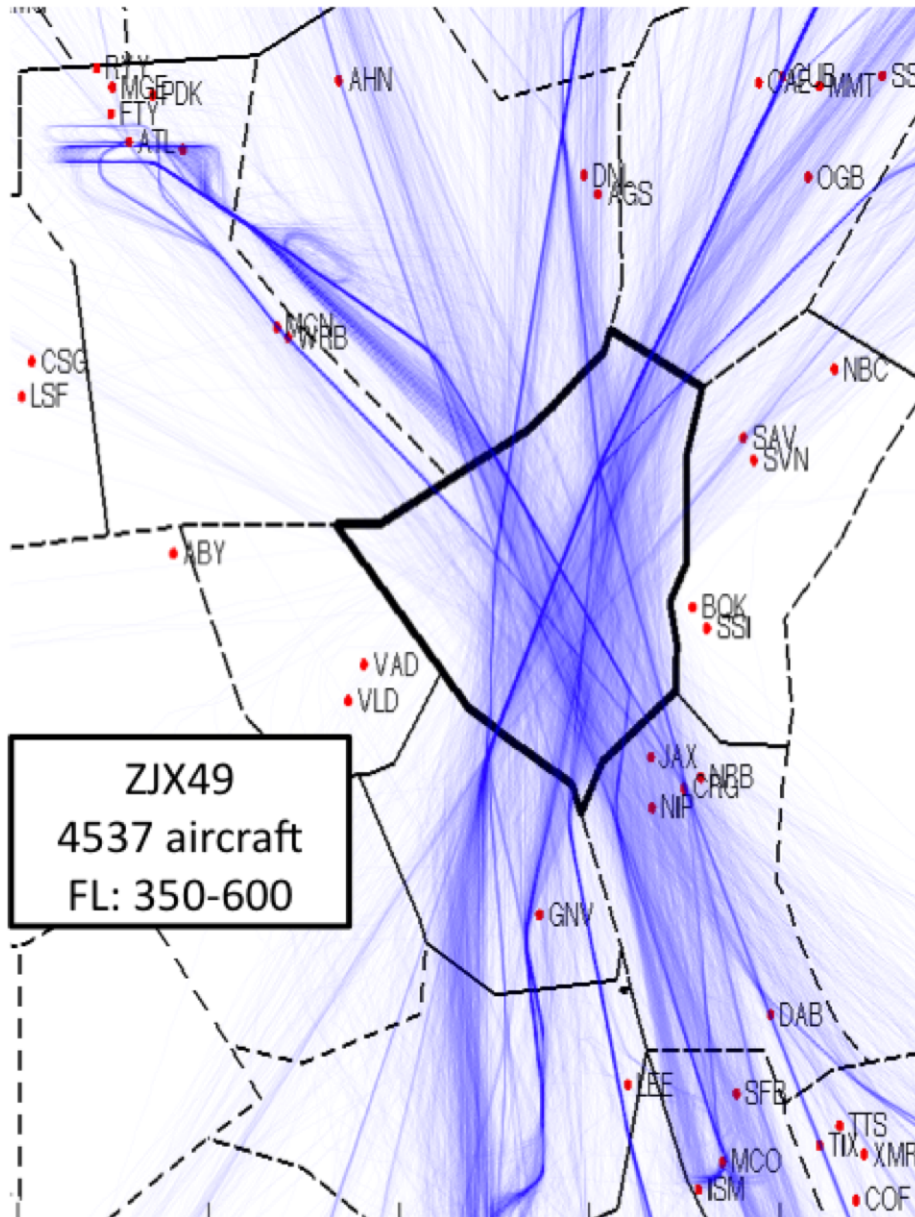
Figure 4-9: Zoomed out view of ZJX49

pose additional constraints on how to manage the traffic. As an example, from the sector binder of ZJX49: "The Moultrie Sector shall ensure that all aircraft landing within the Tampa Complex traffic cross the Moultrie/Lawtey boundary at or below FL380".

In fact, the correlation between origins and destinations with structural features in the sector is consistent with how controllers describe the flows inside the sector. For instance, a controller describing the low altitude sector ZBW22:

"The primary flows are EWR (Newark) area arrivals southbound over ALB..."[1]

Thinking in terms of groupings by origin and destination (OD) is consistent with the grouping structure-based abstraction introduced by Histon and Hansman (2008), whereby the controller distinguishes different parts of the air traffic situation that are expected to present same dynamics and require same actions. This Section analyzes origins and destinations by correlating these groupings with the structural features presented in Section 4.2 and the dynamics of the traffic. The objective is to investigate how OD groupings can possibly decompose the tasks in simpler and separate parts and to generate hypothesis about how controllers manage the traffic.

The correlation between OD groupings and the observed structural features is performed by highlighting the major origins and destinations in the traffic and evaluating how these segregate parts are linked to the major flows and critical points. The correlation between OD groupings and the dynamics of the traffic is conducted by considering lateral and vertical characteristics of the trajectories.

Four OD case studies were analyzed: Cleveland 59 (ZOB59), Boston 38 (ZBW38), Fort Worth 90 (ZFW90) and Albuquerque 98 (ZAB98). These sectors were selected based on the results of the previous Chapter. The motivation to analyze sectors with different characteristics was to consider a wider range of phenomena and how these phenomena were related to groupings by origins and destinations. ZOB59 was classified as a level sector with average complexity traffic; ZBW38 was classified as mixed altitude with low traffic; ZFW90 was classified in the climbing traffic group; and ZAB98 was classified as a level sector with high complexity. Figures 4-10(a) and 4-10(b) illustrate the membership of each of these sectors to the identified clusters in Chapter 3.

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[1]Source: http://nas-confusion.blogspot.com/2010/12/differently-similar.html
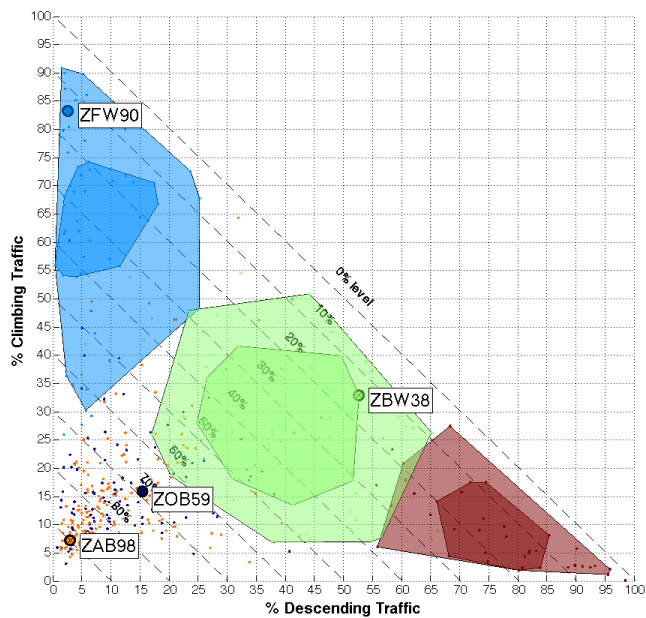
(a) Membership of sectors to clusters with respect to percentage of altitude transitions
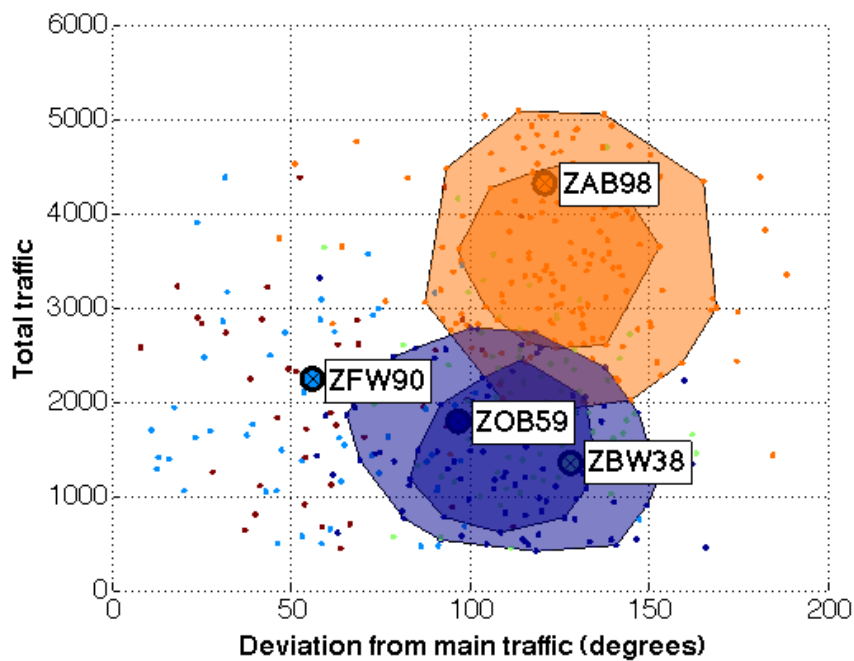
(b) Membership of sectors to clusters with respect to total traffic and deviation from main traffic

Figure 4-10: Illustration of cluster membership of analyzed clusters.

4.3.1 OD Analysis: Cleveland 59 (ZOB59)

The plot in Figure 4-11 suggests three flows that are highly salient and connected to airports in New York and Philadelphia. Other patterns in this sector are a C/D flow and holding patterns associated with one of the dense flows. The analysis of this case study aims to investigate how each of these distinct and salient patterns are related to origins and destinations and if any other secondary structural feature can be identified by highlighting traffic to or from specific airports.

ZOB59 also provides a case study of a member of the moderate complexity cluster (level traffic with some dispersion and medium traffic density - Figure 4-10), presented in Section 3.2. The sector spans the flight levels 330 and above. From the radar track data, 69% of flights were in level flight, 16% were climbing and 15% were descending[2].

Figure 4-12 presents a 3D histogram with the percentage of traffic traveling from the top 15 origins to the top 15 destinations. Figure 4-13 presents the traffic for the top 15 origins and destinations, but separately. Both figures indicate that the traffic is mainly between New York, Philadelphia and Chicago. As an exception, there is a minor pattern from BOS to CVG with approximately 1% of the total traffic (Figure

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[2]In this Chapter, the definition of altitude transition is the same as in Chapter 3, that is, based on total transition from entrance to exit greater or equal to 1000ft.
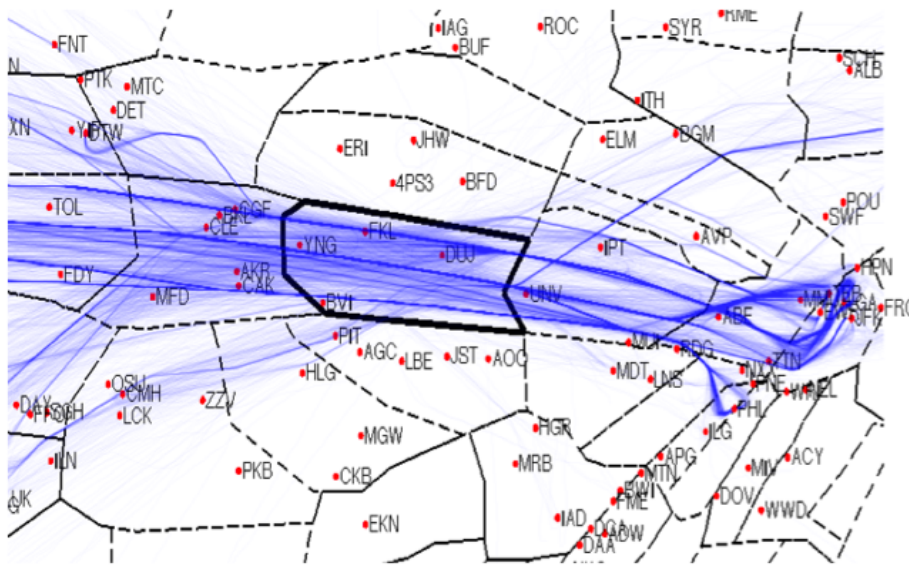
Figure 4-11: ZOB59: Zoomed out view
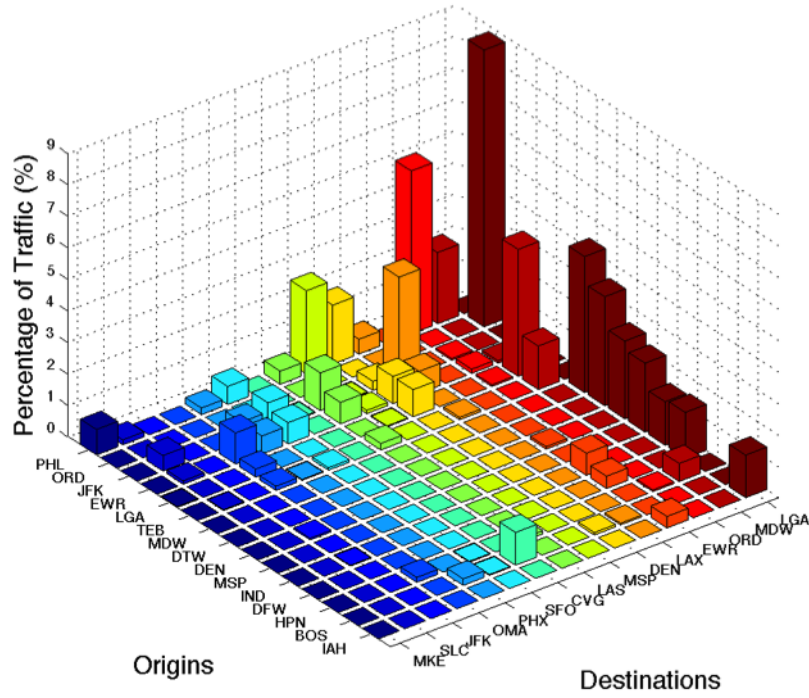
Figure 4-12: ZOB59: 3D histogram containing top 15 Origin and Destinations

4-12). The top destination of the traffic is LGA, whereas the top origin is PHL, even though there is no traffic between these cities.

In Figure 4-14, for sake of brevity when illustrating the method, only the top 3 destination airports are highlighted. Notice how certain structural features can be mapped to specific airports. For instance, the traffic to LGA is associated with a dense flow, a C/D flow and holding patterns, together accounting for 34% of ZOB59 traffic. Flights from ORD, MDW and DTW were observed to follow the dense flow.
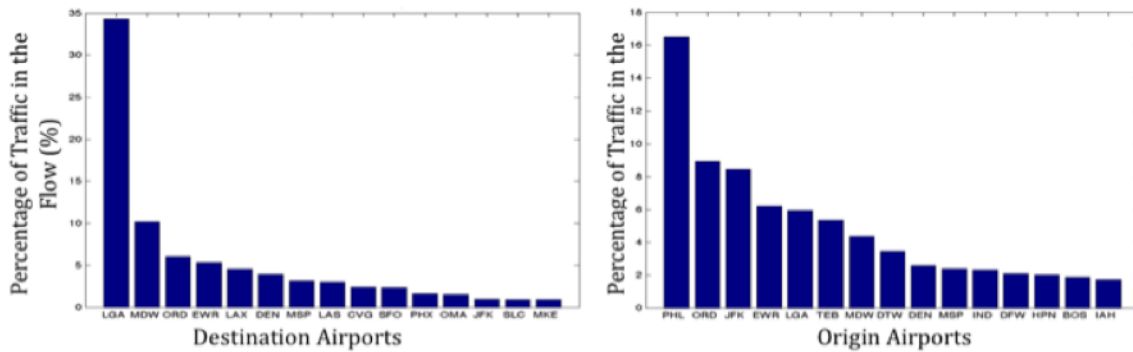
Figure 4-13: ZOB59: Histograms of top 15 Origins and Destinations

86
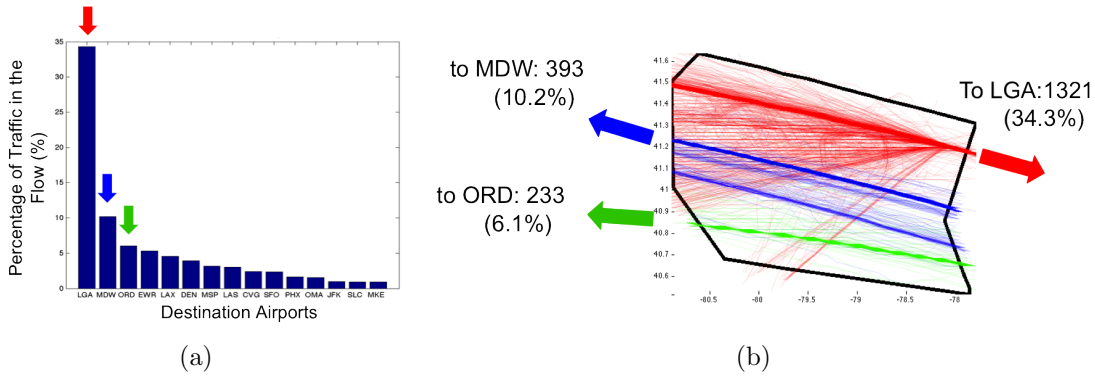
Figure 4-14: Correlating traffic with top destinations

It was also found that the C/D flow is associated with many scattered origins, each accounting for less than 5% of the total traffic to LGA. The holding pattern also has a mix of origins.

The traffic to MDW is associated with a dense flow and lighter parallel flows, accounting for 10.2% of the traffic. The major origins are LGA, PHL and TEB. Traffic to ORD takes only a dense flow in the southern most part of the sector, accounting for 6.1% of the traffic. Approximately 85% of this traffic comes from PHL.

The traffic from the top 3 airports is highlighted in Figure 4-15. Traffic from PHL (16.5%) is scattered across the dense and light flows in the southern most part of the sector. The major destinations for these flows are ORD, MSP, MDW and DEN. The
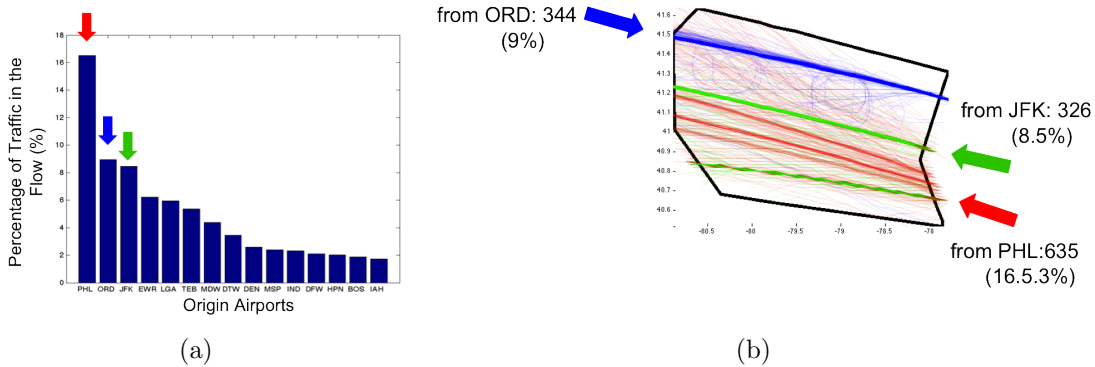
Figure 4-15: Correlating traffic with top Origins

second top origin is ORD (9%), with almost all of it going to LGA (98%). The next top origin is JFK (8.5%), also taking some of the southern flow patterns. This traffic is mainly going to further destinations, such as LAX, LAS, SFO, PHX and SAN.

Figure 4-16 presents a summary of the traffic decomposition of Figure 4-14 and Figure 4-15. This plot correlates the major origins and destinations associated to each one of the densest flows.

Figure 4-17 presents altitude changes for the traffic of ZOB59. Every minute of the radar track data for each flight was evaluated in terms of altitude transitions and colored accordingly. Green color indicates a climb rate greater or equal to 1000ft/min, red indicates a descend rate greater or equal to 1000ft/min and blue indicates an absolute altitude change smaller than 1000ft/min. Note how the C/D flow crosses the entire sector and starts descending to New York on the following sector. Traffic from DTW reaches top of climb right before entering the official boundary of ZOB59 and joining the flow to LGA. The traffic from New York and PHL also reach top of climb right before entering ZOB59. Furthermore, the top of descent of traffic to LGA occurs as soon as entering ZNY ARTCC.

Figure 4-17 also presents a minor pattern that crosses the sector in the southwest direction and starts descending to CVG in the vicinities of PIT. This pattern includes New York traffic, as well as BOS traffic already identified in Figure 4-12. It is clear
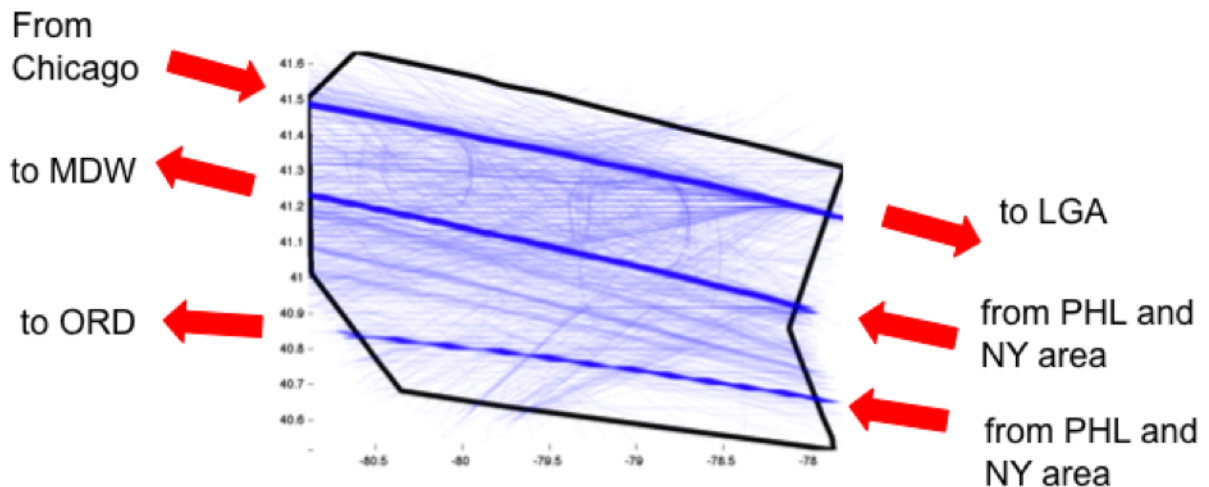
Figure 4-16: ZOB59: Structural features correlated with top Origins and Destinations

88
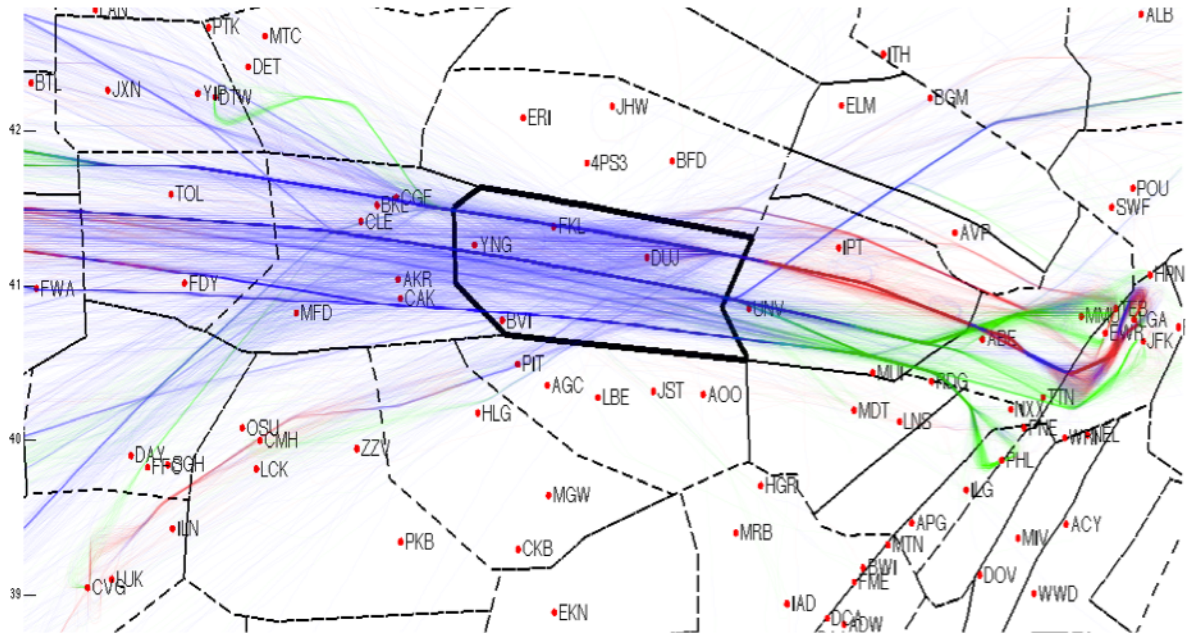
Figure 4-17: ZOB59: Zoomed out view and altitude changes. Green color indicates a climb rate greater or equal to 1000ft/min, red indicates a descend rate greater or equal to 1000ft/min and blue indicates an absolute altitude change smaller than 1000ft/min.

from Figure 4-17 that flights from BOS merge to this pattern around UNV, shortly before entering ZOB59 area of responsibility.

Summary for ZOB59

OD groupings could identify the rationale of different flows and their directions. The converging pattern to LGA was associated with several origin airports. Moreover, it also presented some holding patterns. Traffic from NY area and PHL was found to be generally segregated in different flows, depending on the destination (ORD or MDW).

It was found that not only one, but few flows could be identified when filtering for a specific destination or origin. This might be an indication of user preferred routes and weather effects. Conversely, several origins or destinations were found to be associated with the same flows.

A secondary crossing flow from BOS to CVG could also be identified. This traffic appears as an isolated spike in the origin - destinations pairs histogram (Figure 4-12).

4.3.2 OD Analysis: Boston 38 (ZBW38)

The OD case study of ZOB59 had several origins and destinations related to altitude transitions. But these transitions were mainly outside the sector and the flows appeared not to interact much with each other. ZBW38 is analyzed in order to investigate how origins and destinations can be correlated with structural features in a sector that has mixed altitude transitions: both departing and arriving traffic. Furthermore, ZBW38 also allows the analysis of a star critical point in the southeast portion of the sector, originated from the intersection of traffic associated with Boston and Providence (Figure 4-18). As in ZOB59, this sector also presents a C/D flow with focal point inside the sector, more specifically in the vicinities of ALB.

The altitude transitions for ZBW38 were 52% descending, 33% climbing and 15% in level flight. The sector had low traffic volume and low directional variability. In the analysis of Section 3.2, ZBW38 was classified as a member of the low traffic, mixed operations cluster (low traffic density, low deviation of traffic, medium directional entropy and mixed altitude transitions - Figure 4-10) . The sectors spans from FL240 and above.

Figure 4-19 and Figure 4-20 present counts of traffic to OD pairs, origins and destinations. One can see that the traffic has one main destination (BOS) and two
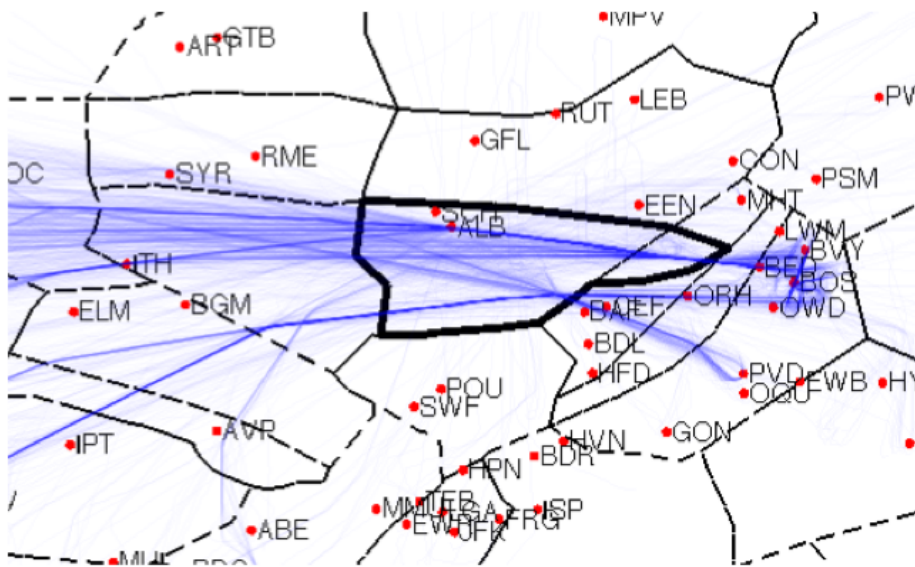
Figure 4-18: ZBW38: Zoomed out view
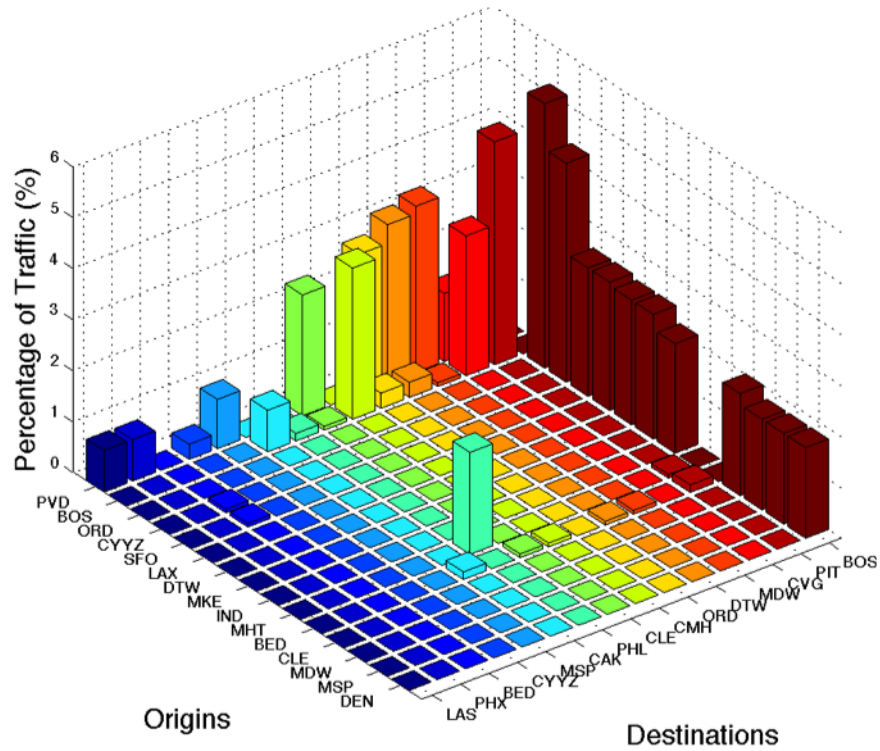
Figure 4-19: ZBW38: 3D histogram containing top 15 Origin and Destinations

top origins (PVD and BOS). 48% of the traffic goes to BOS, coming from several places, such as ORD , CYYZ, SFO, LAX, MKE and DTW. The top origin of the traffic is PVD (16.6%), going mainly to MDW, DTW, ORD and CLE. The second top origin is BOS (13.8%), going mainly to PIT, CMH and CVG. Interestingly, as an isolated peak in Figure 4-19 and ranked as the 15th busiest OD pair (27 flights or 2% of total), is the traffic from MHT to PHL.
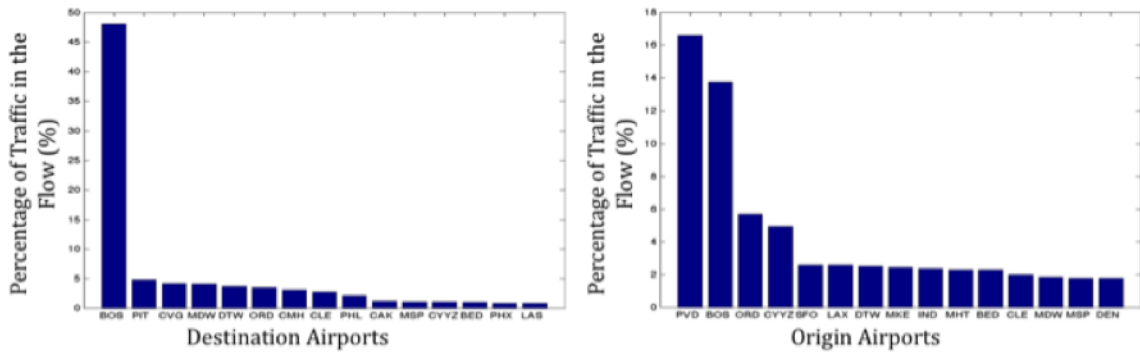
Figure 4-20: ZBW38: Histograms of top 15 Origins and Destinations
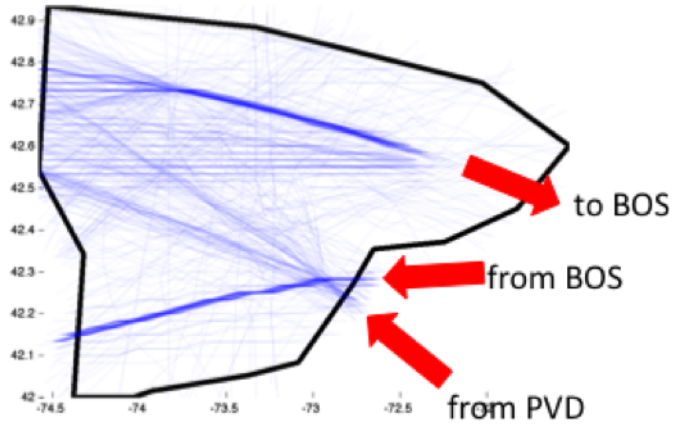
Figure 4-21: ZBW38: Structural features correlated with top Origins and Destinations

Figure 4-21 correlates the major origins and destinations with the subjectively identified structural features. Figure 4-22 presents altitude changes in ZBW38. BOS and PVD departures were found to have a combination of crossing and merging interaction. At the critical point, the traffic from PVD fanned out to its destinations, most notably into two secondary flows, one going to Detroit and the other to Chicago and beyond. Flights in these flows kept climbing almost halfway through the sector, whereas crossing traffic from BOS reached top of climb before the critical point. Some PVD departures also merged with BOS departures If going to CVG or even further
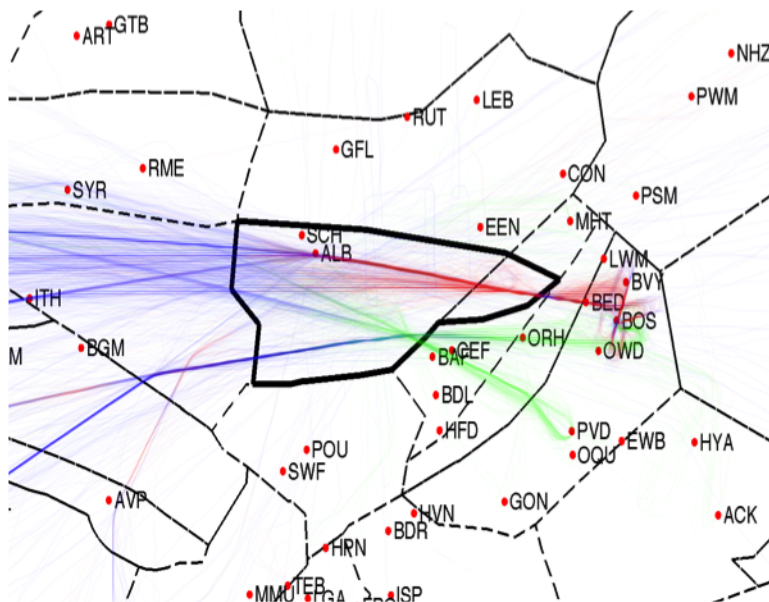
Figure 4-22: ZBW38: Zoomed out view and altitude changes. Green color indicates a climb rate greater or equal to 1000ft/min, red indicates a descend rate greater or equal to 1000ft/min and blue indicates an absolute altitude change smaller than 1000ft/min.

destinations like LAX or PHX. The arrivals to BOS started descending very close to the sector boundary, especially past ALB.

A deeper analysis shows that some of the departures from BOS and PVD actually reach top of climb before entering the official boundary of the sector.Moreover, the background traffic (traffic belonging to less dominant ODs) was found to be mainly in level flight throughout the sector.

Figure 4-23 presents the traffic from MHT to PHL alone. The radar tracks are plotted with greater opacity, so they can be better visualized. This Figure illustrates how a weaker pattern can still be laterally and vertically consistent across different days.
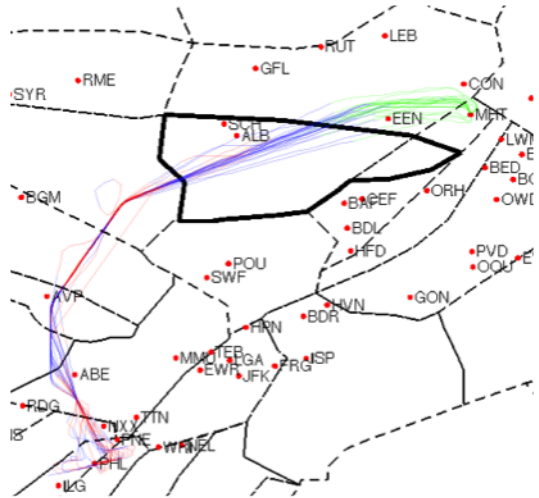
Figure 4-23: ZBW38: Zoomed out view and altitude changes for MHT – PHL traffic (transparency level set to 10%)

Summary for ZBW38

This OD case study presented a high altitude sector with altitude transitions within its lateral boundaries. This sector is a combined case of strong climbing traffic from few origins to scattered destinations and strong descending traffic from varied origins to few destinations. This can be seen as a "L" shape on the distribution of origin - destination pairs in Figure 4-19. The observation that the major task is of managing altitude transitions is further evidenced by the fact that level flights in ZBW38 is mainly amongst the background traffic (traffic outside the "L" pattern).

Both top origins of ZBW38 were correlated with the dynamics at the critical point.

Namely, at this point, most of the traffic from PVD is still climbing and fans out to its destinations, apparently unaffected by the crossing traffic from BOS that had already reached top of climb. Furthermore, the top destination, traffic to BOS, accounts for almost half of the traffic. This traffic was associated with a C/D flow combined with a dense flow, as in ZOB59. These arrivals start descending very close to the sector boundary, especially past ALB.

An isolated origin-destination pair (MHT-PHL) could also be identified. This constitutes in a crossing traffic (Figure 4-23), that was not initially visible in Figure 4-18 due to the transparency settings of the radar tracks.

4.3.3   OD Analysis: Fort Worth 90 (ZFW90)

The objective of the origin and destination analysis of ZFW90 is to identify the rationale for separate flows with traffic departing from the same origin. Figure 4-24 below presents the lateral boundaries of the sector, as well as altitude changes and the traffic extension to the surroundings. There is indication of two major dense flows and a crossing flow on the east-west direction. There is also a background traffic taking most of the airspace between the two major flows, probably as a result of operational variations. Noticeably, the traffic is mainly related to the Dallas and Fort Worth region.
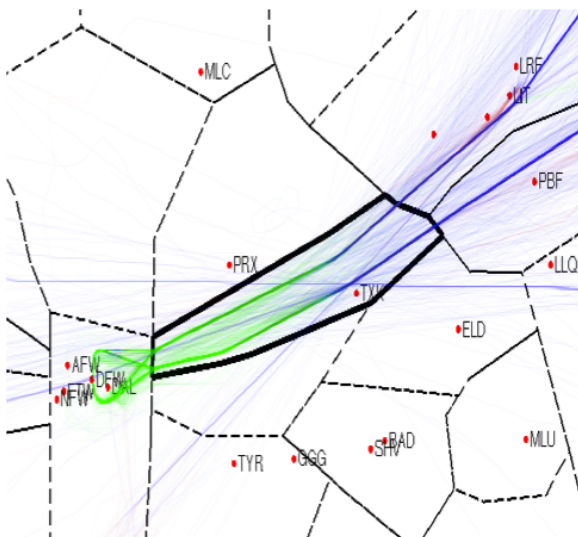
Figure 4-24: ZFW90: Zoomed out view and altitude changes. Green color indicates a climb rate greater or equal to 1000ft/min, red indicates a descend rate greater or equal to 1000ft/min and blue indicates an absolute altitude change smaller than 1000ft/min.

The altitude transitions for ZFW90 were 83% climbing, 2% descending and 15% in level flight. As presented in Figure 4-24, top of climb occurs almost two-thirds past the length of the sector. Traffic to LIT starts descending on the following sector, due to the proximity of this airport. ZFW90 had intermediate traffic volume, very low directional variability and high traffic origin concentration. As such, the sector was classified in the climbing cluster (Figure 4-10), in the analysis of Section 3.2. The sector is from FL240 to FL360.

Figure 4-25 and Figure 4-26 confirm this by showing that most of the traffic is from DFW (77%) and DAL (8%). Destinations of the traffic, however, are quite scattered, the major destinations being LIT (9.5%), then DCA (6.3%) and PHL (5.8%). More specifically, half of the traffic from DAL goes to LIT, in contrast with the traffic from DFW that goes to various destinations in the north and east parts of the country.

A similar analysis as the one conducted for ZOB59 indicates that both dense flows and the background traffic are associated with DFW. The dense flow situated in the north is also associated with DAL and the lighter crossing flow goes from ATL to
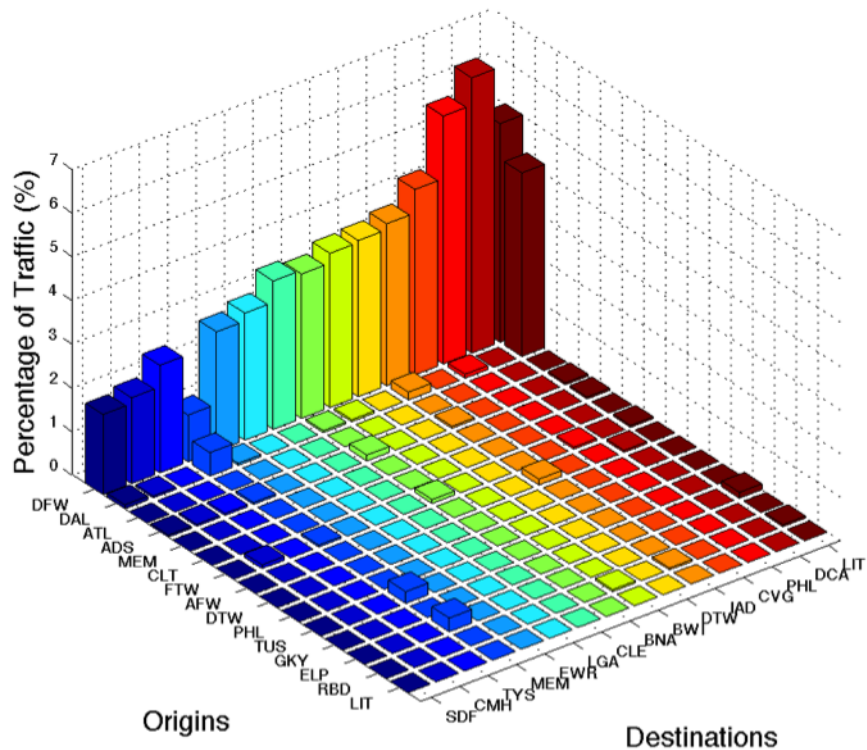
Figure 4-25: ZFW90: 3D histogram containing top 15 Origin and Destinations

95
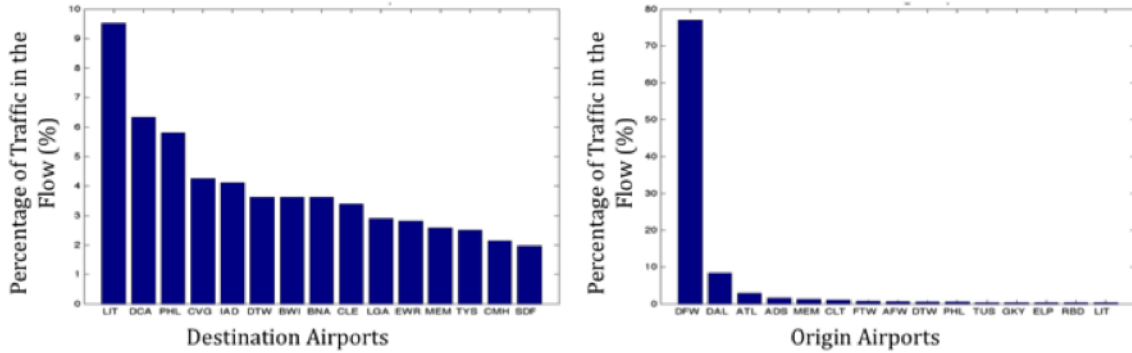
Figure 4-26: ZFW90: Histograms of top 15 Origins and Destinations

western destinations. Figure 4-27 presents a summary of the traffic decomposition. This plot correlates the major origins and destinations associated with each one of the most salient flows.
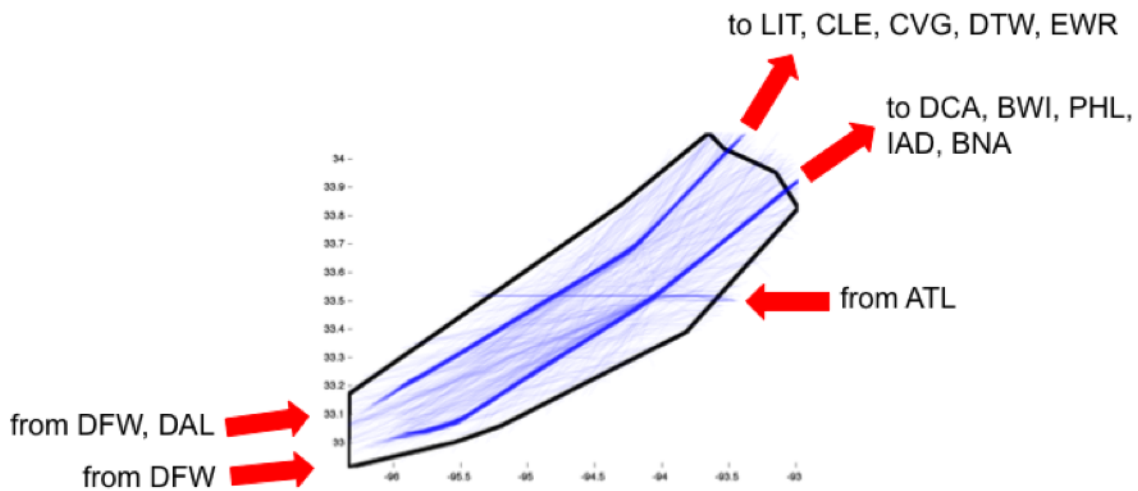
Figure 4-27: ZFW90: Structural features correlated with top Origins and Destinations

Summary for ZFW90

Groupings by origin and destinations indicated that the separation in two different flows for ZFW90 is mainly based on the destination airports of the traffic. Traffic from DAL constitutes a small percentage of the total traffic and it only took the northern flow, suggesting that most of the DAL traffic takes different routes. However, the route from DAL to LIT is more logical if going through ZFW90, which is reflected in the fact that most of the DAL traffic goes to this specific airport.

4.3.4 OD Analysis: Albuquerque 98 (ZAB98)

This OD case study aims to analyze how different origins and destinations correlate with a structure that is clearly more diffuse. The zoomed in view of ZAB98 suggests a star critical and a large portion of background traffic. When looked externally (Figure 4-28), the northwest-southeast traffic is mainly related to C/D flows with focal points outside the sector. There is also indication of a scattered east-west traffic that is not related to any specific airport nearby ZAB98 and takes most of the sector's area.

The altitude transitions for ZAB98 were 7% climbing, 3% descending and 90% level. The sector had high traffic volume and high directional variability, thereby falling in the cluster of high traffic and high directional variability (Figure 4-10) in Section 3.2. The sector includes all the flight levels above FL360.

Figure 4-29 illustrates that the traffic is highly distributed in several origins and destinations. Even the top OD pair accounts for only 3.3% of the total traffic. But there is still some concentration when looking to origins or destinations alone, as shown in Figure 4-30. The major destinations are DFW (8.7%), ATL (8.1%), IAH (7.8%), PHX (6.9%), LAX (6.9%), LAS (5.2%) and DEN (5.2%). As shown in Figure
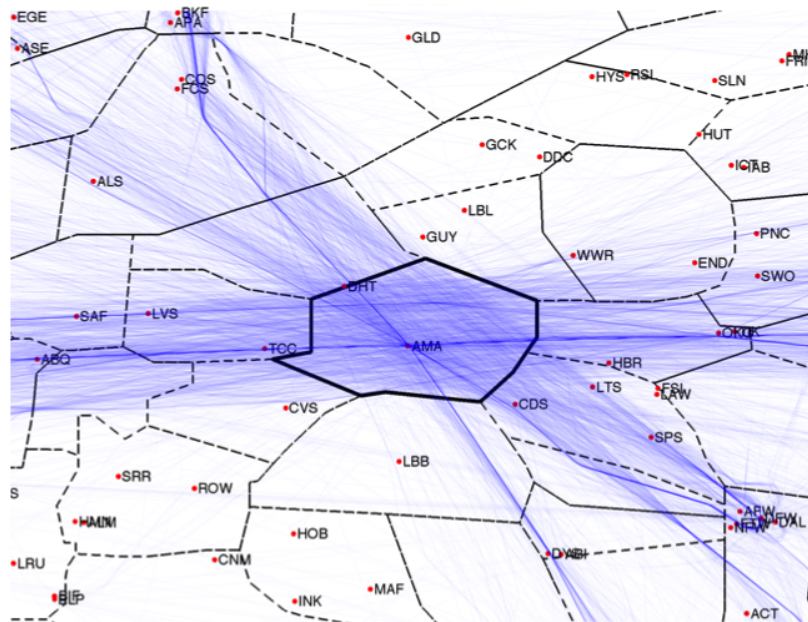
Figure 4-28: ZAB98: Zoomed out view
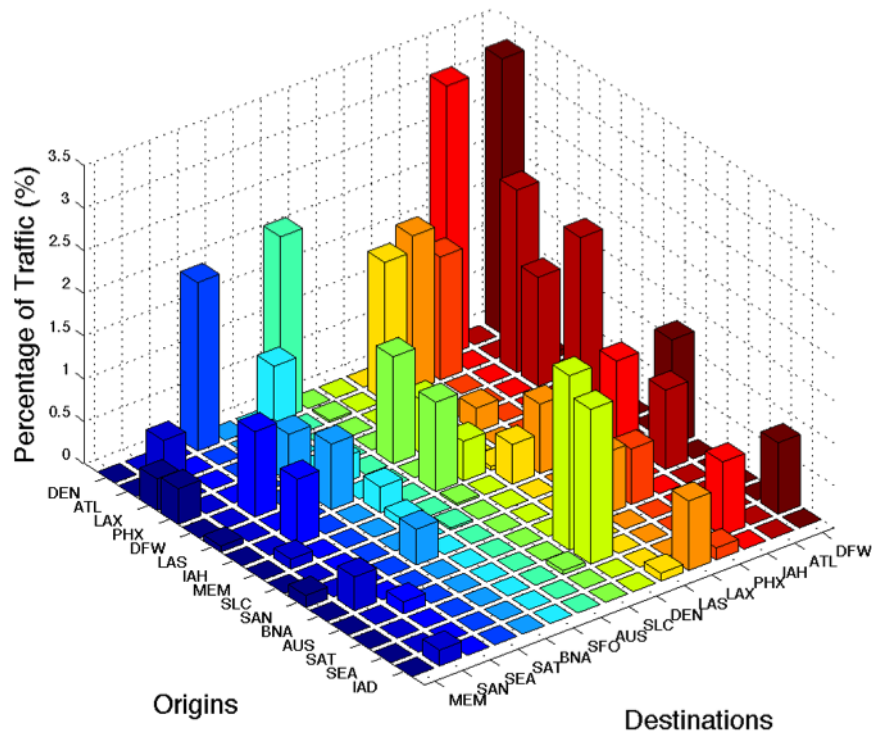
Figure 4-29: ZAB98: 3D histogram containing top 15 Origin and Destinations
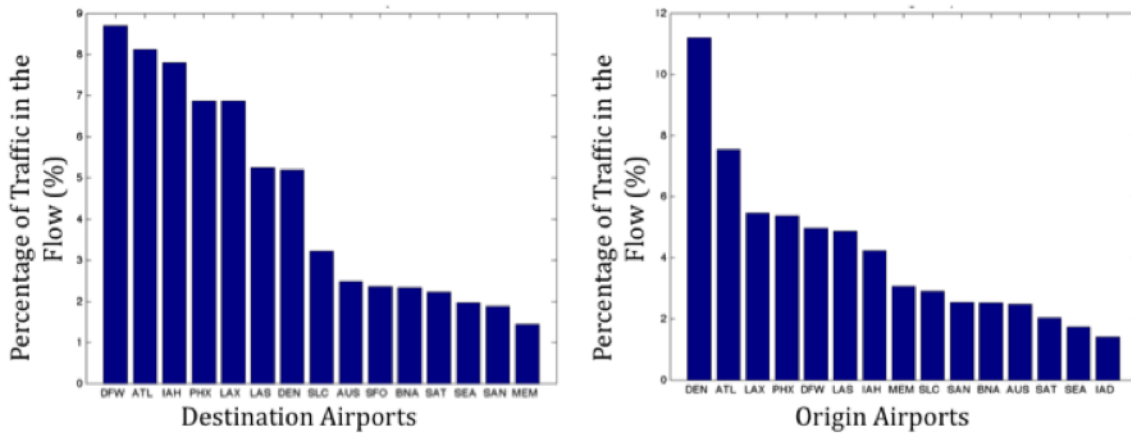
Figure 4-30: ZAB98: Histograms of top 15 Origins and Destinations

4-30, traffic departs mainly from DEN (11.2%), ATL (7.5%), LAX (5.4%) and PHX (5.4%).

Traffic going to or coming from DFW and IAH can be mapped to the C/D flows on northwest-southeast direction. These C/D flows have focal points in the proximity of the respective airports. As an example, Figure 4-31 shows the zoomed out view, with altitude changes, for the traffic to and from DFW, with 10% transparency level.

98
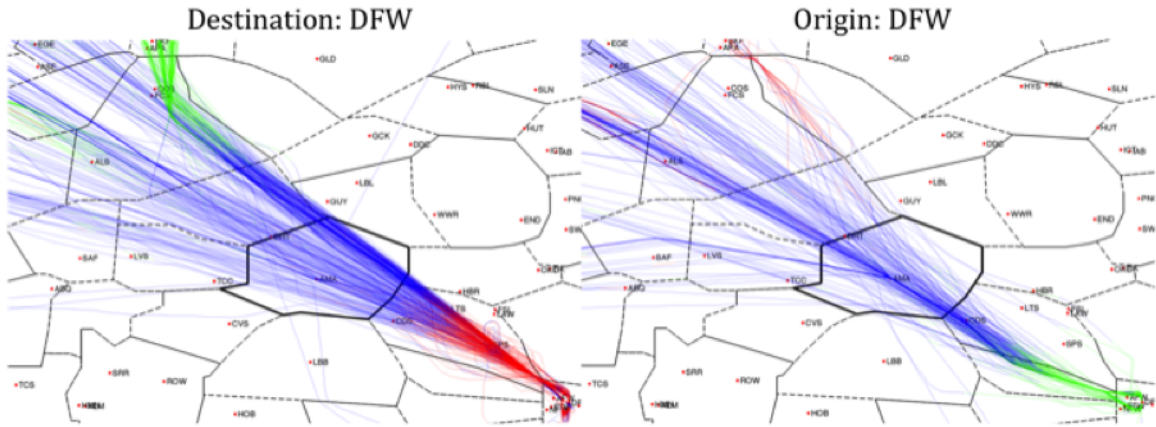
Figure 4-31: ZAB98: Zoomed out view and altitude changes for traffic related to DFW. Green color indicates a climb rate greater or equal to 1000ft/min, red indicates a descend rate greater or equal to 1000ft/min and blue indicates an absolute altitude change smaller than 1000ft/min.

DFW is ranked the first traffic destination and the fifth origin, together accounting for 13.7% of the traffic (the top airport is DEN with 16.2% of the traffic). Figure 4-31 illustrates the C/D flows associated with DFW that can equally be observed for traffic associated with DEN, IAH, SEA and SLC.

Traffic to and from airports to the east (ATL) or to the west (PHX, LAX, LAS) of the sector is generally manifest in slowly converging traffic that spans the entire sectors airspace. Some of this traffic follows more precise paths and pass through the critical point.

Summary for ZAB98

ZAB98 is an example of a sector where the structural features accommodate several origins and destinations, following mainly the east-west and the southeast-northwest directions. This scattered distribution of ODs reflects on the dispersed traffic passing through the sector. Still some correlation between structural features could be found, as in Figure 4-31, where traffic from and to DFW is manifested in two laterally offset C/D flows.

4.4 Summary

The analysis of structural patterns presented in this Chapter started with a simplified approach, whereby traffic from two weeks of ETMS data was collapsed in two-dimensional plots. In this first step, several high altitude sectors were analyzed considering the traffic within the sector's boundaries (zoomed in view), as well as extensions of this same traffic up to 200 nautical miles away from the sector (zoomed out view). This analysis allowed for an appreciation of the enormous structural diversity across the NAS. It also allowed for an understanding of the typology of observed structural features, such as flows and critical points.

The identified types of flows and critical points were also found to vary significantly across the NAS. These structural features were observed to manifest in several possible combinations, yielding structural patterns with different levels of apparent complexity. It was found that some of the apparent complexity in a sector could be explained when referring to the external structure. The external structure also helped to understand deviation of the traffic from what is prescribed from the existing routes.

The dynamics within and between identified structural features were then investigated via an analysis of origins and destinations. Based on the analysis conducted in the previous Chapter, four sectors categorized in distinct traffic dynamics groups were analyzed in more detail. The analysis consisted in correlating origins and destinations in the traffic with the identified structural features.

By analyzing sectors that were classified in different traffic dynamics groups, this Chapter observed different phenomena, such as altitude transitions, mergings, crossings, splits and combinations thereof. OD groupings could identify the rationale for different parallel flows (in ZOB59 and ZFW90), the dynamics in the critical point (in ZBW38), the nature of converging flows (in ZOB59, ZBW38 and ZAB98), existence of secondary flows (in ZOB59 and ZBW38) and flows in diffuse structures that have higher apparent complexity (in ZAB98).

Thus, structural features and their dynamics (merges, splits, crossing and altitude transitions) could be correlated with origins and destinations. This observation

motivated the hypothesis that groups of flights with same planned trajectory might be the structural features that controllers use to manage the traffic. The correlation between groups with same planned trajectories and techniques used by the controllers is the topic of the following Chapter.

Chapter 5

Analysis of Impact of Structure on ATC Techniques

The objective of this Chapter is to investigate whether groups of similar planned trajectories can be correlated with the dynamics of the traffic and the underlying techniques.

In the previous Chapter, structural features and their dynamics could be correlated with origins and destinations of the traffic. This motivated the hypothesis that groups of same planned trajectory are correlated with the underlying structural features and their dynamics. In addition to that, it was also hypothesized that groups with similar planned trajectories would manifest similar dynamics and would be managed by the controller with the same sequences of commands. A planned trajectory is considered to be determined by a flight plan, including planned lateral trajectory as a sequence of reference elements (routes and navaids) and, naturally, an origin and destination.

5.1 Methodology

The methodology consisted in observing controllers actions in managing the traffic and correlating their commands with groups of planned trajectories. The air traffic situation had also to be considered, because it provided the constraints and the

context for analysis, such as possible conflicts that developed, intents manifested via requests or presence of weather interference.

Figure 5-1 highlights aspects of the cognitive process model (Histon & Hansman, 2008) that were observed in this analysis. The execution processes were observed by listening to controller-pilot voice communications. Groupings by flight plans were identified by carefully looking at planned lateral trajectories and origins and destinations of flights through the sector. Plotting the sector traffic just like in Chapter 4 also enabled the subjective determination of flows and critical points.

The commands that were given to members of a given flight plan grouping were analyzed in terms of their repeatability within the same group. Inference of standard techniques was obtained via identification of repetitive sequences of observed clearances within a group, under the context of the air traffic situation. Finally, the identified structural features were correlated with groupings by flight plans, also under the context of the air traffic situation.
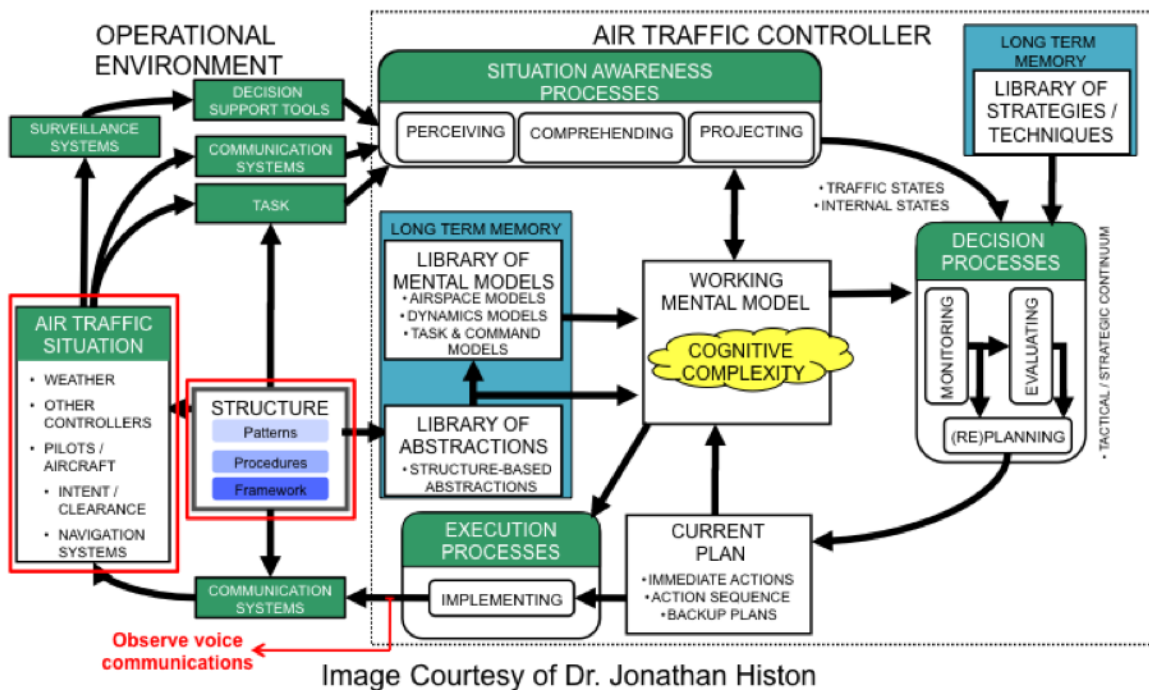
Figure 5-1: Cognitive Process Model including observations (adapted from Histon and Hansman (2008)).

5.1.1   Evaluation Data

The selection of sectors for analysis was restricted by the availability and quality of controller-pilot voice communication data. Voice communications were obtained from `www.liveatc.net`, a publicly available database that contains audio archives for some of the ATC facilities. Only sectors located in the higher stratum of the NAS were considered for this study (ceiling above FL240), since they represent less complex airspace and they are less impacted by local operational constraints.

Furthermore, in low workload situations, controllers work under the Opportunity Mode, thereby not enforcing as much the structure and allowing each aircraft to optimize its own trajectory (Histon & Hansman, 2008). For the objectives of this work, it was necessary to observe the enforcement of structural patterns and how they were related to techniques, i.e. the Route Structure Mode (see Figure 2-5).

Thus, sectors with noticeably low level of communications were not used, since they lacked the time pressure to force controllers to use pre-solved solutions for each traffic pattern. The measure of channel capacity usage was obtained by truncating the silence of the 30 min audio files extracted from `www.liveatc.net`.

Three sectors satisfied these constraints: New York 10 (ZNY10), Chicago 25 (ZAU25) and Miami 40 (ZMA40). The membership of each of these sectors to the identified clusters in Chapter 3 are presented in Figure 5-2. Notice that there is one sector classified as climbing (ZNY10), one sector classified as descending (ZAU25) and one with mixed altitude transitions (ZMA40). The geographical location of these sectors is presented in Figure 5-3. Attention was given to evaluate at least a morning and an evening traffic without weather and under moderate traffic volume. Bad weather was identified from the amount of pilot requests due to ride conditions. Provided by `www.liveatc.net`, METARs at the same time of the audio archives were also used as an indication of bad weather.

Once the flights through a sector were identified, their flight plan and radar track history were extracted from `www.flightaware.com`. The sector boundaries and structural framework in the sector location were taken both from `www.skyvector.com` and
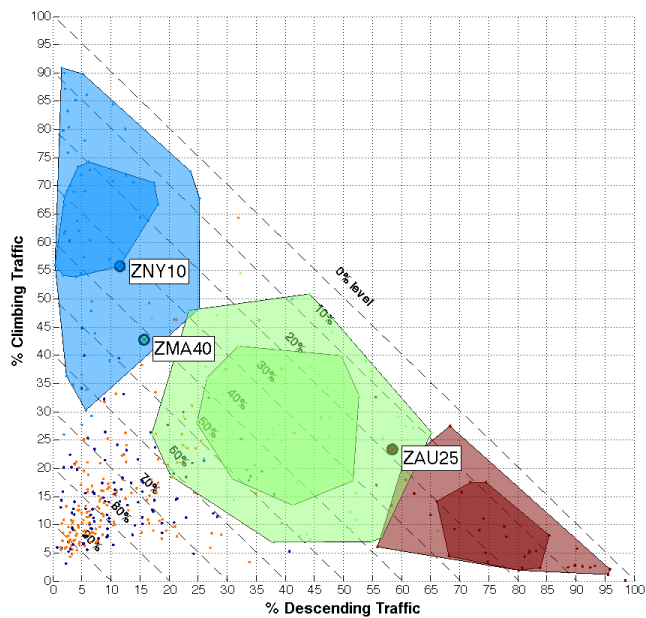
(a) Membership of sectors to clusters with respect to percentage of altitude transitions
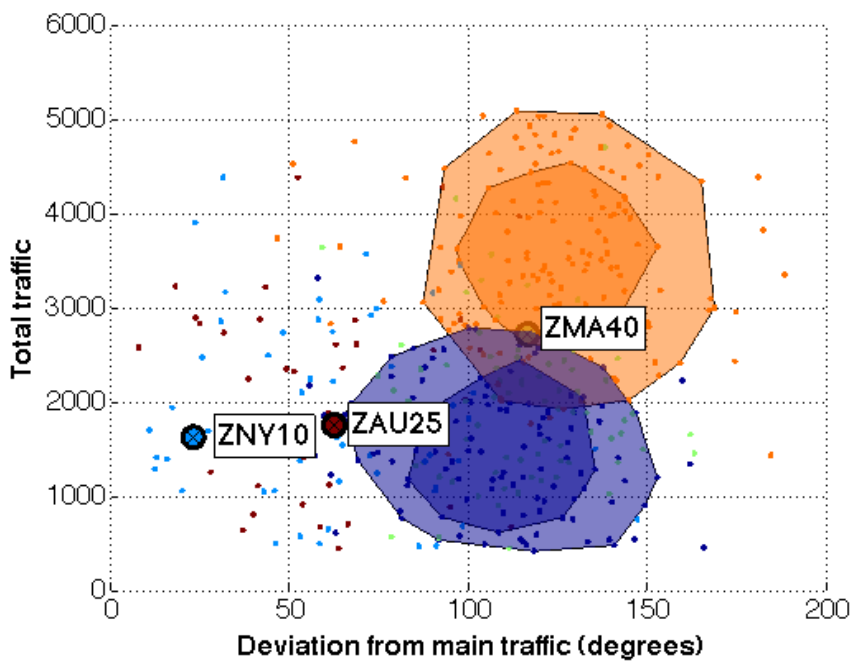
(b) Membership of sectors to clusters with respect to total traffic and deviation from main traffic

Figure 5-2: Illustration of analyzed sectors in each cluster.

Figure 5-3: New York 10 (ZNY10), Chicago 25 (ZAU25) and Miami 40 (ZMA40) were selected for the communication analysis. Among the ATC facilities for which public voice communication was available, these sectors satisfied the constraints of (1) being located in the higher stratum of the NAS (ceiling above FL240); and (2) presenting intermediate level of communications

2009 data provided by FAA. Whenever necessary, sector frequencies were obtained from `www.radioreference.com`.

5.1.2 Analysis of voice communication

The voice communications were converted into transcripts. The details of each controller-pilot communication were coded into a tabulated form, which included information of the check-in and handoff process, pilot repetitions, pilot requests, traffic information, explicit commands of altitude, direction, vector and speed. A flight was only considered as checked-in and under the controller's responsibility after the salute from the controller. After handoff, the same flight was not considered under controllers responsibility anymore. A flight was considered as handed off after the pilot's correct repetition of the next contact frequency. Sometimes the controller would search for the aircraft and would not get a response, in which case a handoff was also

assumed.

A MATLAB script interpreted these details of voice communications. Thereby, the traffic was reconstructed into an animation and the position of each command was estimated.

Since the audio file and the radar track data came from different data sources, care should be taken to make sure they were synchronized. Without synchronization, it is impossible to properly ascertain the position of aircraft when commands were given. In the checking in process, pilots informed their altitude and the flight level they were flying to. If at this moment the flight was not level, then it was possible to use their claimed altitude for synchronizing the time of the radar track data and of the audio file. This analysis showed that both data sources were synchronized. Therefore, this additional calculation became only a confirmation test.

Not all flight call signs could be identified from the voice communication. And some identified call signs, particularly those that were general aviation, did not have their information available in `www.flightaware.com`. Without their radar track data, these flights could not appear in traffic reconstructions. Without their flight plan, these flights were also not included in any group analysis. Thus, only flights with complete voice communication available (i.e. from check in to check out) and complete flight data (i.e. radar track and flight plan) were analyzed. The exact number of the discarded flights is mentioned when appropriate.

Moreover, it should be noted that the controller-pilot communications were analyzed per chunks of continuous voice communications, named as "traffic interval". The chosen length of traffic intervals varied per sector. The reason for variable length was that each time of the day and each sector presented a different traffic per hour. The different time intervals of traffic were determined in a *ad hoc* basis, in order to get a reasonable number flights from each traffic interval (complete flight data and communication, as explained). For example, for ZMA40, after analyzing a traffic interval of one hour, complete radar track data could be obtained for 25 identified aircraft. But the handoff was not observed for 15 of them, which would allow the analysis of only 10 aircraft. By including another 30 minutes of traffic, these 15 flights

could be included, as well as other 10, yielding a total of 35 flights. Thus, there was no standard length of traffic interval.

The planned trajectories were used to identify flight plan groupings. As part of the flight plan, same origin or destination and same planned route inside the sector were used as grouping criteria. A group was generated for a given analyzed traffic period if a planned trajectory or origin/destination was common for at least two flights. It was observed that the traffic volume for each group fluctuated with respect to each traffic interval, which motivated the distinction of groups in terms of how prominent they were. As such, the identified groups were classified either as a "key group" , as a "minor group" or as a "minor temporal group". The distinction is as follows:

1. **Key group:** This group had at least 2 flights with similar planned trajectory in all analyzed traffic interval;

2. **Minor group:** This group had at least 2 flights with similar planned trajectory in only one traffic interval, or it had zero flights in a given traffic interval;

3. **Minor temporal group:** This group had at least 2 flights with similar planned trajectory at different traffic intervals.

5.2   Limitations of Voice Communication Analysis

As presented in Section 5.1, the selection of sectors to analyze was based on availability and quality of voice communication archives. Moreover, the choice of traffic hours of the selected sectors was primarily based on weather interference (trying to avoid weather) and comparable communication length after removal of periods of silence. Continuous communication length was used as a surrogate for workload and traffic volume. Attention was also give to extract at least one morning and one evening traffic period per sector. The voice pilot-controller voice communications were then converted into a transcript and then, further analysis was conducted on those flights for which radar track and flight plan could be found.

A problem with this method is that the identification of flight plan groups, for any sector, is sensitive to the length of the time window being analyzed. Moreover, due to day-to-day variabilities of traffic, different groups may or may not be observed. For instance, the identification as a minor temporal groups may be an artifact of the specific hours that were analyzed. In order to mitigate this problem, two measures were taken. It was first observed that the detailed transcript analysis appeared to work fine for the selected traffic intervals for ZNY10. As such, the observed traffic volume in ZNY10 was taken as a baseline when choosing the time and length of the traffic interval to be analyzed. The second measure was to set a very low threshold for a group to be created. In fact, the chosen threshold of 2 similar flights, is the smallest threshold possible. Despite of these counter measures, confirmation of the characteristics of each group is most likely to be obtained after talking with the respective controllers.

By considering only flights with complete voice communication, radar track data and flight plan data, part of the picture was inevitably lost. In order to mitigate this issue, longer traffic intervals were considered. But some general aviation flights could not be analyzed due lack of data.

Another problem is the control over certain variables that impact the traffic situation and/or observed commands. For instance, in the ZNY10 analysis, it was not possible to find one traffic period that had only the effect of higher traffic or only the effect of weather. Another important confounding variables is related to who was responsible for the traffic at what time. Ideally, the analysis of traffic periods should balance out the number of hours controlled by different air traffic controllers. In this analysis, controller was not a controlled variable, which makes it difficult to distinguish personal versus generic techniques for each sort of pattern. Other more subtle but still relevant variable is for how long the controller has been working (related to the development of the 'picture' and tiredness).

Due to the lengthly process of carefully analyzing trajectories, air traffic situations, estimated position of commands, pilot requests and deciphering voice communications, only few traffic intervals could be analyzed for each sector. This limited

number of "observed traffic situations" clearly indicate a lack of significance in identifying all sorts of groups, techniques and their possible variations.

Despite these limitations, this Chapter presents a methodology that can be scaled up to more hours and sectors. With more appropriate access to data, more controllable experiments can be done. For instance, a greater data source, not being constrained by availability from web archives and easier access to data (not having to pull out data, flight by flight, from `www.flightaware.com`) would allow to:

- Conduct a balanced analysis in terms of who is controlling the traffic, thereby distinguishing general versus individual techniques on managing the traffic;

- Have more observations for the same traffic volume;

- Consider a wider range of traffic volumes;

- Investigate specific weather effects;

- Analyze sectors with distinct characteristics;

- Analyze sectors that are judged to present similar dynamics or similar structural pattern (for instance, from analyses as presented in Chapters 3 and 4);

- Observe more variations of techniques for same groups of flight plan

5.3 Results of Voice Communication Analysis

This section presents an overview of the major results for each analyzed sector. The detailed description of findings includes the following items:

1. General statistics from ETMS data, as computed in Chapter 3;

2. Sector's structural framework relevant for flight plan group analysis;

3. Selection of days and time of traffic for analysis, including details of traffic situation, such as traffic volume, usage of channel capacity, weather interference and amount of pilot requests;

4. Identified groups of flight plans and general statistics of commands per group and air traffic situation;

5. Nuances of each group: sequences of commands and variations of these sequences; and

6. Summary of major findings of employed techniques and the effect of the air traffic situation.

In the interest of brevity, all these items are only presented for ZNY10, in order to illustrate the method. Results corresponding to the nuances of flight plan groups (item 5) of ZAU25 and ZMA40 are presented in Appendix B.

5.3.1   Communication Analysis: New York 10 (ZNY10)

From the ETMS data, ZNY10 had 1662 aircraft in two weeks of data, 53% climbing, 11% descending and 36% level flights[1]. The sector was categorized as member of the climbing cluster in Section 3.2. The sector is from FL220 to FL340. Figure 5-4 below presents the most frequently used jet routes, Q routes and reference points in ZNY10. These structural elements were identified from the planned routes of flights that were identified in the sector's traffic, as well as from `www.skyvector.com`. The exact latitudes and longitudes of these elements came from 2009 data provided by FAA.

Table 5.1 shows the four separate hours that were analyzed for ZNY10 and also provides some of the context for each observed traffic period.

The third column (number of airplanes, NAC) in this table presents the number of different airplanes that were heard. The fourth column (not identified or no data, NIND) presents how many of the heard airplanes could not be analyzed, either because communication was garbled, or because no radar track and flight plan data could be found at `www.flightaware.com`. The next and fifth column (identified but incomplete communication, IIC) presents how many of the airplanes could not be

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[1]According to the definition of altitude transition in Chapter 3, that is, based on total transition from entrance to exit greater or equal to 1000ft.

Table 5.1: ZNY10: General information about analyzed traffic intervals. $NAC =$ **N**umber of **A**irplanes; $NIND =$ number of airplanes **N**ot **I**dentified or **N**o **D**ata; $IIC =$ number of airplanes that were **I**dentified but with **I**ncomplete **C**ommunication; $TA =$ **T**otal **A**nalyzed ($NAC - NIND - IIC$); $W =$ if there was **W**eather; $CL =$ continuous **C**ommunication **L**ength after silence removal (in minutes); and $ARTR =$ ratio of **A**pproved **R**equests over **T**otal **R**equests

Day	Time	NAC	NIND	IIC	TA	W	CL	ARTR
03/18/2011 Friday	9:00 10:00	59	7	9	43	NO	29:00	5/6
06/17/2011 Friday	9:00 10:00	42	6	8	28	NO	19:45	5/6
07/05/2011 Tuesday	17:30 18:30	59	6	17	34	NO	29:02	7/7
06/28/2011 Tuesday	18:00 19:00	87	12	28	47	YES	50:07	23/33

analyzed because complete voice communication from check in to check out could not be captured. As a result, the sixth column (total analyzed, TA) presents the total of airplanes that could actually be analyzed. The weather column (W) indicates if the operation was impacted by weather either inside or outside the boundary of the
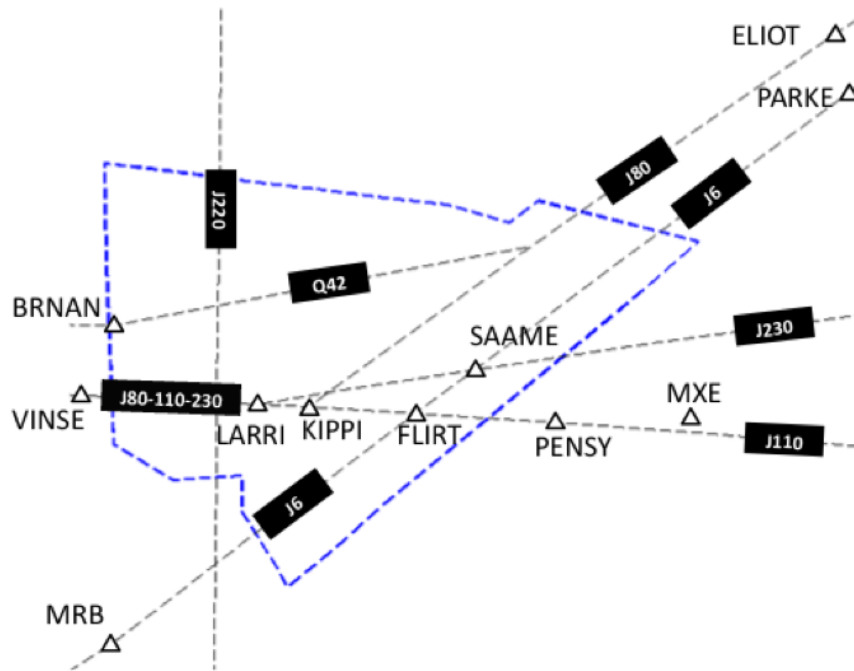
Figure 5-4: ZNY10: Structural framework

sector. The communication length column (CL) shows the usage of the channel capacity in terms of how much of continuous talk would exist if silence were removed. The last column (approved requests over total requests, ARTR) presents the ratio between approved pilot requests and total pilot requests, only considering the flights counted in column six.

As indicated in Table 5.1, the controller faced a particularly higher traffic demand, together with bad weather, in the evening of June 28. The change in these two variables (demand and weather presence) impacted the amount of continuous communication, as well as the total number of requests.

In the evening of June 28, there was bad weather in many states of the country, forcing the flights to take different routes. ZNY10 had bad ride conditions at FL290 and above, but it still had good weather when compared to its surroundings. Figure 5-5 below exemplifies this by presenting the planned and executed trajectory for ASA35 for June 28 (Figure 5-5(a)) and July 27 (Figure 5-5(b)). Both ASA35 flights were scheduled for late afternoon, from Boston to Portland International. Not only flights going to the northwest, but also those that would otherwise fly along the coast to southern destinations had to fly through ZNY10. This additional traffic took mainly

(a) Trajectory of ASA35 on June 28   (b) Trajectory of ASA35 on July 27
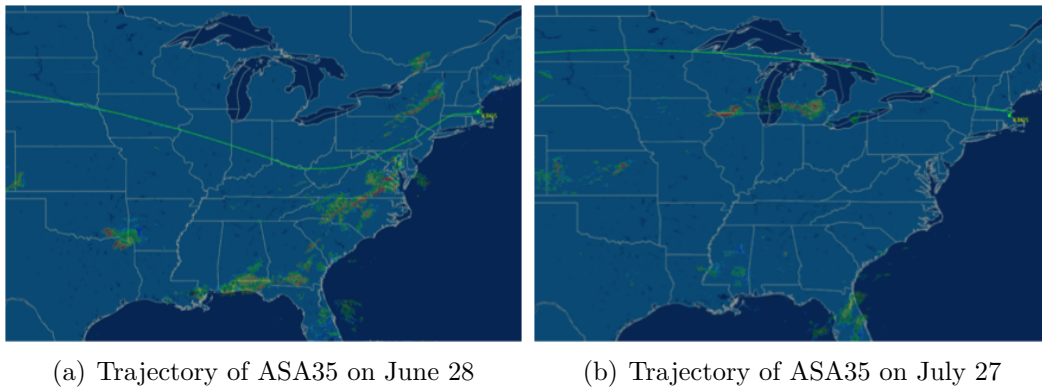
Figure 5-5: ZNY10 had bad ride conditions at FL290 and above, but it still had good weather when compared to its surroundings. Flights like ASA35, that normally would take a different trajectory, filed a route taking J6 through ZNY10. Also flights that would otherwise fly along the coast to southern destinations had to fly through ZNY10.Images extracted from `www.flightaware.com`
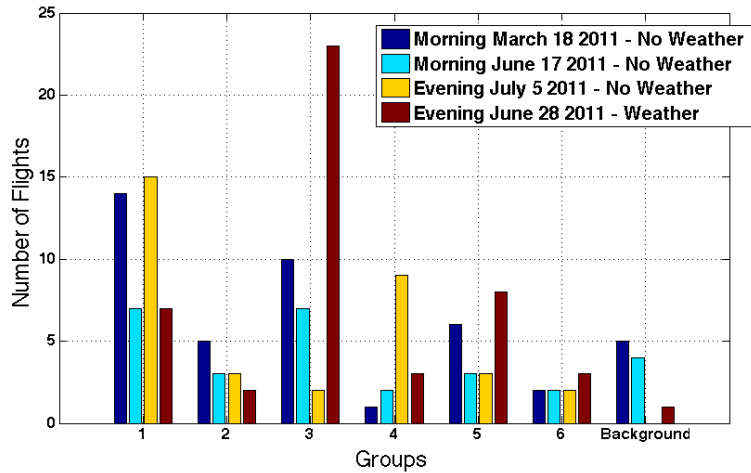
Figure 5-6: ZNY10: Number of flights per group. Only flights with complete voice communication, radar track and flight plan data are displayed.

jetroute J6 (see Figure 5-4).

Figure 5-6 presents the number of flights with complete voice communication, radar track and flight plan data per identified flight plan group. Visual inspection indicates that most of the additional traffic in ZNY10 in the evening of June 28 was due to incremental traffic in groups 3 and 5. These two groups encompass traffic that exits New York Center to Washington Center via J6 (see Figure 5-4).

ZNY10 faced peaks in groups 1 and 4 on the evening of July 5. No special reason for this phenomenon was found. This might be the result of temporal variation of the traffic patterns. Together with group 2, groups 1 and 4 include the traffic that leaves New York Center via J230 and Q42.

Selection of Traffic Hours

The morning traffic of March 18 (Friday), with a communication length of 29:00 minutes (Table 5.1), was chosen as one of the busiest mornings that were available at the time of the analysis and development of the method. As a comparison, the week from Sep 19 (Monday) to September 25 (Sunday) had an average of 23:09 minutes of continuous voice communication between 9:00AM and 10:00AM. There was a maximum of 33:17 minutes on Wednesday and a minimum of 11:39 minutes on

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Saturday. For better understanding of the March 18 traffic, it would be desirable to observe another Friday morning with different traffic volume and also not impacted by weather. After careful search, the morning of June 17 was included in the analysis.

For the choice of an evening traffic, the week from July 4th (Monday) to July 10th (Sunday) was analyzed. That week presented an average of 26:33 minutes of used channel capacity between 5:30PM to 6:30PM. There was a maximum of 29:15 minutes on Wednesday and a minimum of 24:56 minutes on Monday. July 5 was chosen because it is little bit to the higher end (29:02 minutes, Table 5.1) and comparable with March 18.

The evening of June 28 was chosen for analysis of variations on techniques given a different air traffic situation. June 28 had both poor ride conditions and higher demand due to reasons already explained. Unfortunately, a traffic situation impacted only by weather or demand could not be found, so the isolated effect of these two variables was not investigated.

Figure 5-7 presents all the flights that went through the sector in the morning traffic of March 18. Note that there are symbols at the estimated location of where commands were given, with the associated legend presented underneath the map. This same symbology is used in the entire voice communication analysis of this section.

Notice in Figure 5-7 that red squares (estimated handoff locations) are usually inside the sector, whereas green circles (estimated check-in locations) are upstream the flows. This is consistent with the procedure for transfer of control, whereby flights are handed off to a downstream controller before reaching the actual sector boundary (Nolan, 2011). As noted by Histon and Hansman (2008), this has consequences from the cognitive standpoint, thereby yielding the distinction between "area of regard" and "area of responsibility" or the actual physical boundary of the sector.

Flight plan groups

Six key flight plan groups were found in ZNY10. Each group was identified from repeatable planned trajectories inside the sector, that is, same flight plan from the controller's perspective. A group was generated for a given analyzed traffic period if

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a planned trajectory was common for at least two flights.

Figure 5-8 provides a summary and respective planned trajectories (lateral trajectories and typical origins or destinations) of the identified groups.

Notice that members of groups 1, 2 and 4 are planned to merge around KIPPI and LARRI. Moreover, groups 2 and 4 have to cross group 3 (through J6) at FLIRT and and SAAME, respectively. Group 5 is planned to merge with group 3, either at
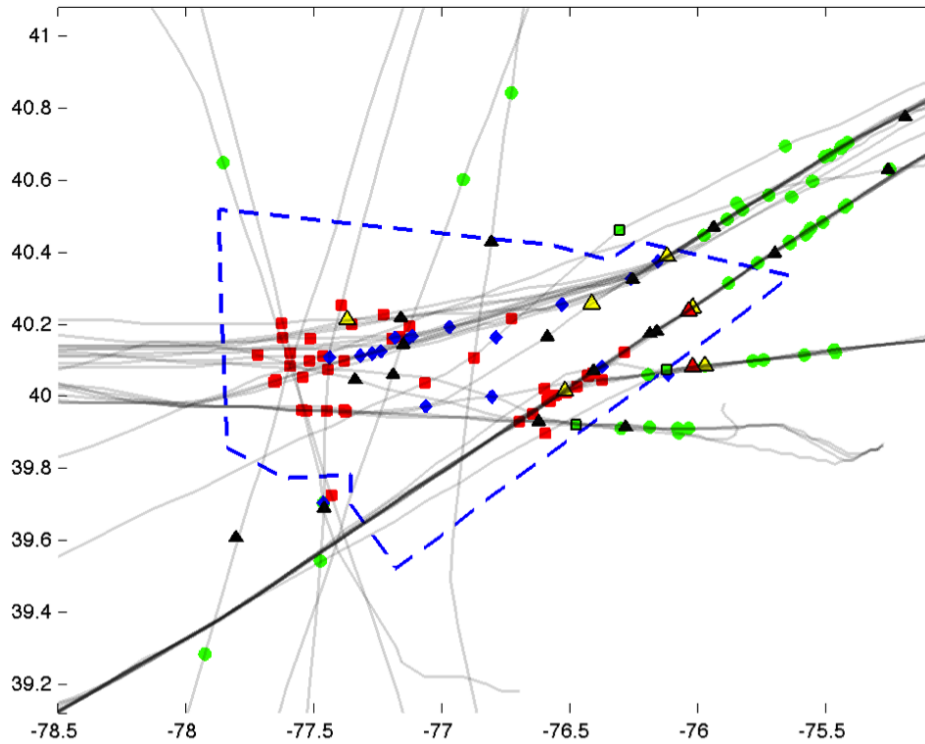
(a) Estimated location of commands
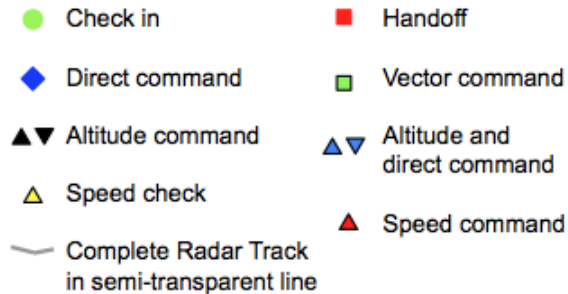
(b) Legend of commands

Figure 5-7: ZNY10: Trajectories and estimate position of commands for all the traffic on 03/18, 9:00-10:00AM

FLIRT or SAAME, depending on the origin of the traffic. And group 6, composed of departures from Washington DC, crosses groups 1, 2 and 4. Also note from Figure 5-3 that KEWR, KLGA and KJFK are very close to ZNY10. KPHL is even closer and is associated with groups 2 and 5 (MXE is the departure FIX for that airport). Thus, from Figure 5-8, some of the merging, crossing and climbing tasks of the controller
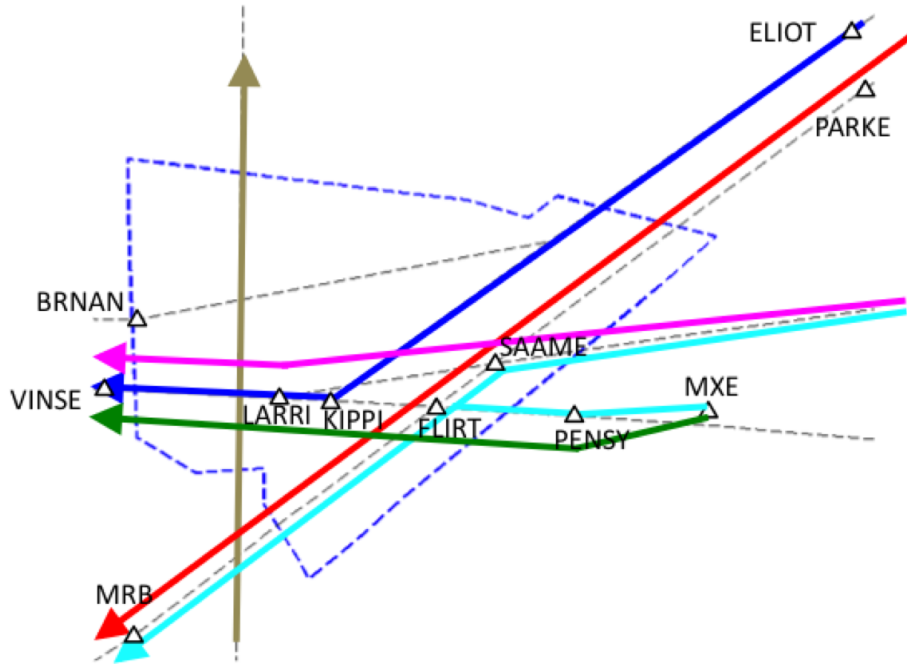
	Group 1: from KEWR and KLGA
● (blue)	... ELIOT – J80 – KIPPI – J110 – VINSE ...
	Group 2: from KPHL
● (green)	MXE – PENSY – J110 ...
	Group 3: mainly from KEWR, KLGA and KBOS
● (red)	SAX/PARKE – J6 – BWG/HVQ ...
	Group 4: from KJFK
● (magenta)	RBV - J230 – LARRI – J230 – AIR ...
	Group 5: Traffic merging to J6:
	from KJFK
● (cyan)	RBV – J230 – SAAME – J6 – HVQ ...; and
	from KPHL
	MXE – PENSY – J110 – FLIRT – J6 – HVQ ...
	Group 6: from KDCA and KIAD
● (olive)	... J220 ...

Figure 5-8: ZNY10: Summary of identified flight plan groups. Routes and reference elements related to the planned trajectories of each group are highlighted

can already be identified.

Figure 5-9 presents the percentage of aircraft that received each kind of command for groups those groups that were not affected by weather (groups 1, 2, 4 and 6). Figure 5-10 presents the same data but for groups 3 and 5, that were observed to be affected by weather. That is, the red bars in Figure 5-10 account only for the traffic in June 28, the weather impacted hour. It should be emphasized that Figures 5-9 and 5-10 do not indicate the existence of multiple commands of a certain type for the same aircraft or the typical combination/sequence of commands that were observed. These nuances are covered next, on the following sub Sections about each group.

Right at the outset, however, one can see in Figures 5-9 and 5-10 how certain types of commands were prominent for each group. For instance, 93.0% of the members of group 1 received a direct at some point, 84.6% of members of group 2 received altitude commands (departures from KPHL) and 73.3% of members of group 4 received direct at some point. This illustrates how the merging task is performed: group 2 is climbed due to the proximity of the originating airport and it is treated as the baseline or the "main flow" for the merging task, whereas the others are directed.

Figure 5-10 highlights the impact of weather. Members of group 3, mainly in level traffic, received little amendments from the controller under normal weather. With weather, the percentage of flights that did not received commands decreased from
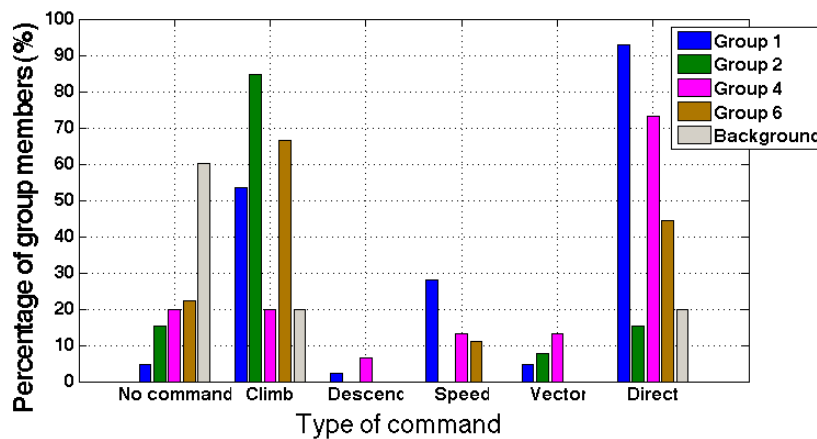
Figure 5-9: ZNY10: Distribution of commands for flight plan groupings not affected by weather.
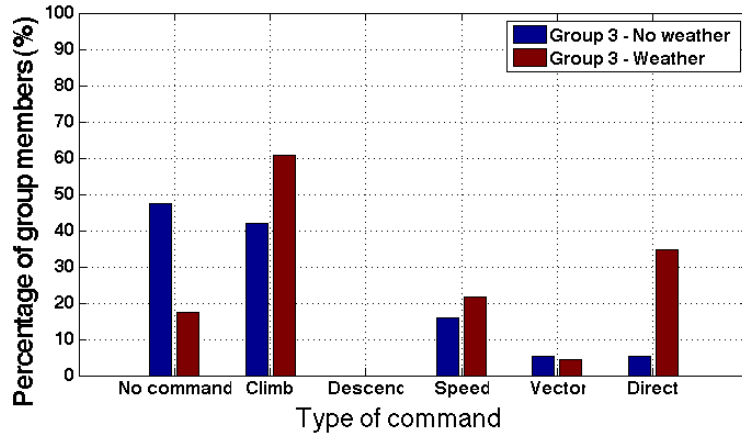
(a) Distribution of commands for group 3: southwest bound traffic from KEWR, KLGA and KBOS via jetroute J6
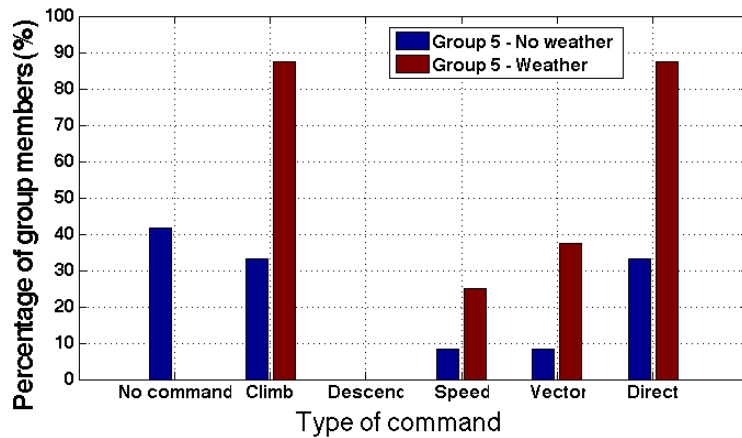
(b) Distribution of commands for group 5: southwest bound traffic from KJFK and KPHL merging to jetroute J6

Figure 5-10: ZNY10: Distribution of commands for flight plan groupings affected by weather.

47.4% to 17.4% and the percentage of altitude and direct commands also grew. In terms of traffic group 3 experienced 6.3 flights per hour on the non-weather hours and 23 flights per hour on the weather hour, an increase of more than three times. Moreover, members of group 5, although merging to J6, received only few climbing and direct commands when there was no weather. With weather, the number of flights per hour doubled from 4 to 8 flights per hour and the flights received much more amendments.

The following subsections present more details for each group, including the ob-

served shift from planned and actual trajectories.

Group 1: westbound traffic from KEWR and KLGA

Figure 5-11 shows planned trajectory, actual trajectories and estimated position of commands for group 1 on June 17. Group 1 is defined as aircraft that had flight plans equivalent to: ELIOT – J80 – KIPPI (See Figure 5-8). The traffic is mainly from Newark Airport (KEWR) and LA Guardia Airport (KLGA), with minor traffic from other airports. There are no specific destinations. Figure 5-11(d) presents trajectories and position of commands for group 1, but with respect to time (minutes of analyzed traffic) and altitude (flight levels or hundreds of feet). Dashed thick blue lines in all

(a) Planned trajectory for group 1   (b) Legend of commands

(c) Top view   (d) Side view
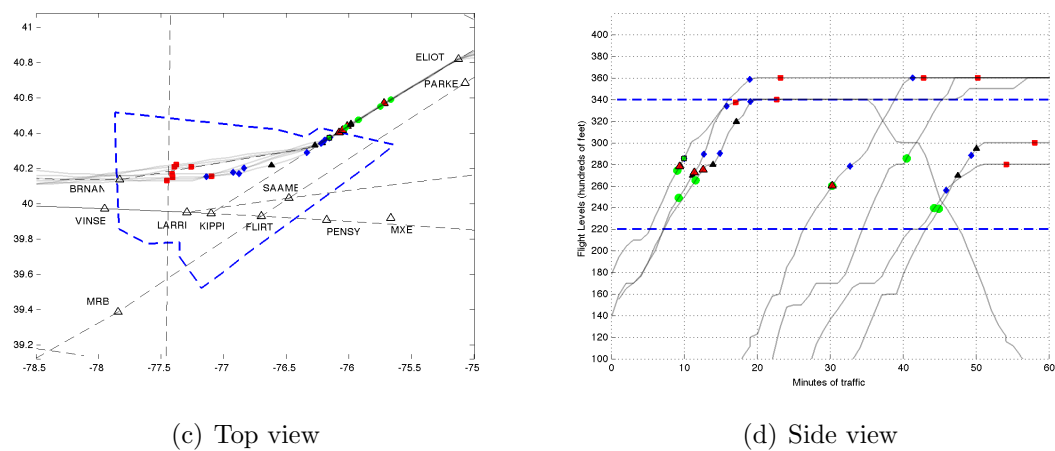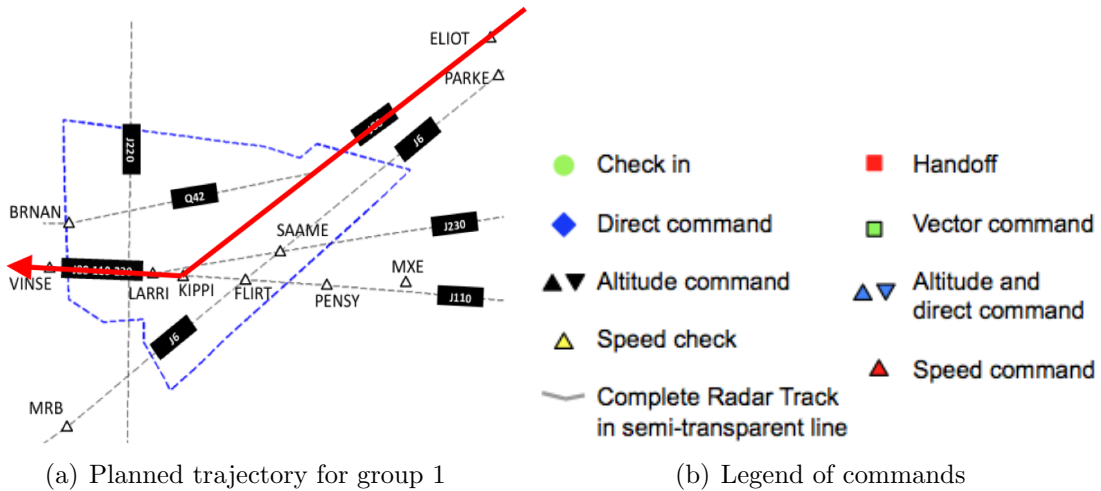
Figure 5-11: ZNY10: Results for 7 flights in group 1 on 06/17, 09:00 – 10:00 AM

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the pictures represent the sector boundary.

As presented in Figure 5-9, 93.0% of the 43 flights received a direct command at some point. 47.6% received direct commands at the check-in. In terms of the destination, 19% of the flights received direct straight to VINSE, 31% were directed to VINSE and then to Bellaire (AIR) or nearby fix point and 43% received direct straight to Bellaire (AIR) or nearby fix point. This means that 74% of this group had Bellaire or nearby FIX as final direct.

The direct commands are part of the technique for merging groups 1, 2 and 4 (Figure 5-8) and also to provide a shortcut from a longer route going through KIPPI. These directs have the effect of enforcing group 1 to fly along Q42 (compare Figures 5-4 and 5-8). Also concerning the merging task, 27.9% of aircraft in group 1 also received speed checks or speed amendments.

Flights checked-in still in the climbing phase (Figure 5-11(d)), which naturally reflected in the amount of climbing amendments (53.5%). Most notably, 33.3% received climbing command at check-in.

There were 12 request across all traffic periods in group 1 (Table 5.2). Only two of those took a while to be approved, all the others being immediately approved. Requests were mainly characterized by directs to VINSE or Bellaire and specific flight

Table 5.2: ZNY10: Pilot requests from aircraft in group 1.

Traffic	Call Sign	Request	Approved
03/18 MORN	AWI3720	direct to VINSE	yes
03/18 MORN	N801SS	to FL380	yes
06/17 MORN	N700XF	to FL300	yes
06/17 MORN	BTA2234	to FL300	yes
07/05 EVEN	AAL2223	mach 78 and FL340	yes
07/05 EVEN	COA1596	to FL360	yes, in 2 min
07/05 EVEN	LOF3535	direct to VINSE	yes
07/05 EVEN	N1127M	direct to VINSE	yes
06/28 EVEN	BTA2144	to FL300	yes
06/28 EVEN	TCF1275	direct to Bellaire	yes, in 1:30 min
06/28 EVEN	UAL525	normal speed	yes
06/28 EVEN	UAL525	direct to Bellaire	yes

levels.

Handoffs to the next sector occurred shortly after the flight had changed its course to its destination. Few flights actually climbed higher than the sector boundary, but they were only handed off once they were on the right direction.

Group 2: westbound traffic from KPHL

Figure 5-12 shows planned trajectory, actual trajectories and estimated position of commands for group 2 on March 18. Group 2 is defined as aircraft that had flight plans equivalent to: MXE – PENSY – J110 (See Figure 5-8) and from there to other

(a) Planned trajectory for group 2

(b) Legend of commands

(c) Top View

(d) Side view
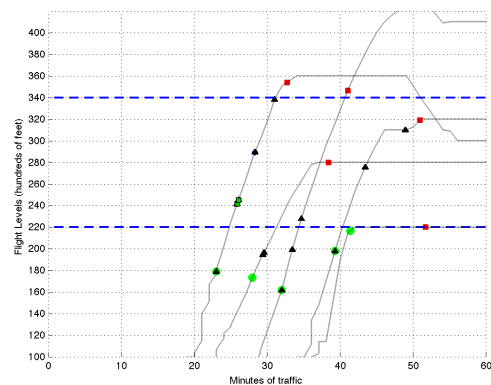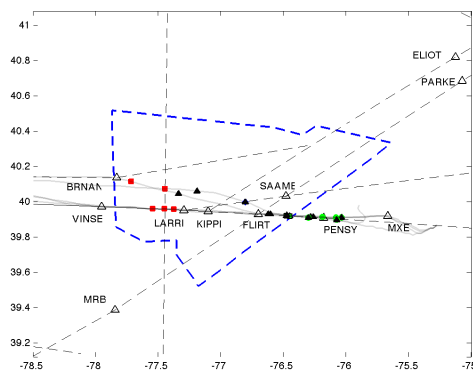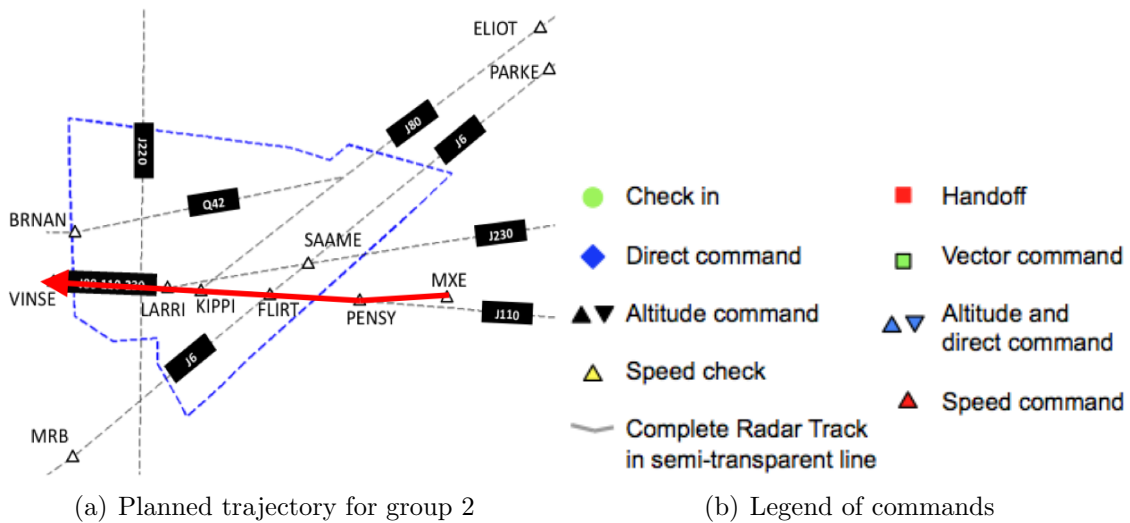
Figure 5-12: ZNY10: Results for 5 flights in group 2 on 03/18, 09:00 – 10:00 AM

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waypoint downstream J110, such as VINSE, LEJOY and Bellaire (AIR).Group 2 is mainly characterized by departures from Philadelphia International Airport (KPHL) and destinations scattered across the country.

As evidenced in Figure 5-8, group 2 merges with groups 1 and 4. No special commands were given to group 2 for accomplishing this merging task. This suggests that group 2 is treated as the "baseline" or main flow to be merged to, even though it presents lower traffic volume than groups 1 and 4.

A succession of climb commands were observed as part of the crossing technique of groups 2 and 3. All the flights that received commands (11 or 84.6% of the total) were given climb commands up to FL300 at or shortly after check-in, and then to higher altitudes when reaching or crossing J6 around FLIRT (Figure 5-8). Thus, group 2 was controlled to fly underneath group 3, which flies along J6.

Directs appeared not to be prevalent in group 2, as the traffic was not changing direction, but climbing along J110. Directs were only given when flights were shifting from J110 to its parallel, Q42, and an entrance point to that route was necessary.

Controller handed the flights off, once past KIPPI and reaching (or at) final altitude.

Group 3: southwest bound traffic from KEWR, KLGA and KBOS

Figure 5-13 shows planned trajectory, actual trajectories and position of commands for group 3. This group is identified by flights that take J6 all the way through ZNY10. This can happen by flight plans that include SAX/PARKE – J6 – BWG/HVQ. Group 3 is mainly characterized by departures from Newark Airport (KEWR) and La Guardia Airport (KLGA), but it also includes some traffic from Boston Airport (KBOS). Destinations are scattered across the country. Table 5.3 summarizes the pilot requests considering all analyzed traffic hours.

The three traffic periods without weather impact are first considered and then the weather impact is discussed. Figures 5-13(c) and 5-13(d) correspond to the actual trajectories for June 17, illustrating a traffic period without weather impact.

The three periods of traffic without weather interference had a total of 19 flights
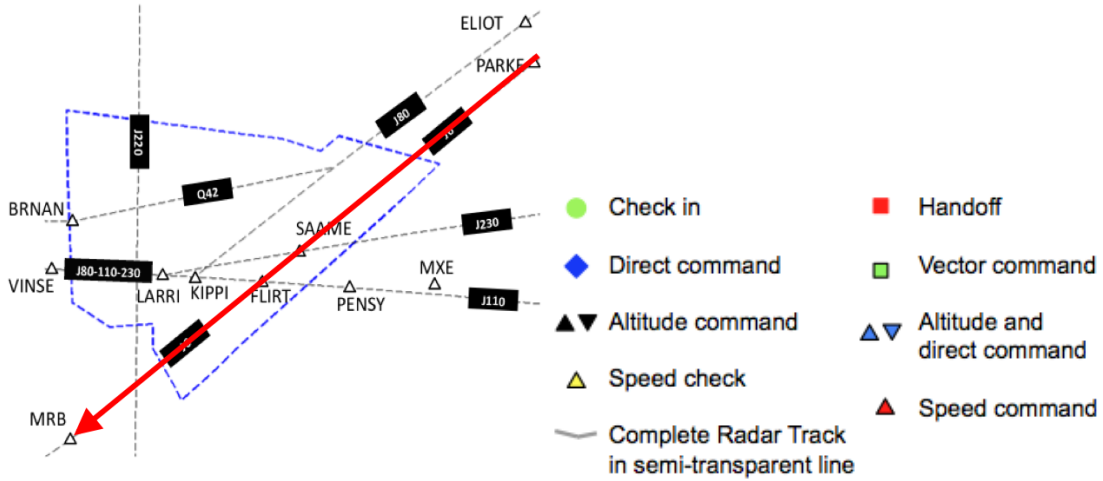
(a) Planned trajectory for group 3

(b) Legend of commands
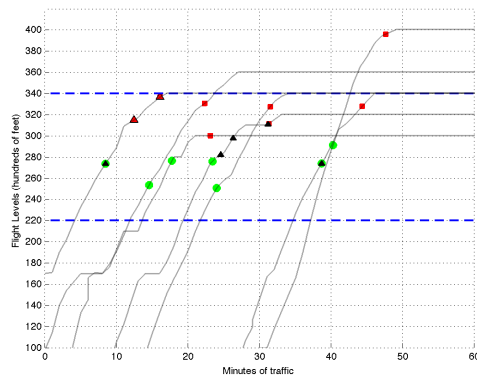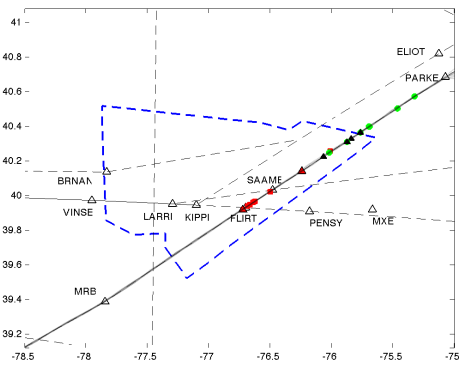
(c) Top view: 7 flights in group 3 on 06/17, 09:00 – 10:00 AM

(d) Side view: 7 flights in group 3 on 06/17, 09:00 – 10:00 AM
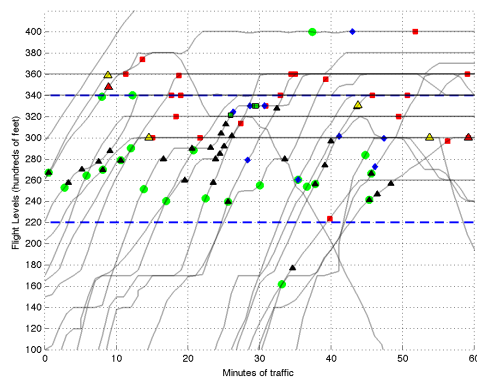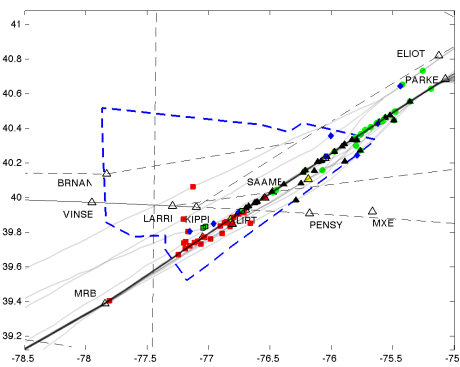
(e) Top view: 23 flights in group 3 on 06/28, 05:30 – 06:30 PM

(f) Side view: 23 flights in group 3 on 06/28, 05:30 – 06:30 PM

Figure 5-13: ZNY10: Results for group 3

Table 5.3: ZNY10: Pilot requests from aircraft in group 3.

Traffic	Call Sign	Request	Approved
06/17 MORN	COA1402	to FL320	no
06/28 EVEN	CHQ3037	to FL360	yes
06/28 EVEN	COA1737	to Martinsburg	yes
06/28 EVEN	COA328	to Martinsburg	yes
06/28 EVEN	EGF4413	to Martinsburg	yes
06/28 EVEN	N46F	to FL340	yes
06/28 EVEN	JBU509	to Martinsburg	no
06/28 EVEN	VNR175	higher altitude	no
06/28 EVEN	VNR175	any shortcut	yes, in 1 min

or 6.3 flights per hour. 9 (47.4%) did not receive any commands and 3 (15.8%) had speed checked or received speed commands in the vicinities of SAAME. As shown for the traffic in June 17 in Figures 5-13(c) and 5-13(d), altitude commands were issued moments after the check-in, directing the aircraft to their final altitude. The early climbing commands are part of the crossing technique with group 2 and 4, in order to guarantee separation. Direct command combined with vector were only issued to flights that were already off J6.

Handoffs occurred usually between the SAAME and FLIRT (intersections with group 2, 4 and 5). Thus, after solving the merging and crossing problem, the controller handed the flight off to the next sector in Washington Center, even though the aircraft was still half way through ZNY10. Flights in group 3 were handed off when reaching or shortly after reaching their final altitude.

As mentioned earlier, in the evening of June 28, there was bad weather in many states of the country, forcing flights to take different routes. This had a significant effect on group 3 in the evening of June 28, as many of the rerouted flights passed through ZNY10 via J6. On top of that, there were still poor ride conditions in ZNY10.

Figures 5-13(e) and 5-13(f) present the top and lateral view of flights in group 3 under weather effects. Noticeably, many flights did not follow J6 precisely, as the jet route was clearly saturated. From 5:30 to 6:30 PM of June 28, group 3 had a total of 23 flights. Only 4 (17.4%) of these flights received no commands. 5 (21.7%) airplanes

had either speed check or speed commands in the proximities of SAAME and FLIRT. Moreover, via a succession of altitude commands, the controller tightly monitored the climb of 14 (60.9%) aircraft to assure separation (in addition to this statistic, notice the number of black triangles in Figures 5-13(e) and 5-13(f)). 6 (26.1%) were directed to Martinsburg (MRB), Charlie West (HVQ) or other downstream points on J6, as some of them entered ZNY10 already off J6. There were also 5 pilot requests for shortcuts and 3 for altitudes with better ride conditions.

It is evident, from visual inspection of Figure 5-13(e) that handoffs in the evening of June 28 occurred past FLIRT. This delayed handoff is most probably the combination of two effects: (1) usage of channel capacity close to the limit, not allowing the controller to hand flights off earlier; and (2) solution of the merging and crossing problem was postponed due to a harder merging problem, hence delaying the handoff itself.

Group 4: westbound traffic from KJFK

Traffic in group 4 comes from John F Kennedy Airport (KJFK), with flight plan including RBV - J230 – LARRI - J230 - AIR. Destinations are scattered just like in group 1. It should be noted that some temporal variation was observed in group 4: 9 out of the 15 flights in this group were in July 5. Figure 5-14 shows planned trajectory, actual trajectories and position of commands for group 4 in July 5.

As presented in Figure 5-9, 3 out of the 15 flights in group 4 (20%) did not receive any command. 10 flights were directed to Bellaire (AIR) and 1 to VINSE and then to Bellaire. Directs were observed to be part of the merging of groups 1, 2 and 4. The directs also allowed the flights to cut the corner, not flying to LARRI.

The controller only amended climbing altitude of 3 flights, 2 of these instances in the bad weather evening of June 28. Most of the flights in group 4 were observed to cross J6 above group 3. However, it was difficult to identify a clear crossing technique (as for groups 2 and 3), because of lack of observations on other traffic periods.

Handoffs occurred at the same location, similar altitudes and with same direction to Bellaire as in group 1 and 2.

(a) Planned trajectory for group 4   (b) Legend of commands

(c) Top view   (d) Side view
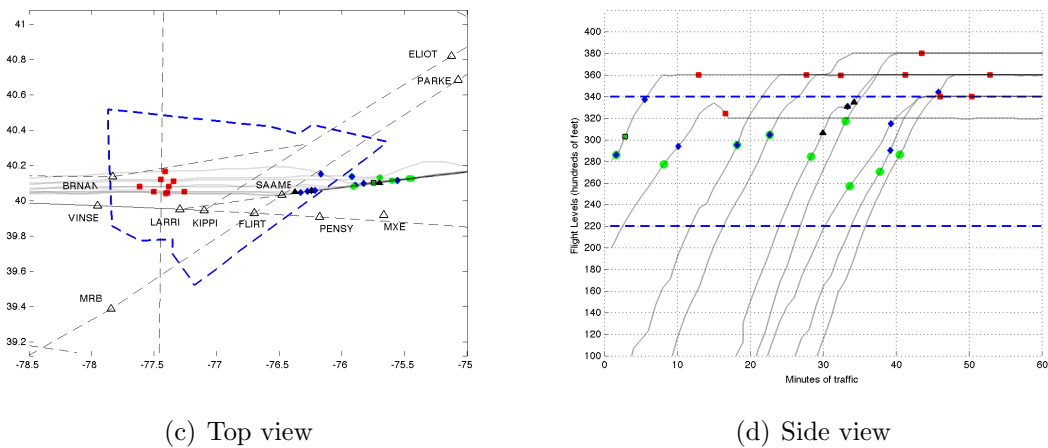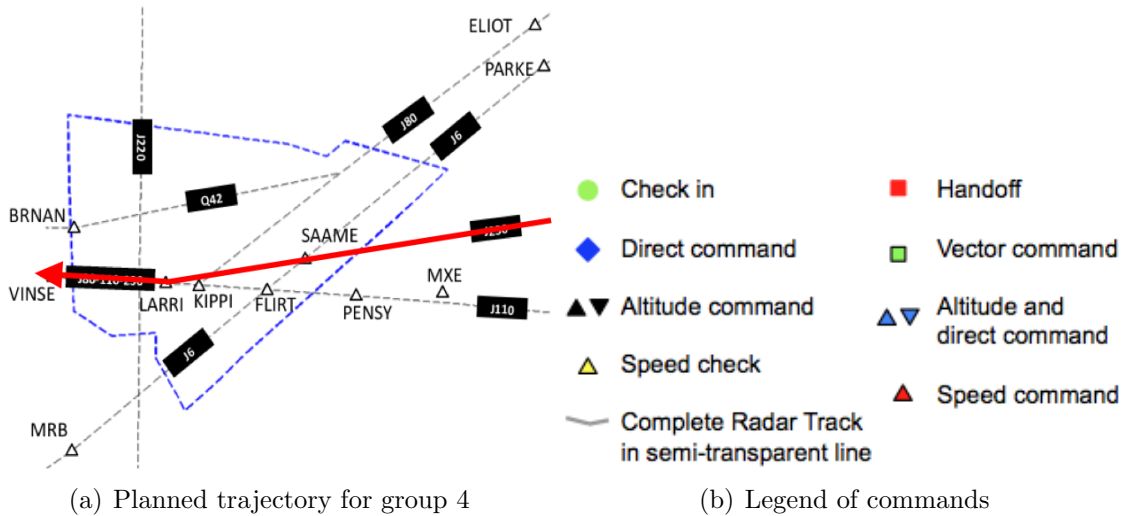
Figure 5-14: ZNY10: Results for 9 flights in group 4 on 07/05, 05:30 – 06:30 PM

Only two pilot requests were observed for this group and both were immediately approved. One was in July 5 asking for Bellaire and the other was in June 28 asking for FL310.

Group 5: southwest bound traffic from KJFK and KPHL

This is the merging traffic from John F Kennedy Airport (KJFK) and Philadelphia Airport (KPHL) into J6. The traffic from New York follows RBV – J230 – SAAME - J6 – HVQ, whereas the traffic from Philadelphia follows MXE – PENSY – J110 – FLIRT - J6 – HVQ. Destinations are scattered across the country.

Since group 5 was also affected by weather, Figure 5-15 presents a case with-
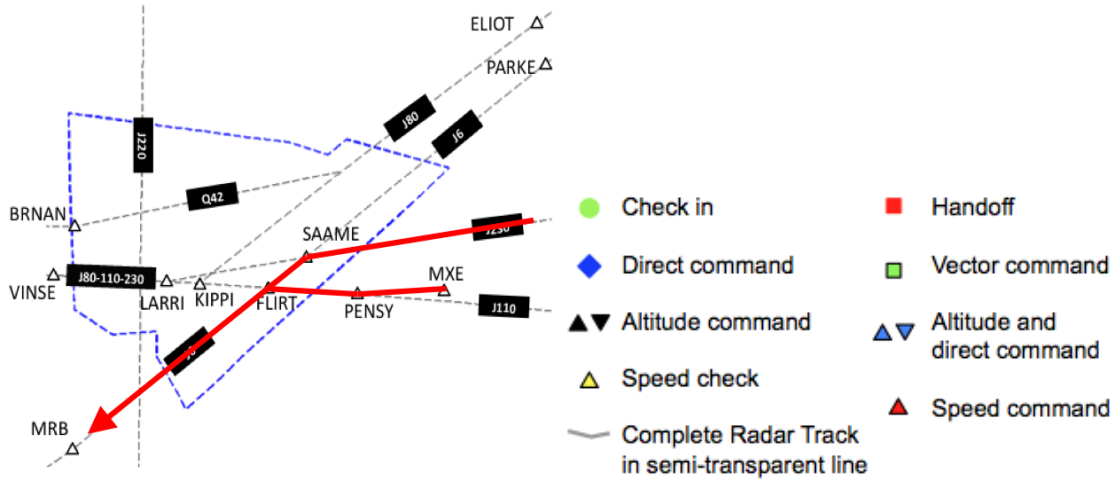
(a) Planned trajectory for group 5

(b) Legend of commands
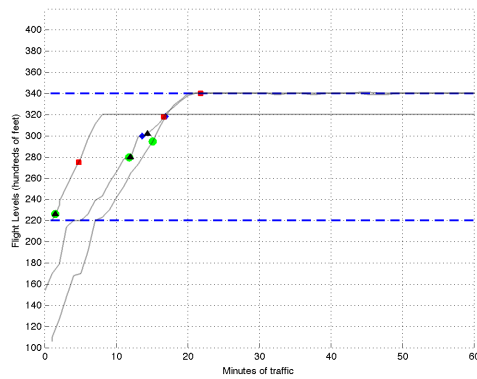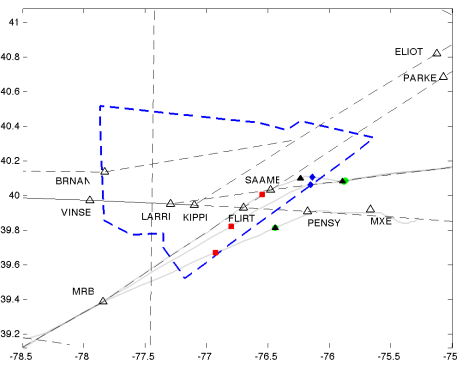
(c) Top view: 5 flights in group 5 on 06/17, 09:00 – 10:00 AM

(d) Side view: 5 flights in group 5 on 06/17, 09:00 – 10:00 AM
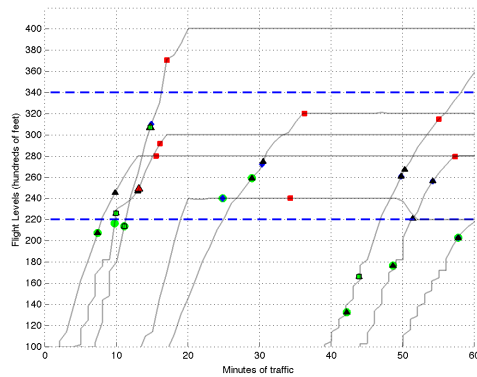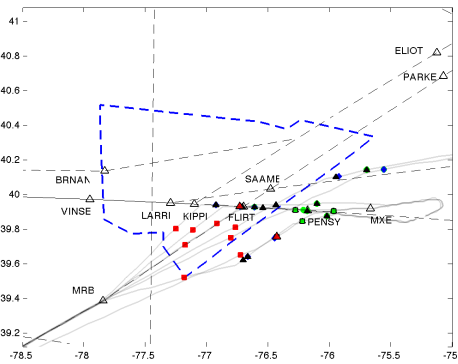
(e) Top view: 8 flights in group 5 on 06/28, 05:30 – 06:30 PM

(f) Side view: 8 flights in group 5 on 06/28, 05:30 – 06:30 PM

Figure 5-15: ZNY10: Results for group 5

out weather interference (Figures 5-15(c) and 5-15(d)) and with weather interference (Figures 5-15(e) and 5-15(f)).

Table 5.4 summarizes the pilot requests considering all analyzed traffic hours.

In the three days without weather interference, a total of 12 flights were observed, almost half of them did not receive any commands. 4 flights were merged to group 3 via directs to Martinsburg (MRB) or Charleston (HVQ). There were 3 PHL departures, 1 in June 17 and 2 in July 5, and they only received climbing commands to final altitude (FL320 and above). There was one climb request in June 17 that was immediately approved (Table 5.4)

Handoffs occured usually shortly after the merging point (SAAME or FLIRT), once they were in J6 reaching final altitude and directed to a downstream waypoint. In June 17 and July 5, there was less indication of conformance to the structure, as the combined traffic of groups 3 and 5 were much lower than in March 18.

The situation changed in June 28, when there was weather interference and the controller of ZNY10 faced a larger traffic demand. There were a total of 8 flights in this group. All flights received commands, 87.5% received altitude commands and 62.5% got multiple altitude commands. This means that the whole climbing process had to be controlled more tightly.

Also, the structure could not accommodate the traffic demand from groups 3 and 5 together, and many of the flights only merged to J6 outside the sector, at MRB. More specifically, 7 flights (87.5%) were directed to MRB or other points for merging. 3 of them were also deviated with vector commands and 2 of the deviated ones did not enter the actual sector boundary, as illustrated in Figure 5-15(e).

Handoffs were observed to occur past FLIRT, but, as already noted in the group

Table 5.4: ZNY10: Pilot requests from aircraft in group 5.

Traffic	Call Sign	Request	Approved
06/17 MORN	JBU353	to FL340	yes
06/28 EVEN	MJR932	deviation for weather	yes
06/28 EVEN	COA1737	to FL280	no

3 analysis, this might be the combined effect of time pressure for talking with pilots and actual delayed solution of a harder merging problem.

Group 6: northbound traffic from KDCA and KIAD

Figure 5-16 presents trajectories and position of commands for group 6. Group 6 was identified as departures from Ronald Reagan Washington National Airport (KDCA) and Washington Dulles International Airport (KIAD). These flights followed J220 northbound.

All of the 9 flights in this group were still in the climbing phase when they checked-

(a) Planned trajectory for group 6   (b) Legend of commands

(c) Top view   (d) Side view
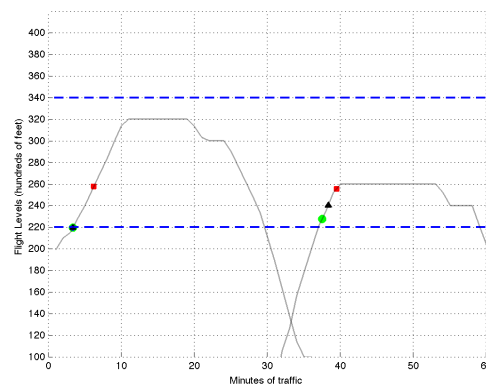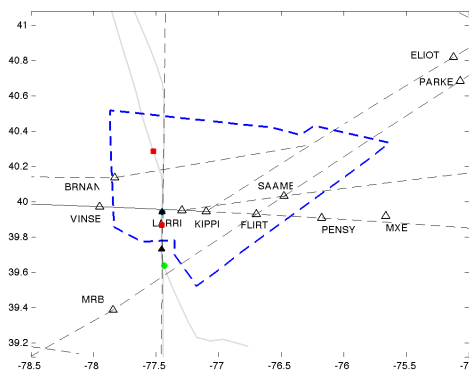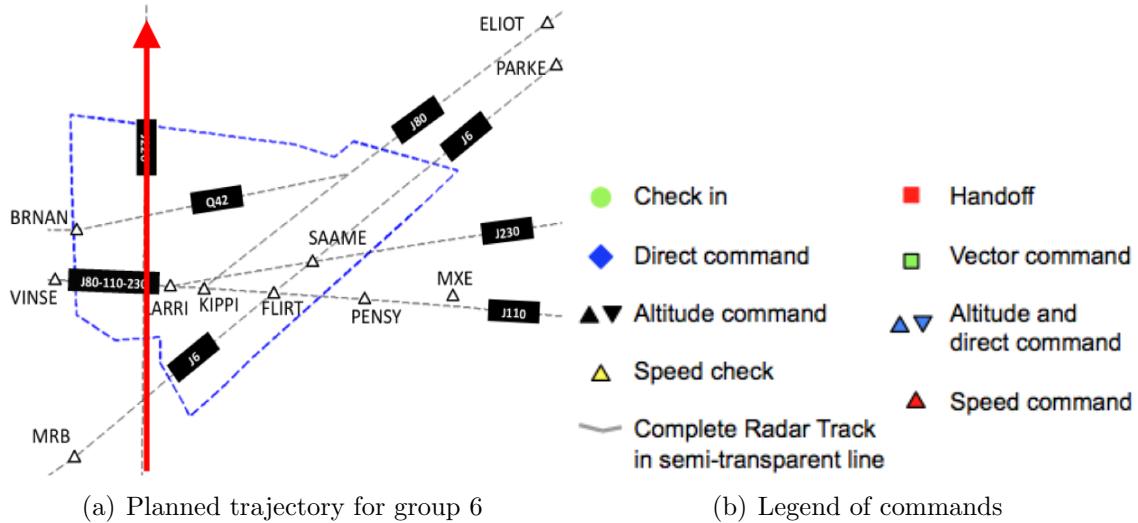
Figure 5-16: ZNY10: Results for 2 flights in group 6 on 03/18, 09:00 – 10:00 AM

in. As such, 6 flights received climbing commands shortly after or at check-in. More-over, 4 flights received directs for shortcut to their destinations. 8 of the flights were handed off before reaching FL280, which means that they were vertically separated from the traffic of other groups.

Background Traffic

Figure 5-17 presents 10 flights that could not be categorized in any specific flight plan pattern (traffic of July 5 is not presented because there was no background traffic). 6 of these flights passed through the sector without any command. There was no specific climbing or level traffic pattern in this miscellaneous group. The only flight

(a) 03/18, 09:00 – 10:00 AM

(b) 06/17, 09:00 – 10:00 AM

(c) 06/28, 05:30 – 06:30 PM
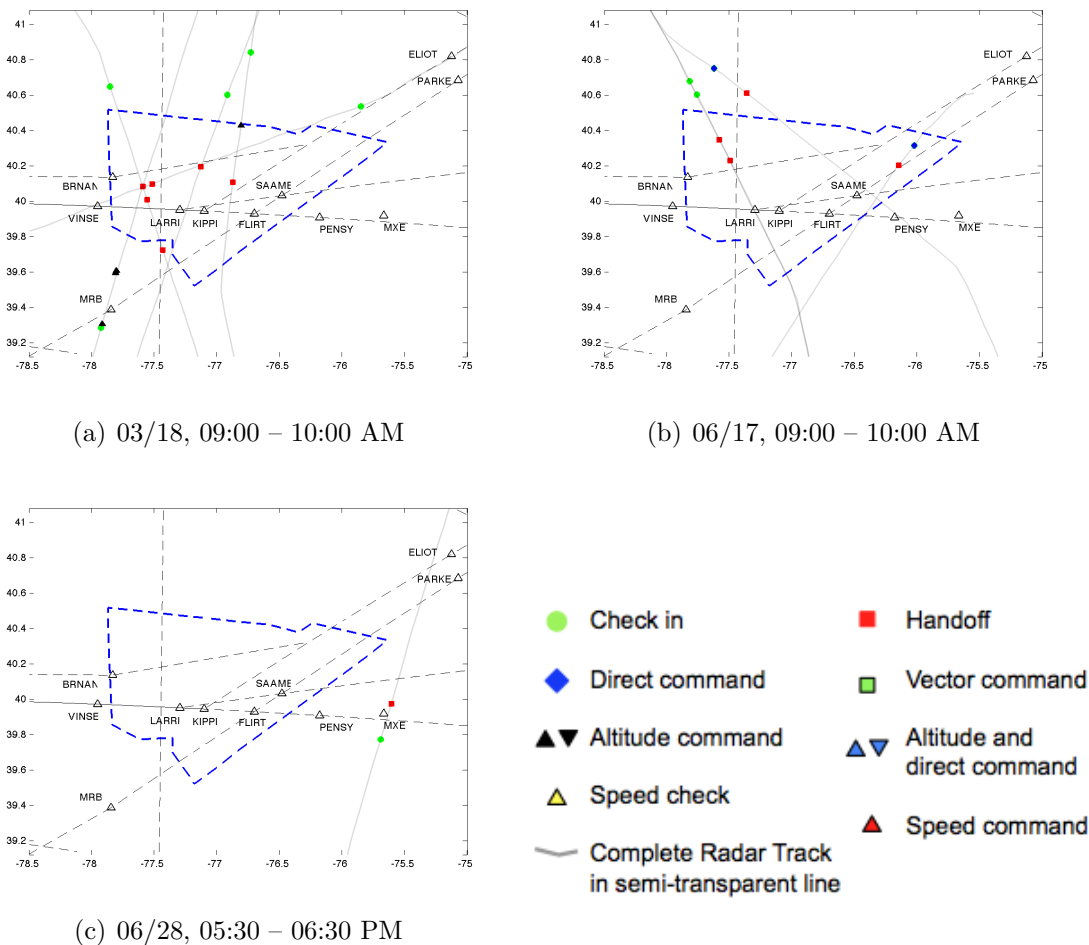
Figure 5-17: ZNY10: Background traffic

in June 28 was a wrong check-in.

Summary of ZNY10

Based on the identified flight plan groupings, four main tasks were observed (illustrated in Figure 5-18). These are the higher level tasks that the controller has to do. As presented in the previous sub Sections, the execution of each one of these tasks has a specific pattern for each group. in accordance with Pawlak et al. (1996), given that an aircraft is identified as a member of a group, the controller knows the plan and the set of actions (or technique) to be executed.

Figure 5-18 also presents the standard technique observed for each group, in terms of the major tasks. Noteworthy is the fact that the presented techniques of groups 3 and 5 were devised from the hours with normal weather. As a result, the sum of total traffic on the second column does not include groups 3 and 5 on June 28.

The conditional probability of receiving a technique, given that a command was issued to a member of the group is also presented in Figure 5-18). This measure indicates that most of the members of the groups received a standard adjustment, given that a command was issued. That is, there is indication of a technique for each flight plan group. Figure 5-18) also shows that the technique was not as clear for group 5, as it was for the other groups.

The tasks are reviewed as follows, in order to summarize the specific pattern of commands for each group:

Merging Task 1 (merging of groups 1, 2 and 4). Groups 1 and 4 received a sequence of clearances that ended with final direct to Bellaire. Group 2 was treated as a baseline for the merging task. Group 1 and 4 had some climb commands due to the proximity of New York City to ZNY10.

Merging Task 2 (merging of groups 3 and 5). There were speed checks in group 3, but it was not clear if it was due to the merging task or for limiting the handoff speed to Washington Center. In group 5, a third of the aircraft received directs to MRB to cut the corner and a third (corresponding to the KPHL departures) received final altitude to match with the altitude of group 3. But aircraft usually just

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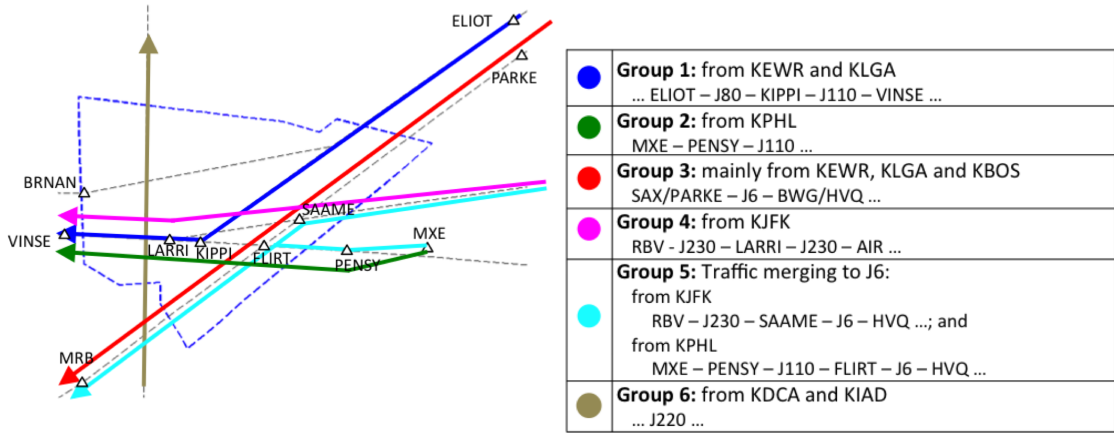
Group	% total traffic	Technique	P(RC)	P(T|RC)
● 1	36%	MT1	95%	98%
● 2	11%	CT1 – MT1	85%	100%
● 3 *	16%	MT2	53%	80%
● 4	12%	CT1 – MT1	80%	92%
● 5 *	10%	MT2	58%	57%
● 6	7%	CT2	78%	86%
Background	8%	-	40%	

* Only considering normal weather days

Merging Task 1 (MT1): merging of groups 1, 2 and 4
Merging Task 2 (MT2): merging of groups 3 and 5

Crossing Task 1 (CT1): crossing of groups 2, 4 with 3
Crossing Task 2 (CT2): crossing of group 6 with groups 1, 2, 4

Figure 5-18: ZNY10: Summary of identified tasks and techniques for flight plan groups. $P(RC)$ = Proportion of flights that received commands. $P(T|RC)$ = Proportion of flights that received technique, given that they received commands.

changed their heading naturally around FLIRT or SAAME.

Crossing Task 1 (crossing of groups 2 and 4 with group 3). Group 2 received climbing commands first restricting the altitude when aircraft crossed J6. Then, shortly before crossing J6, these flights received a second amendment to final altitude. A clear crossing technique could not be observed between groups 3 and 4, as most of the traffic in group 4 was in July 5, which did not present as much traffic in group 3. However, it was observed that members of group 3 received final altitude early after check-in or crossing the sector's boundary, thereby maintaining vertical separation with groups 2 and 4.

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Crossing Task 2 (crossing of group 6 with groups 1, 2 and 4). Group 6 received climbing commands shortly after check-in and were handed-off before reaching FL280, which put them underneath the other groups.

Impact of weather. Groups 3 and 5 were the most affected by the weather and higher demand situation on June 28. Higher demand occurred due to re-routes of other aircraft that ended up flying through J6 (Figure 5-5). Higher demand was clearly evidenced by looking at the number of total aircraft in the sector in Table 5.1, total aircraft per group in Figure 5-7(a) and flights per hour. Higher demand also changed the nature of the situation, yielding more continuous communication time, more requests in total and lower rate of approved requests (Figure 5-10).

The combined effect of higher demand and weather also altered the number of aircraft that received certain types of commands: more altitude and directs were given for members of each group. For the merging task, group 5 also received far more vector commands and some of the aircraft did not even entered the sector's official boundary, due to saturation of J6. Another evidence of route structure saturation is the more disperse distribution of flights around centerline of J6.

General observations. Traffic reconstructions and Figure 5-7 also indicated that handoffs usually occurred after a certain problem or task was solved, such as reaching final altitude and/or speed, merging the traffic or directing to a certain downstream point. This early handoff behavior supports the area of regard concept from the perspective of the upstream controller. Considering that most of the commands are issued in early minutes after checking-in (Histon & Hansman, 2008), it is noticeable that the area of regard works as a time buffer for controllers to deal with the traffic situation.

Under weather conditions, the problem was clearly harder to solve, which could have been a reason for postponed handoffs. However, the late handoffs could also have been the lack of sufficient time to properly hand flights off, due to saturation of the communication channel (Table 5.1).

5.3.2   Communication Analysis: Chicago 25 (ZAU25)

From the ETMS data, ZAU25 had 1717 aircraft in two weeks of data, 24% climbing, 56% and 20% level flights. The sector spans from FL195 to FL324. The sector was categorized as a member of the descending cluster in Section 3.2. Figure 5-19 below presents the most frequently used jet routes and reference points in ZAU25.

Selection of Traffic Hours

Two separate traffic periods were analyzed for ZAU25. The archived audio files at hand did not present as much traffic volume as in the case study of ZNY10. June 17, a Friday, was chosen because it was one of the days with most traffic and not affected by weather. Both morning and evening traffic for the same day were analyzed. Notice that two hours were considered for each traffic period. The reason was to capture more traffic in order to increase the chances of observing the patterns, dynamics and techniques in the sector.

Table 5.5 shows general statistics for each analyzed traffic period. It presents the number of airplanes that were heard and how many flights ended up being analyzed for each data point. As it was done for ZNY10, reasons for discarding flights were the non-identification of the call sign, lack of radar track and flight plan data and incomplete voice communications. Voice communications were only considered complete if the check-in and handoff were heard. Note that, despite of considering double of the time
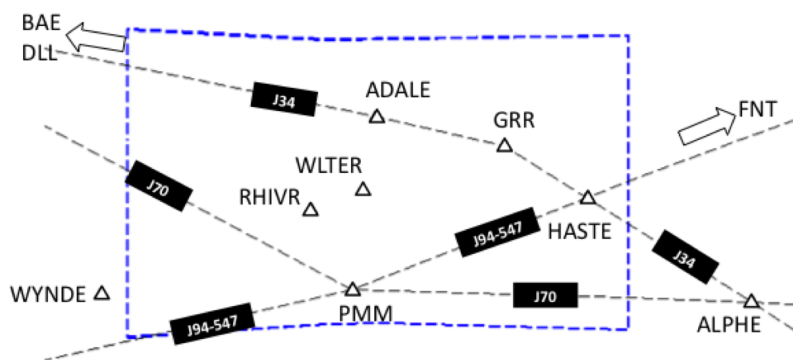
Figure 5-19: ZAU25: Structural framework

interval, the final number of analyzed aircraft and continuous communication length are very close to that presented in Table 5.1 for ZNY10.

Table 5.5: ZAU25: General information about analyzed traffic intervals. $NAC =$ **N**umber of **A**irplanes; $NIND =$ number of airplanes **N**ot **I**dentified or **N**o **D**ata; $IIC =$ number of airplanes that were **I**dentified but with **I**ncomplete **C**ommunication; $TA =$ **T**otal **A**nalyzed $(NAC - NIND - IIC)$; $W =$ if there was **W**eather; $CL =$ continuous **C**ommunication **L**ength after silence removal (in minutes); and $ARTR =$ ratio of **A**pproved **R**equests over **T**otal **R**equests

Day	Time	NAC	NIND	IIC	TA	W	CL	ARTR
06/17/2011 Friday	9:00 11:00	77	5	11	60	NO	36:47	2/3
06/17/2011 Friday	17:00 19:00	63	10	8	45	NO	24:21	6/6

Flight plan groups

As presented in the methodology, for a given analyzed traffic period, a group was generated if at least two flights had a planned trajectory or origin/destination in common. From this method, five key flight plan groups were found in ZAU25. Group 6 was only identifiable in the morning traffic, therefore constituting a minor group.

Figure 5-20 presents how many aircraft were analyzed for each goup. Figure 5-21 provides information about the common features in each group, as well as an illustration of the typical flight plans for each group.
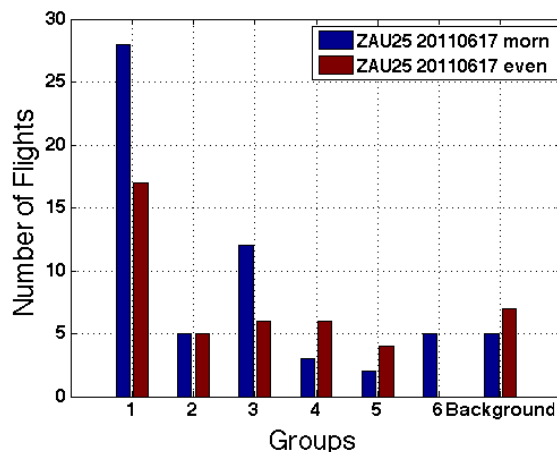
Figure 5-20: ZAU25: Number of flights per group. Only flights with complete voice communication, radar track and flight plan data are displayed.

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Notice that, except for the minor group 6, there is a high correlation between planned trajectories and ODs for each identified group in ZAU25. Three groups have high correlation with destinations (group 1 to KORD, group 2 to KCLE and group 4 to KMKE), two groups have high correlation with origins (group 2 from KMSP and KMKE and group 3 from KDTW). In particular, group 5 represents a specific OD pair: traffic from KDTW to KORD.

The interrelationship between groups is more diverse and apparently more complex than it was for ZNY10. For instance, members of group 1 cross all other groups and present some merging traffic, group 2 and group 6 have opposite directions, group 3 is associated with a diverging traffic and group 4 with a converging traffic (focal point is located outside ZAU25). Moreover, group 5 also goes to KORD, thereby merging
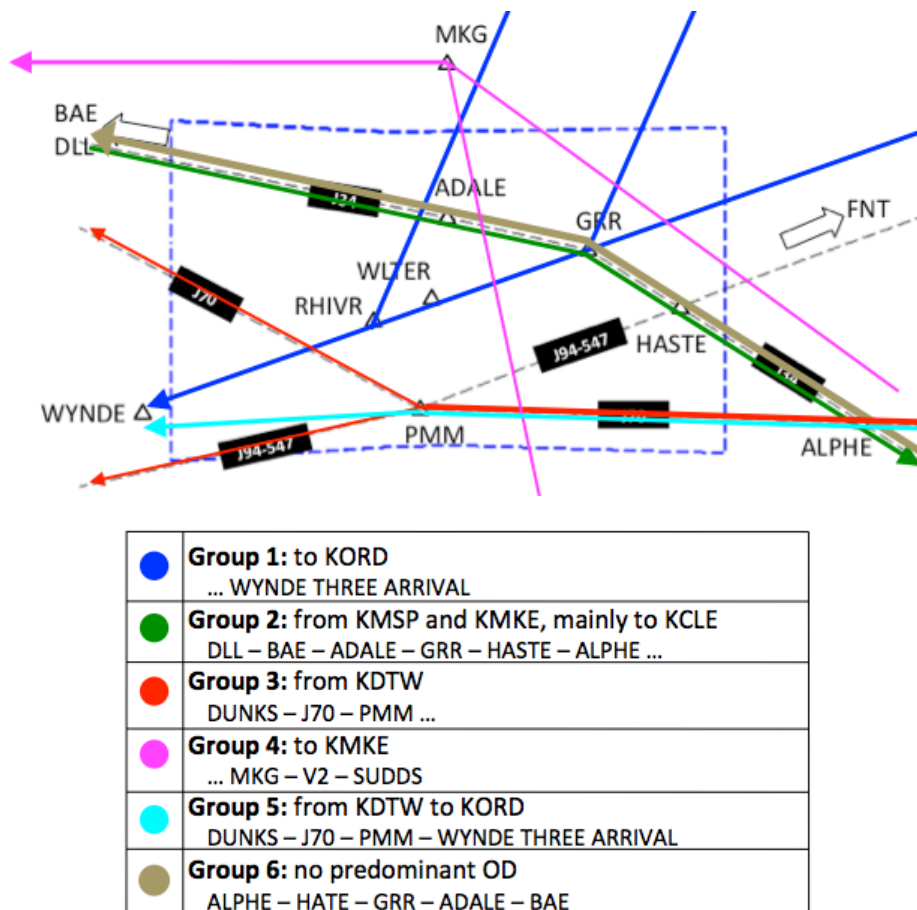
Figure 5-21: ZAU25: Summary of identified flight plan groups. Routes and reference elements related to the planned trajectories of each group are highlighted
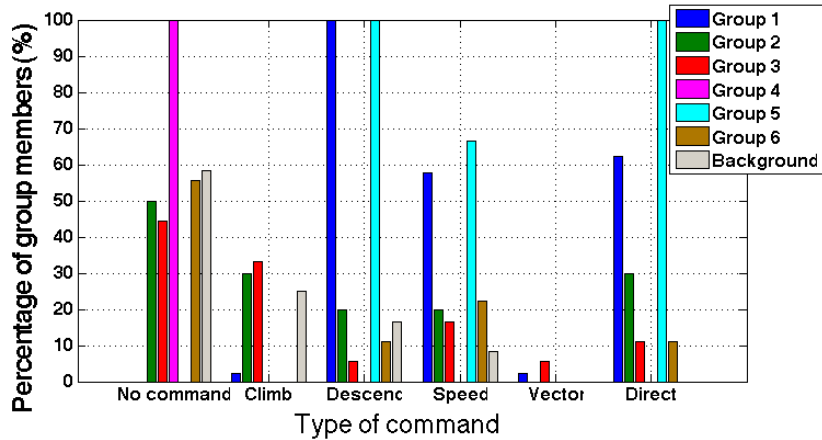
Figure 5-22: ZAU25: Types of commands and flight plan groups.

with group 1.

Figure 5-22 presents the percentage of members in each group that received specific types of commands. One can see in this Figure that the controller used a combination of several commands when managing each group. Groups 1 and 5 had the most prevalent pattern of types of commands: all aircraft received descend commands and many received speed commands, as well as direct commands. Details about each group can be found in Section B.1. The following section presents a summary of the major findings.

Summary of ZAU25

Based on the identified flight plan groupings, six main higher level tasks were identified (illustrated in Figure 5-23). As it was the case for ZNY10, the execution of each one of these tasks followed a specific pattern for each group. Figure 5-23 also presents the techniques in terms of the sequence of tasks that must be performed for each group.

The conditional probability of receiving a technique, given that a command was issued to a member of the group is also presented in Figure 5-23). This indicates how consistent the techniques were for each flight plan group. The lack of such metric for groups 4 and 6 is because a clear technique was not observed for these groups, even though a sequence of potential tasks was identified.

The major tasks were observed to be performed as follows:
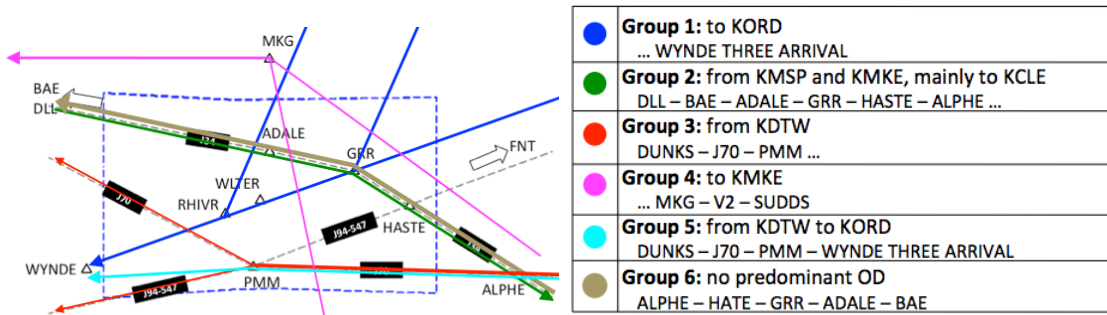
Group	% total traffic	Technique	P(RC)	P(T|RC)
● 1	43%	MT1 – Seq,KORD	100%	100%
● 2	10%	HH – CT1	50%	60%
● 3	17%	split	56%	60%
● 4	9%	CT2 – MT2	44%	-
● 5	6%	Seq,KORD	100%	100%
● 6	5%	HH – CT1	0%	-
Background	11%	-	42%	

Sequence to KORD (Seq,KORD): groups 1 and 5
Merging Task 1 (MT1): merging of members in group 1
Merging Task 2 (MT2): merging of members in group 4

Crossing Task 1 (CT1): crossing of group 1 with all others
Crossing Task 2 (CT2): crossing of group 4 with all others
Head to head (HH): group 2 with 6

Figure 5-23: ZAU25: Summary of identified tasks and techniques for flight plan groups. $P(RC)$ = Proportion of flights that received commands. $P(T|RC)$ = Proportion of flights that received technique, given that they received commands.

Sequence to KORD (groups 1 and 5). Groups 1 and 5 were arriving to KORD. All KORD arrivals received direct to a FIX in the WYNDE3 arrival and received final descend command to FL200 prior to the handoff. Moreover, the controller executed varied speed control, assigning speeds between 280 and 300 knots, both for speeding up or slowing down.

Flights in group 5 to KORD were managed for a proper merge with group 1, but the merging task was not explicitly executed by the ZAU25 controller. The actual merging of the trajectories was underneath ZAU25, and after the controller had handed-off flights from both groups 1 and 5. As such, handoffs of flights in group 5 to KORD were executed before reaching PMM, thereby providing enough handling latitude to the downstream controller.

Merging Task 1 (merging of members in group 1). Merging traffic flying through ADALE was managed in two possible ways, apparently based on the situation. In the first way, flights received directs to WLTER or to RHIVR to join the main stream to KORD, while still in ZAU25. In the second way, they were directed straight to a FIX in WYNDE3 arrival, thus deferring the final merging task to the downstream controller. Merging traffic flying through GRR was always merged to the main stream to KORD. These later flights were also treated in a case-by-case basis in terms of directs (either to GRR or straight to WYNDE3), since the main stream in group 1 had not descended enough by GRR.

Merging Task 2 (merging of members in group 4). Group 4 was composed of traffic merging to a focal point outside the sector, and from there going to KMKE. The merging appeared to have been solved by upstream controllers. Thus, this group only required some monitoring and speed control.

Crossing Task 1 (crossing of group 1 with all others). Flights in group 1 received an intermediate altitude before crossing GRR and then, past GRR, received final to FL200. This altitude control solved the crossing task with groups 2 and 3, which, in turn, did not receive any amendments for the crossing. Group 4 and 6 also did not receive amendments, as the former checked-in almost at the sector's floor and the latter checked-in almost at the sector's ceiling, which put their flights separated from all other groups.

Crossing Task 2 (crossing of group 4 with all others). Traffic in group 4 checked-in in much lower altitude than all other groups. Thus, the controller did not have to issue any further altitude or lateral amendments to flights in group 4. This group only required some monitoring and speed control.

Head to head conflict 1 (group 2 with group 5). Group 6 was composed of flights with opposite flight plans of that of group 2. Group 6 entered in level flight almost at the sector's ceiling and they appeared to have been already directed to their destinations by upstream controllers. Thus, these flights were vertically and laterally separated from group 2 and the controller only had to monitor these flights.

General observations. As a member of the descending cluster, most of the

observed altitude commands were for lower altitudes. However, only traffic converging to KORD presented descending behavior, thereby responding for all descending commands. As such, these flights also presented vertical handoffs, close to the sectors floor and within the lateral boundaries.

General sets of commands could be found for the other key flight plan groups, but those sequences of commands were not as consistent as they were for groups 1 and 5. A probable reason for that was the low traffic volume faced by the controller in the observed traffic periods of ZAU25. As presented in Figure 2-5, low traffic volume does not enforce controllers to enforce the use of structure, and, therefore, makes it harder for techniques for each group to be observed. Histon and Hansman (2008) anticipated that in such circumstances controller would let pilots optimize their own trajectories. Indeed, half of the flights not belonging to group 1 did not receive any command (the only pilot-controller communication was check-in and handoff).

The impact of upstream controllers was observable in ZAU25. For instance, group 2, traffic from KMSP and KMKE, had a flight plan which resulted in a line with a turn inside the sector, but featured a converging pattern to GRR, where it crossed with the stream of flights in group 1. Likewise, group 6, flying the opposite direction of group 2, entered the sector already directed to its destinations, thereby requiring little action from the controller.

Moreover, group 3, traffic from KDTW, presented a split critical point inside the sector. The splitting was managed either with no interference from the controller or with directs to scattered destinations.

Once again, there was a confirmation of the area of regard in contrast to the area of responsibility, or the actual physical boundary of the sector (Histon & Hansman, 2008). Handoffs (red squares) occurred inside the lateral boundaries of the sector, whereas check-ins (green circles) were upstream the flows. Moreover, there was evidence that handoffs occurred after the major task of each group was accomplished for groups 1, 2 and 5.

5.3.3 Communication Analysis: Miami 40 (ZMA40)

ZMA40 had 2909 aircraft in two weeks of ETMS data, 40% of flights were climbing, 18% were descending and 42% were level. The sector spans from FL240 and above. In the analysis presented in Section 3.2, this sector was categorized as in the cluster with mixed altitude transitions. Figure 5-24 presents the jet routes and reference points that were most frequently found in the flight plans in ZMA40.

FLIPR is plotted as an illustrative point of the FLIPR2 STAR to Miami International Airport (KMIA). Likewise, WAVUN is a FIX in the WAVUN1 STAR to Fort Lauderdale/Hollywood International Airport (KFLL). SKIPS and EONNS are fixes in the SKIPS1 and EONNS1 Standard Instrument Departure (SID) from KMIA. ZQA is a VOR outside ZMA40. Flights going to ZQA may require coordination with Nassau FIR or with Miami Center itself. Nassau FIR extends from the surface to FL180 when Miami Oceanic is online and to FL600 when Miami Oceanic is offline. The analyzed traffic was handed off to ZMA60 at frequency 127.22 MHz, indicating that Miami Oceanic was online. TANIA and URSUS interface with Havana FIR.
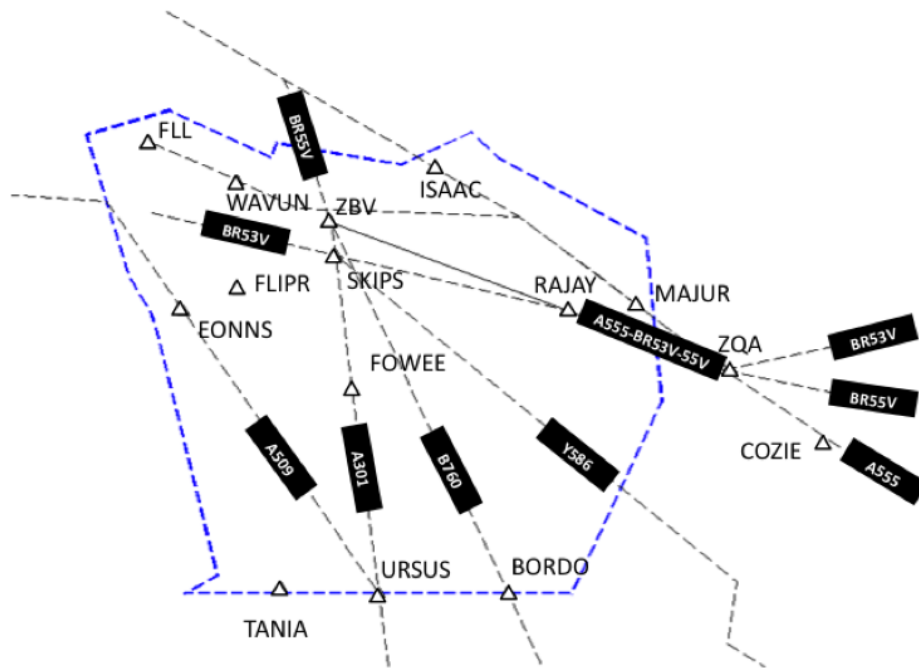
Figure 5-24: ZMA40: Structural framework

Selection of Traffic Hours

Table 5.6 shows the three traffic periods that were considered in this analysis. Care was taken to find an evening without significant weather interference. Weather and poor ride conditions could be identified from METARS and by briefly listening to the communications. When extracting the voice archives from `www.liveatc.net`, only communications in June and July of 2011 were available, and those months had systematic poor weather in the evening.

July 11 was chosen because it had an evening without significant weather interference. Then July 5 was chosen as an evening with weather and with similar level of communications, when compared to July 11.

The morning of July 23 was selected also due to weather considerations and also because its level of communication was not too low for a non-weather morning. In July 23, the observed continuous communication from 9:00AM to 10:00AM was of 17:27 minutes. As it can be seen in Table 5.6, however, the analyzed morning traffic was actually from 9:00AM to 10:30AM. Half an hour was added due to several incomplete voice communications from 9:30AM to 10:00AM. This allowed the inclusion of identified airplanes in the analysis. Therefore, the final continuous communication was of 30:48 minutes, with a total of analyzed airplanes comparable to the other days.

Table 5.6: ZMA40: General information about analyzed traffic intervals. $NAC =$ **N**umber of **A**irplanes; $NIND =$ number of airplanes **N**ot **I**dentified or **N**o **D**ata; $IIC =$ number of airplanes that were **I**dentified but with **I**ncomplete **C**ommunication; $TA =$ **T**otal **A**nalyzed ($NAC - NIND - IIC$); $W =$ if there was **W**eather; $CL =$ continuous **C**ommunication **L**ength after silence removal (in minutes); and $ARTR =$ ratio of **A**pproved **R**equests over **T**otal **R**equests

Day	Time	NAC	NIND	IIC	TA	W	CL	ARTR
07/05/2011 Tuesday	17:30 18:30	41	5	12	24	YES	31:53	5/6
07/11/2011 Monday	17:00 18:00	58	10	12	36	NO	35:19	4/6
07/23/2011 Saturday	9:00 10:30	45	5	5	35	NO	30:48	2/3

Flight plan groups

Three key flight plan groups were identified. These three key flight plan groups are presented in Figures 5-25(a) and 5-25(b).

Traffic in ZMA40 revealed to be very diverse, being entirely composed of international flights. There was a large mix of general aviation and commercial flights, as well as climbing, descending and level traffic. As a result of this diversity, other five minor flight plan groups and one minor temporal group were also identified (Figures 5-25(c) and 5-25(d)). Groups 4, 5 and 6 were only observed in the morning traffic and group 7 and 8 were most predominant in the evening traffic. Group 9 had only one flight on each of the evening traffic intervals, thereby being classified as a minor

(a) Summary of identified key flight plan groups

(b) Legend for key flight plan groups

(c) Summary of identified minor flight plan groups

(d) Legend for minor flight plan groups
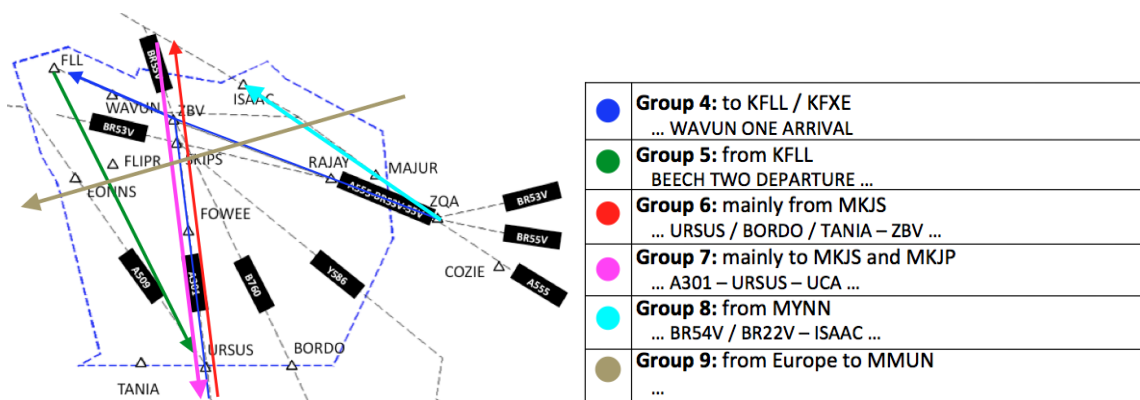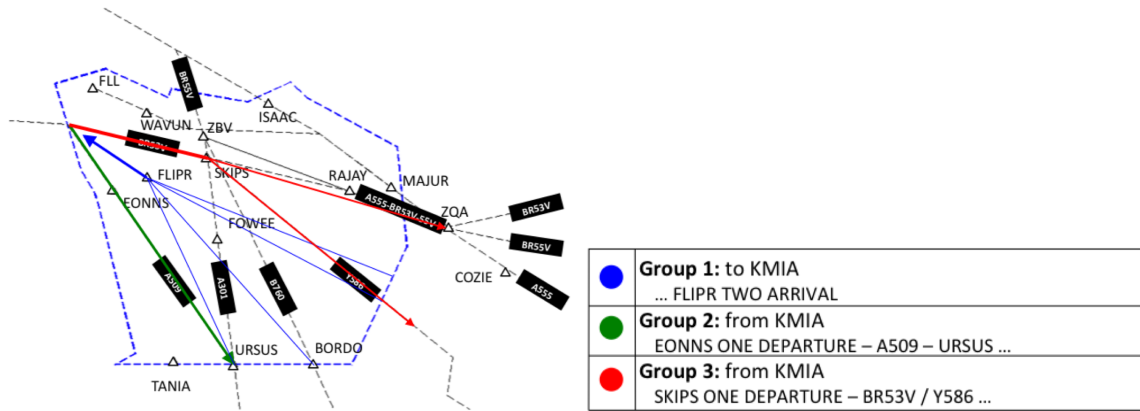
Figure 5-25: ZMA40: Summary of identified flight plan groups. Routes and reference elements related to the planned trajectories of each group are highlighted
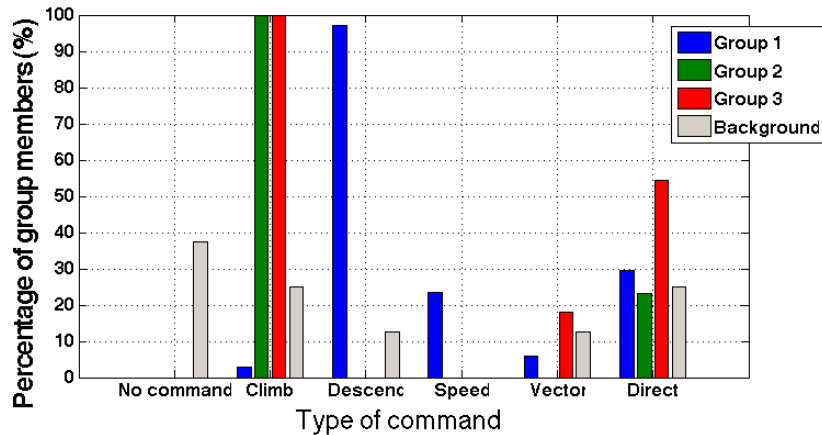
Figure 5-26: ZMA40: Types of commands and flight plan groups.

temporal pattern. Groups 6 and 7 are mainly traffic from and to the Caribbean, respectively, and the planned lateral trajectories are only illustrative of some of the members of these groups. Group 9 was composed of traffic from Europe to Cancun (MMUN) and the planned trajectory is was only illustrative of the trajectories of this group.

Figure 5-26 shows percentage of aircraft in each key group that received each type of command. The three key groups responded for 58 analyzed aircraft, or 61.0% of the total analyzed traffic. Almost all of the traffic to or from Miami International Airport (KMIA), in groups 1, 2 and 3, received altitude commands at some point. In the interest of brevity and due the smaller sample sizes for the minor groups, similar statistics are not presented for groups 4 to 9. However, it is worth noting that all the traffic to or from Fort Lauderdale (KFLL and KFXE), in groups 4 and 5, received altitude commands. Details about each group are presented in Section B.2. The following sub Section presents the major findings for ZMA40.

Summary of ZMA40

The traffic in ZMA40 proved to be very diverse in terms of origins and destinations, aircraft types and dynamics of the traffic. Furthermore, much more temporal variability on the groupings was observed, in comparison to ZNY10 and ZAU25. There was an effort to analyze a traffic period with and another without weather. The

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Figure 5-27: ZMA40: Summary of identified tasks and techniques. $P(RC)$ = Proportion of flights that received commands. $P(T|RC)$ = Proportion of flights that received technique, given that they received commands.

only observation about weather was that some flights in group 1, traffic to KMIA, requested deviation.

Figure 5-27 presents the key and minor groups, the identified major tasks and the sequence of tasks to be executed for each group. Parenthesis is used when only part of the group was subject to that kind of task and slash is used when only one of the tasks applies. As it was the case for ZNY10 and ZAU25, the execution of each one of these tasks followed a specific pattern for each group. This Figure also emphasizes the reduced amount of traffic related to each minor flight plan group. Therefore, the techniques that were identified for these minor groups are mostly illustrative and should be taken with caution, due to the reduced sample size.

Both **Sequence to KMIA (group 1)** and **Sequence to KFLL/KFXE (group 4)** were observed to receive a series of descending commands and being assigned to final altitude of FL240, prior to handoff. Some flights in group 1 received directs to a FIX in the arrival procedure, as well as speed commands. Flights in group 4 only observed to receive only descend commands.

Group 1 and 4 also presented **Merging Task 1** and **Merging Task 2**, respectively. Even though these merging tasks were identified from the flight plans, the flights in these groups entered the sector already directed to their respective focal points. Moreover, flights in these groups were handed off before reaching the focal point, indicating that the final merging was performed by the downstream controller.

Crossing Task 1 (crossing of group 9 with all others). Group 9, a minor temporal group composed of traffic from Europe to Cancun, checked-in above FL380. Thus, these flights were vertically separated from the rest of the traffic and the crossing task was performed without amendments from the controller.

Crossing Task 2 (crossing of groups 6 and 7 with groups 1, 3 and 4 along A301). The separation for the crossing task was guaranteed on the altitude dimension. Group 6 and 7, flying along A301, were in level traffic above FL340 when they entered the sector. Group 3, departing from KMIA, was still climbing when crossing A301 and was handed off before reaching or at FL340. Group 4, descending to Fort Lauderdale, received early descend commands, usually right after check-in. Group 1 also received early descend commands after check in and was below FL340 when crossing A301.

Head to head conflict 1 (groups 2, 5 and 7 with 1, 4 and 6 at URSUS).
This head to head conflict was partially solved laterally by the upstream controllers. The departing flights of groups 2 entered the sector directed to TANIA, thereby avoiding the head to head conflict with the other groups. Group 7 entered the sector directed to downstream destinations and offset from A301, thereby also avoiding the potential conflict. Thus, part of this task was pre-solved by upstream controllers. Controller intervention was only observed for group 5. Flights in this group received direct commands to UCA in the south, effectively forcing them to cross TANIA. These flights also received final altitude to FL330, thereby lower than group 6.

Head to head conflict 2 (group 1 with 3 at the southeast border). Early climbing commands to group 3 and early descending commands to group 1 avoided head to head conflict when crossing the southeast boundary of the sector via Y586. Directs to group 1 also appeared to further laterally separate these groups. The controller still had to give one traffic advisory for an instance of a potential conflict.

Head to head conflict 3 (group 3 with 4 at the east border). As mentioned in the description of Crossing 2, group 4, descending to Fort Lauderdale, received descend commands usually right after check-in. Since group 3 received early climbing commands, both streams of traffic were vertically separated.

General observations. Group 6, northbound traffic from Jamaica, and group 7, southbound traffic to Jamaica, had their planned trajectories overlapping along A301. Thus, these two groups constituted a case of a head to head conflict. However, group 6 was predominant in the evening and group 7 was predominant in the morning, thus not providing enough observations of head to head conflict management. Therefore, this task was not considered in this analysis.

Note that, even tough many potential tasks were identified, few of them actually demanded active management from the controller. This is likely to be a combination of some factors. First, many of the flights entered ZMA40 already directed, thereby pre-solving merging and head to head conflict tasks. Second, vertical handoffs for arriving traffic were executed very early, which transferred part of the merging and sequencing tasks to the downstream controller. Third, six of the identified groups were

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minor groups with low traffic, which reduced the occurrence of situations demanding controller management.

5.4 Summary

This Chapter presented the adopted methodology for identification of techniques with respect to flight plan groupings in the structure. Pilot-controller voice communication and the traffic itself were extracted from publicly available databases (`www.liveatc.net` and `www.flightaware.com`, respectively) for airspace sectors that met certain criteria (explained in Section 5.1.1).

The analysis of details of planned trajectories of ZNY10, ZAU25 and ZMA40 allowed the identification of potential tasks that had to be performed by the controller. These high level tasks were managing crossings, mergings, splits of traffic, head to head conflicts and sequencing for arrivals. From analysis of voice communications, altitude transitions were also identified as major tasks. The observed descending tasks were all part of the sequencing for arrivals, whereas the observed climbing tasks were all associated with departures.

Each high level task was observed to be executed with a specific set of commands for each group. Naturally, each group presented a specific sequence of high level tasks. These particular sequences of tasks were the source of the techniques, or sequence of commands, that were identified for each group. These standard modifications to each group produced noticeable changes from planned to actual trajectories. The actual trajectories were also observed to repeat across the analyzed traffic intervals. Thus, the final traffic patterns were intrinsically related to the flight plan groups and their respective management techniques used by the controller.

Weather impact was also analyzed. In ZMA40, the weather interference was manifest in pilot requests for deviation, but only among those flights arriving to KMIA. Conversely, ZNY10 provided a case of severe weather effects. In this case, weather was found to affect only specific groups, mainly because of reroutes that aircraft suffered due to decremental weather in other parts of the country. Consequently, the analyzed

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weather scenario imposed harder constraints and more user requests. Since this was a specific case of weather interference and confounded by higher traffic volume, general conclusions could not be drawn from it.

In summary, for the three analyzed case studies, it was found a relationship between flight plan groupings and management techniques. Within each group, there was an identifiable and repeatable set of adjustments, or techniques. These repeated modifications generated structural features such as flows and critical points, which were naturally related to the flight plan groupings in the traffic. These findings help validate the grouping structure-base abstraction introduced by Histon and Hansman (2008). Moreover, these results motivate the adoption of a grouping-focused analysis of the traffic for evaluation of how controllers manage the traffic.

Chapter 6

Conclusion

6.1   Thesis Summary

The ultimate objective of this work was to investigate how distinct structural patterns are used by controllers for managing air traffic.

In order to accomplish this objective, structural patterns first had to be identified and then investigated in terms of how they were managed. The search for such structural patterns started with the identification of different types of sectors, considering metrics for the dynamics of the traffic. These metrics were motivated by research on complexity and workload of air traffic controllers, as these metrics were likely to correlate with the underlying tasks to be performed.

Based on the calculated traffic metrics from ETMS data, a data mining technique was used in order to identify distinct types of sectors, in terms of traffic dynamics. Five such types were identified. Three of them had clear distinctions in terms of altitude transitions: one was predominantly composed of climbing and other was predominantly composed of descending traffic. The other type presented a significant mix of altitude transitions. The other two groups presented level traffic and different combinations of traffic volume and directional variability, what appeared to be different levels of apparent complexity. This typology of sectors allowed the selection of sectors for further detailed analysis of their structural patterns. Based on the identified types of dynamics, these sectors were likely to present certain combinations of

tasks and patterns of traffic.

Then, a descriptive and subjective evaluation of the traffic was conducted, with the goal of observing variations in the patterns and generating hypothesis about how controllers manage the traffic. It was found that, by partitioning the traffic in terms of origins and destinations, much of the dynamics of the traffic could be identified. Moreover, the origins and destinations suggested many of the potential tasks that controllers had to execute. This motivated the hypothesis that controllers might employ common management techniques to common sets of flights with same planned trajectories.

Descriptive evaluation of the controllers' commands were added to the descriptive evaluation of the traffic, in order to investigate how the structural patterns (groupings by planned trajectories) were being managed. This detailed pilot-controller voice communication analysis was presented with respect to elements of the cognitive process model, as introduced by Histon and Hansman (2008). From the identification of flights through the sector, it was possible to distill groupings by flights plans. Via detailed voice communication analysis, each flight plan grouping was found to be associated with a specific technique, or sequence of commands

6.2   Conclusion

The grouping structure-based abstraction introduced by Histon and Hansman (2008) anticipated that controller would collect together similar parts of the situation and incorporate them into his/her mental model. By capturing these segregated parts of the traffic, the controller would be able to decompose the tasks into smaller and simpler parts. This work provided evidence that helps validate the grouping abstraction in terms of flight plan groupings.

The interactions between the identified flight plan groupings allowed the identification of potential major tasks, such as mergings and crossings. It was observed that each major task was performed with a particular set of commands for each group. More importantly, each group was found to be related to a repeatable and specific

sequence of commands, or particular management technique. These standard adjustments to the traffic created repeatable changes from planned to actual trajectories, resulting in patterns in the structure, such as flows and critical points. Therefore, the structural patterns were found to be related to the standard flight plan groupings and their respective techniques.

Consequently, these groupings are a critical factor in how controllers abstract and manage the traffic. This work, however, does not discount the importance of flows and critical points.

These results motivate the adoption of a grouping-focused decomposition of the traffic when tackling the issue of how controllers manage the traffic. This type of analysis should allow for the determination of (1) the impact of sector changes on how controllers manage the traffic; and (2) comparison of sectors in terms of the required tasks and management techniques.

For instance, changes in standard routings could result in the addition or removal of flight plan groupings, thereby impacting the interactions of groupings and, therefore, major tasks and techniques. The addition or removal of groupings could be either static (i.e., as part of a plan for permanently rearranging the traffic) or dynamic (i.e., as a response to imbalances of capacity and traffic demand in the airspace). The latter case fits in the concept of dynamic airspace configuration (also known as flexible airspace), which is being evaluated by FAA (2010) for better distributing workload among controllers and reducing impacts of capacity shortages on the system.

Pairwise comparison of sectors, under a grouping-focused perspective, should provide a listing of differences in tasks and techniques between the traffic structures. These listings can be used as a roadmap for determining the required differential training when moving from one facility to another. Therefore, results of these formal comparative analyses could aid on the cross-training processes, thereby improving the capability of FAA to move controllers from one airspace to another and increasing the staffing flexibility of current air traffic controllers.

Interestingly, a NAS-wide grouping-focused analysis could also aid on the identification of groups of sectors that already have similar groupings patterns and, therefore,

require similar tasks and management techniques. This latter type of analysis would be applicable for the generic airspace concept. This concept, also currently evaluated by the FAA (2010), is imagined as composed of sectors that allow for the easy transferability of mental models across different facilities. Thus, one can potentially identify candidates for constituting generic airspace by looking for sectors that already require similar tasks and management techniques

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Appendix A

Background: Air Traffic Control System

Air Traffic Control (ATC) is a critical part in the operations of the National Airspace System (NAS). Nolan (2011) provides a historical evolution of the system and the logic throughout its development. As currently practiced, ATC is a human-centered process in which controllers and flight crews or dispatchers negotiate for access to airport and airspace recourses (Belobaba et al., 2009). This occurs by a contract where controllers provide a "clearance", that is executed by the flight crews and its conformance is monitored by the controller.

The purpose of ATC is to ensure safe and efficient flow of air traffic. In order to achieve this goal, several tasks have to be performed. Histon and Hansman (2008) segregate these tasks in seven categories: separation, monitoring, constraint, requests, coordination, information and other tasks. Safety is supported mainly from the separation and monitoring tasks. Controllers are responsible for keeping minimal horizontal separation of 5 nautical miles (3 nautical miles in terminal airspace) and vertical separation of 1000 feet between aircraft. Separation has also to be assured between aircraft and hazardous weather, terrain and wake vortices of other aircraft. Monitoring of conformance to current clearance within acceptable tolerances is also fundamental for providing safety.

In order to fulfill all these tasks, any ATC system is composed of basic compo-

nents, such as communication, navigation, surveillance and automation systems, the human air traffic controllers themselves and procedures (Parkinson & Spilker, 1996). Communication systems, navigation systems and procedures are briefly discussed below.

Currently, most of ATC communications occur via voice radio channels. These channels are shared between pilots and controllers and they operate in very high-frequency (VHF) reserved for aviation use. Only one communication can be conducted at a time, otherwise there is a painful "squeal". Therefore, multiple communications end up blocking the channel and there is a requirement for read-back of ATC clearances. Ambiguity and sources of error are also reduced by the use of standard phraseology.

The navigation system provides the basis for definition of airways and reference points, which are then critical for the controllers when issuing commands and organizing the traffic. Navigation on the en-route system must cover long-range distances, while on the approach system it must be more precise for collision avoidance (Belobaba et al., 2009).

The fundamental airspace elements for navigation are radio beacons such as Very High Frequency Omni-Directional Ranges (VORs), Nondirectional Radio Beacons (NDBs) and Very High Frequency Omni-Directional Ranges /Tactical Air Navigation (VORTACs). Like any VHF radio communication, the VOR system is limited to line of sight, so a network of these stations is required.

New technologies have emerged as a means to complement the VOR network. These include the Inertial Navigation System (INS) and satellite-based navigation systems, such as Global Positioning System (GPS). The guidance provided by these systems is space-based and worldwide in scope, so they are not limited to support navigation between pairs of stations, there is no line of sight restriction and there are no associated symbols on aeronautical charts. As such, these systems are very useful above Oceans or in any region with limited or no ground station network.

Standard Operating Procedures (SOPs) are defined for most ATC systems (Belobaba et al., 2009). In Table 10-5 of Appendix III, Histon and Hansman (2008) provide a

list of examples for identified SOPs. The identified categories of procedures were routing requirements, crossing restrictions, control delegation, coordination, sequencing responsibilities, holding, military airspace / training routes, automated handoff transfers an simultaneous approaches / protected airspace.

FAA Order 7110.65 determines air traffic control procedures and phraseology for use by those providing air traffic control services in the US. An overview of standard procedures, the delegation of responsibility and phraseology can also be found in Nolan (2011). One important example of standard procedure is the standard altitude for flights: westbound flights are assigned even thousands of feet, whereas eastbound flights are assigned odd thousands of feet. There exist also published standard routings, such as Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs). Another SOP is the holding pattern, which is a racetrack-like trajectory. Holding patterns are used as buffers in the systems by delaying aircraft in the air. They are particularly useful when aircraft cannot be handed off to the next sector, when there is weather or for any other reason. There are also specialized procedures that the ATC system adopts in order to cope with local conditions. These are Letters of Agreement (LOA) and they usually define interface conditions between areas of responsibilities, such as restrictions on handoffs.

A.1 The Airspace

FAA categorizes the airspace above the United States in four main categories (Nolan, 2011; Neufville & Odoni, 2003):

- In **positive controlled airspace**, the FAA either absolutely prohibits VFR operations or separates both VFR and IFR aircraft.

- In **controlled airspace**, the FAA separates IFR aircraft. Under permitting weather situations, IFR aircraft are also responsible for separating themselves from VFR aircraft. And VFR aircraft flying in controlled airspace are also responsible for separating themselves from other aircraft.

- ATC separation services are not provided by the FAA in **uncontrolled airspace**. All aircraft must provide their own separation, regardless of their type

- The FAA also specifies airspaces wherein certain activities are confined or restrictions must be imposed on nonparticipating aircraft. This constitutes on the **special use airspace** category, where special operating restrictions and rules are applied. Special use airspace can be situation inside controlled and uncontrolled airspaces, thereby affecting aircraft in these regions. Types of special use airspace are prohibited, restricted, warning, military, alert and controlled firing areas. Table 3-4 in Nolan (2011) details each of the special use airspaces, including a general description, entry requirements, IFR restrictions, VFR restrictions and how they are displayed in charts.

The airspace can also be divided in Classes. Within positive controlled airspaces, there are Classes A and B. Within controlled airspaces, there are Classes C, D and E. Class G is uncontrolled. Each Class of airspace has different characteristics in terms of dimensions, geographical location, entry requirements, services provided to IFR flights, services provided to VFR flights, minimum visibility for VFR and minimum distance from clouds for VFR (Nolan, 2011).

Of special interest in this work is Class A airspace. Evolved from the **jet advisory areas** created in the 1960s to provide advisory services to turbojets at high altitudes, Class A currently extends from 18,000 feet MSL up to and including FL600 (Nolan, 2011). As a positively controlled airspace, FAR 91.135 requires all aircraft flying in Class A to operate under IFR at a route and altitude assigned by ATC, in addition to be transponder equipped. Pilots also must have proper ratings for instrument flight.

With the increase of traffic volume in airports surrounding areas, FAA responded with the creation of **terminal control areas (TCAs)**, which then evolved to the current Class B airspace. This airspace extends up to 10,000 feet MSL, usually within an "upside down wedding cake" shape. The dimensions and format is such to accommodate all published instrument procedures (STARs and SIDs) of the respective airports.

Initially implemented as **airport radar service** in 1984, Class B airspace surrounds medium activity airports up to 4,000 feet AGL. Class D airspace is defined from the ground up to 2,500 feet above the airport elevation. It surrounds airports that possess an operational control tower. Class E airspace is generally what is not Class A, B, C or D and is still controlled airspace. Most of the uncontrolled airspace, Class G, is far from major airports and below 1,200 feet AGL.

The FAA further delegates the separation responsibility to 24 air route traffic control centers (ARTCC) in the United States. Due to the extensive dimension of the geographical areas assigned to these centers, separation responsibility is further partitioned both vertically and horizontally into airspace sectors. The current shape, dimensions and design of sectors is a consequence of traffic and the arrangement of reference elements (Chatterji et al., 2008; Nolan, 2011).

Within ARTCCs, sectors are usually separated into low (ground to 18,000 feet MSL) and high (18,000 feet MSL to FL600) sectors. In busier centers, however, there is a further stratification where high sectors range from FL180 to FL350 and super-high sectors range from FL360 to FL600. Notwithstanding, this definition is not standard among studies involving high altitude concepts and different researchers such as Chatterji et al. (2008); Kalbaugh and Levin (2009); Simmons (2010); Cho, Histon, Albuquerque Filho, and Hansman (2010) have adopted different criteria.

Each controller is tasked with aircraft separation with the his or her own are of responsibility. Typically, the **transferring controller** directs the pilot to contact the **receiving controller** on a different radio frequency prior to crossing the sector boundary, in a process named **transfer of communication** (Nolan, 2011). Handoffs constitute on "the process of transferring control and communication of an aircraft from one controller to another" (Nolan, 2011).

Each sector typically has 1 to 3 controllers: flight data controller (D-side), radar controller (R-side), radar associate (ATA, non-radar controller). D-side is responsible for assisting the other controllers, handling pertinent flight information, detecting potential conflicts and coordinating with other controllers. R-side provides separation between all IFR flights, in compliance with the various standard procedures and

letters of agreement and facilities directives that may apply to the sector. This is executed by the R-side by communicating and issuing altitude, heading, or airspeed changes to the pilots. The non-radar controller duty is to update the flight strips and to help the radar controller to separate aircraft that are not in the radar screen.

There are also the air traffic control towers (ATCTs). An overview of control tower procedures can be found at Nolan (2011).Within the control tower, there is ground control, responsible for taxing aircraft and any ground vehicles operating on airport movement areas (Nolan, 2011). Also in the tower, there is the local control, responsible for runway control and for aircraft operating in the most immediate surrounding are of the airport (5 miles around the airport and up to 2500 or 3000 ft AGL) (Belobaba et al., 2009). At busy facilities there might be also approach and departure control. In even larger and busier airports, there may be a separate facility for arrivals and departure control, the terminal radar approach control (TRACON). The terminal airspace under responsibility of TRACON facilities usually extends 50 miles from the airport and up to 18,000 AGL (Belobaba et al., 2009).

Appendix B

Flight Plan Groups and Techniques

This Appendix provides detailed observations from the flight plan groups in sectors ZAU25 and ZMA40, from the analysis described in Chapter 5. General information about the sector, the selection of traffic times and a summary of major findings can be found in the main text.

B.1   Flight Plan Groups: Chicago 25 (ZAU25)

Group 1: traffic to KORD

Figure B-1 presents planned trajectory, actual trajectories and estimated position of commands for group 1 on June 17. Group 1 is characterized by arrivals to Chicago O'Hare International Airport (KORD). Besides the destination to KORD, the flights had WYNDE3 at the ending of the flight plan. Table B.1 presents pilot requests for group 1 for each analyzed data point. Ride conditions were worse at higher altitudes during the evening.

All of the 45 flights in group 1 checked-in at level flight, then received descend commands down to FL200. 28 (62.2%) flights were directed to a FIX in the KORD WYNDE3 arrival procedure (Figure B-2). Some flights were first assigned to an intermediate altitude (such as FL260 or FL280) and only after crossing GRR they received direct to WYNDE3 and descend to FL200. 26 (57.8%) flights also received

(a) Planned trajectory for group 1

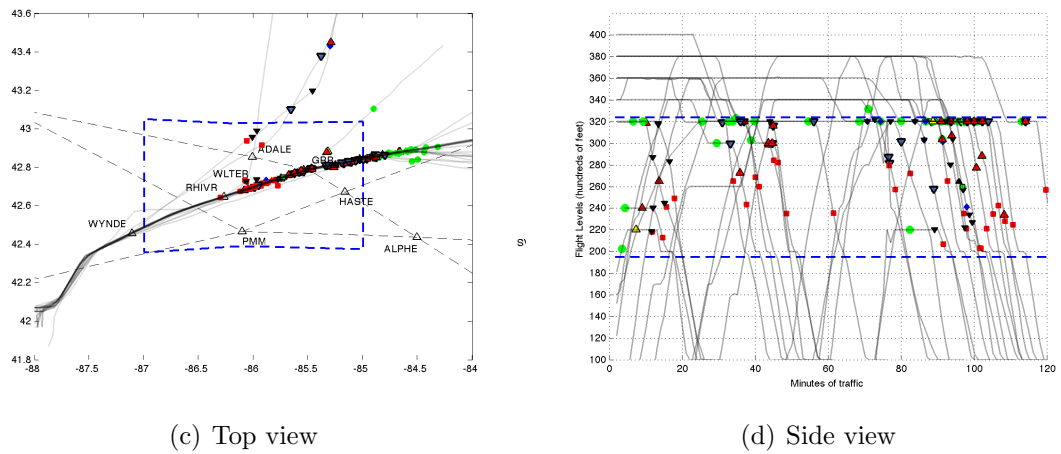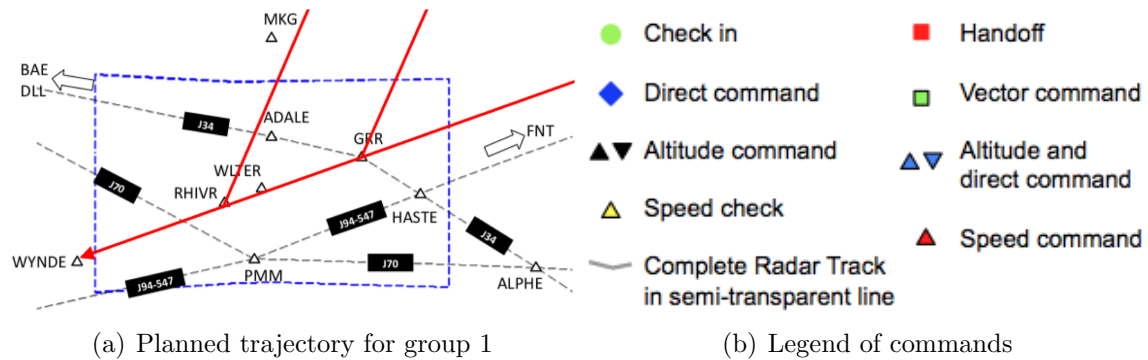(b) Legend of commands

(c) Top view

(d) Side view

Figure B-1: ZAU25: Results for 28 flights in group 1 on 06/17, 09:00 – 11:00 AM

speed commands, both for speeding up and speeding down. The speed restriction was usually between 280 and 300 knots. Once the aircraft was properly directed to a FIX in the WYNDE3 procedure and descending to FL200, the controller handed it off before RHIVR.

There is also merging traffic from the north. Some of these flights had ADALE – WYNDE3 or GRR – WYNDE3 in their flight plan. Those flying through ADALE

Table B.1: ZAU25: Pilot requests from aircraft in group 1.

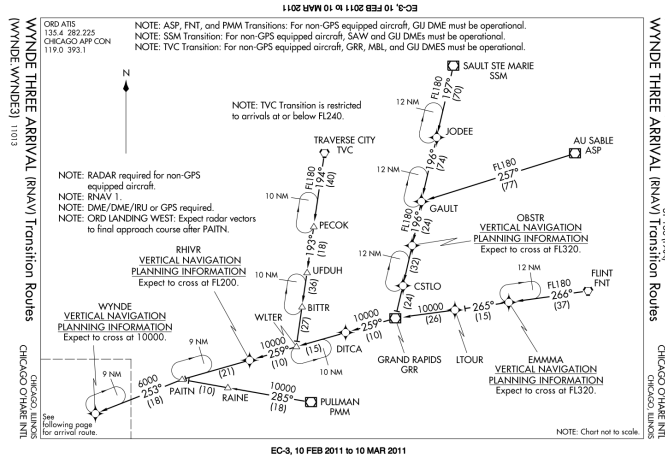| Traffic	Call Sign	Request	Approved
06/17 MORN	TCF3526	lower	yes
06/17 EVEN	BTA5811	lower	yes
06/17 EVEN	EGF3792	lower	yes

Figure B-2: ZAU25: WYNDE THREE Arrival Procedure. Source: www.flightaware.com

were directed to WLTER or to RHIVR as they approached the stream going to KORD. Since most of group 1 had not descended enough by GRR, the merging traffic through GRR ended up being treated in a case-by-case basis, in terms of directs.

Note that many descending, descending with direct, direct and speed commands overlap from the check-in location to the check-out location. This is a consequence of the need for several descending, speed and direct commands both to the straight and the merging traffic.

Group 2: southeast bound traffic

Figure B.2 shows trajectories and position of commands for group 2, which is defined as aircraft that had flight plans equivalent to: DLL – BAE – ADALE – GRR – HASTE - ALPHE or simply J34 eastbound (See Figure 5-21). Departures are from Minneapolis-St Paul International Airport (KMSP) or General Mitchell International Airport (KMKE) and destination is usually to Cleveland-Hopkins International Airport (KCLE), but also including flights to Washington DC, Philadelphia and Pittsburgh. Table B.2 presents pilot requests in this group.

Since this group flies eastbound, aircraft take odd flight levels (FL250 and FL270 in Figure B-3(d)). The controller limited the altitude to FL260 or FL280 to some aircraft in group 1, thereby guaranteeing separation with group 2. After the crossing
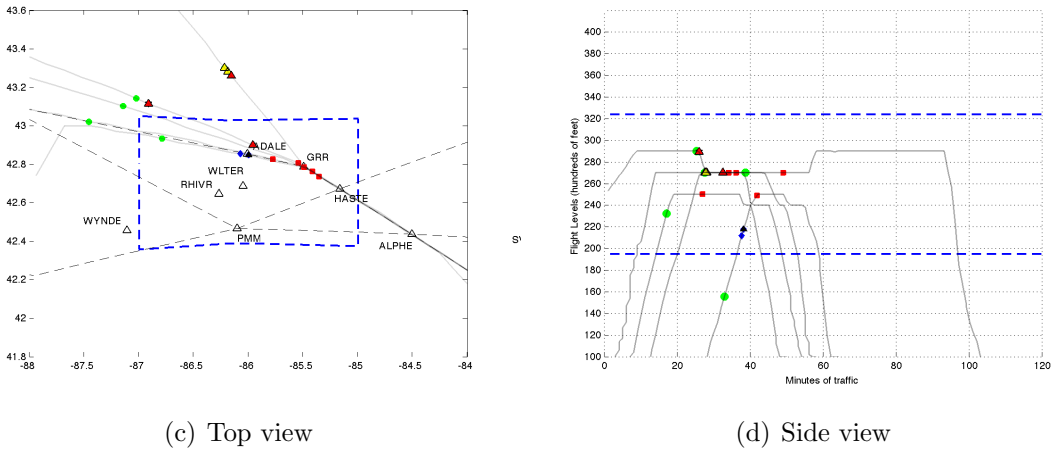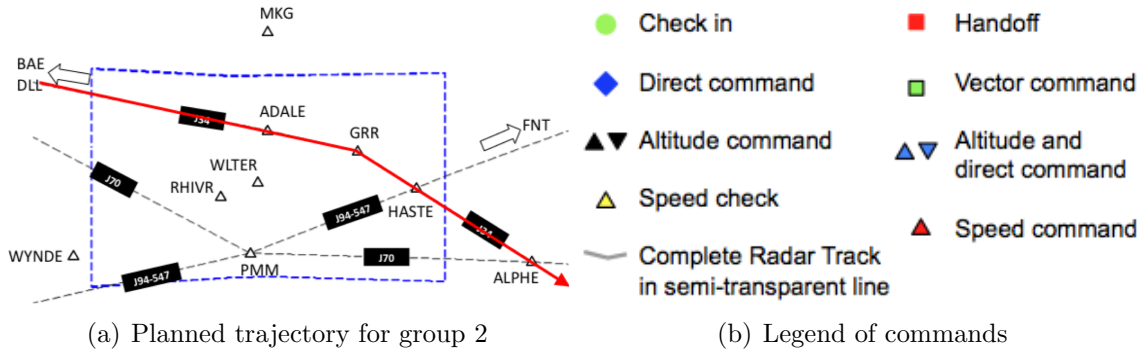
(a) Planned trajectory for group 2   (b) Legend of commands

(c) Top view   (d) Side view

Figure B-3: ZAU25: Results for 5 flights in group 2 on 06/17, 05:00 – 07:00 PM

Table B.2: ZAU25: Pilot requests from aircraft in group 2.

Traffic	Call Sign	Request	Approved
06/17 MORN	CHQ1964	reduce speed	yes
06/17 EVEN	BTA3004	via Gran Rapids	yes
06/17 EVEN	DAL1664	higher	ATC convinces current ride conditions are better

point, aircraft in group 1 were directed to WYNDE3 arrival procedure and descended to FL200 and aircraft in group 2 were handed off.

Half of the flights in group 2 did not get amendments from the controller and there were no specific patterns in terms of speed and direct commands.

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Group 3: westbound traffic from KDTW

Figure B-4 shows trajectories and position of commands for group 3. This group is composed of departures from Detroit Metropolitan Wayne County Airport (KDTW) that take DUNKS – J70 – PMM. From PMM they take all sorts of destinations, such as J94-547 and J70. Table B.3 presents pilot requests in this group.

Table B.3: ZAU25: Pilot requests from aircraft in group 3.

Traffic	Call Sign	Request	Approved
06/17 MORN	DAL2149	direct	no
06/17 EVEN	DAL1217	higher	ATC convinces current ride conditions are better
06/17 EVEN	MES2566	to FL280	yes

(a) Planned trajectory for group 3

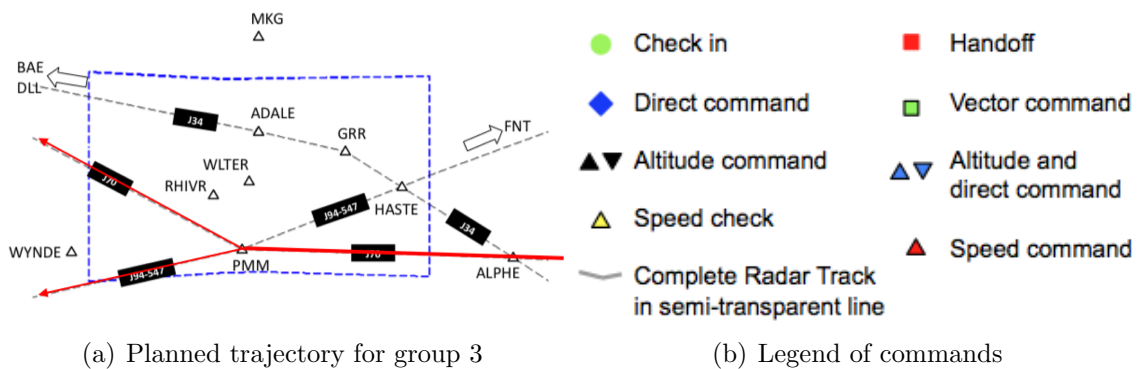(b) Legend of commands

(c) Top view

(d) Side view
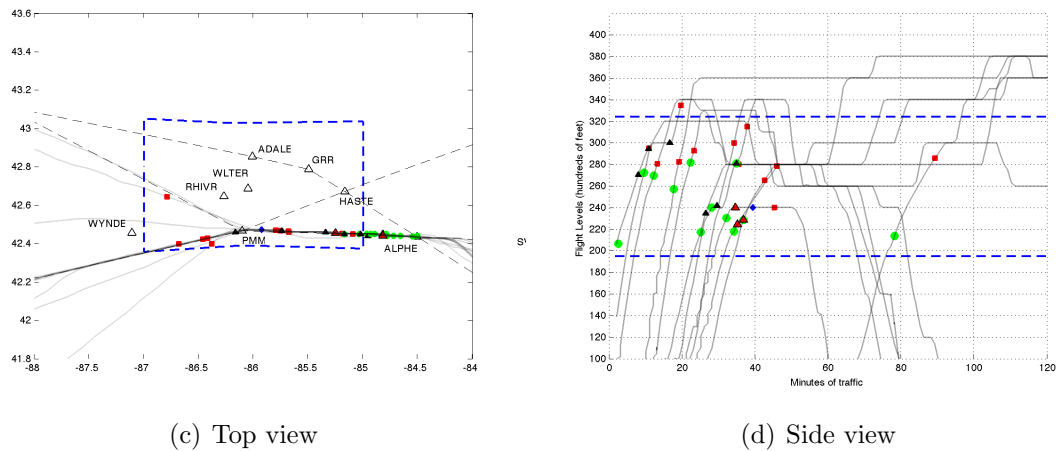
Figure B-4: ZAU25: Results for 12 flights in group 3 on 06/17, 09:00 – 11:00 AM

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The 18 departures from KDTW in group 3 checked-in above FL200, but outside the lateral limits of the sector. 8 of them received no commands. 5 of them received climbing commands only. Direct commands, when issued, were to varied downstream waypoints. Speed commands were only to resume normal speed. As illustrated in Figure B-4(c), handoffs occurred in different locations, some of them almost at the sector boundary.

Group 4: traffic to KMKE

Figure B-5 shows trajectories and position of commands for group 4. This group is characterized by arrivals to General Mitchell International Airport (KMKE) and Waukesha County Airport (KUES). The flight plan has an ending equivalent to MKG – V2 – SUDDS. This common section of the flight plan, however, is outside the
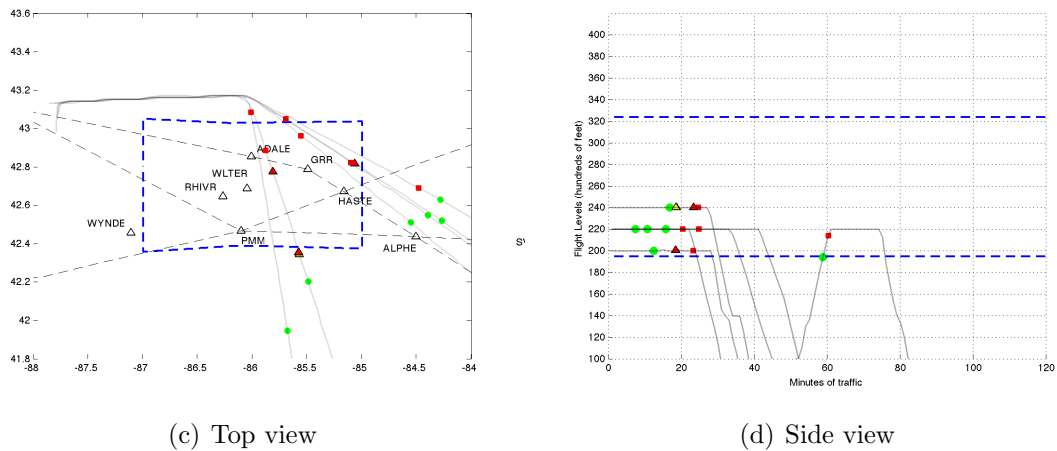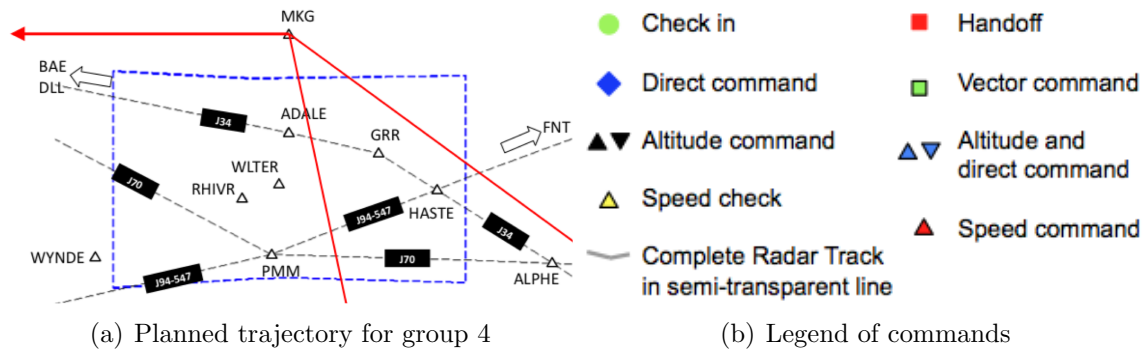

(a) Planned trajectory for group 4

(b) Legend of commands

(c) Top view

(d) Side view

Figure B-5: ZAU25: Results for 6 flights in group 4 on 06/17, 05:00 – 07:00 PM

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boundaries of ZAU25.

As depicted in Figure B-5(c), these 9 flights constituted a fan pattern with focal point external to the sector. As illustrated in Figure B-5(d), group 4 is a lower altitude traffic that entered the sector below FL240 and did not receive climbing commands. Moreover, all aircraft entered in the sector already direct to MKG.

Due to this lower altitude, this traffic interferes very little with other groups, thereby not requesting much management from the controller. And since everyone was already properly directed, there was no need for lateral interference from the controller. Indeed, only two airplanes got speed commands. CHQ1933 got 260 knots for sequencing and then resume to normal speed; and BTA2350 got 310 knots or greater for sequencing. Therefore, the controller technique was to monitor the sequencing of the fan flow and to issue direct or speed commands when necessary.

**Group 5: traffic from KDTW to KORD**

Figure B-6 shows trajectories and position of commands for group 5. This group is composed of departures from Detroit Metropolitan Wayne County Airport (KDTW) to KORD that take DUNKS – J70 – PMM – WYNDE3.

The 6 flights in this group were climbing at the check-in and were already descending before reaching PMM. All of them received directs to WYNDE and descend command to FL200 (not necessarily in this order). Speed commands varied among these flights. In order to maintain separation along J70 or to properly merge this group with group 1, 4 flights received speed commands, either for speeding up or for slowing down. Once an aircraft was properly directed to a FIX in the WYNDE THREE procedure and descending to FL200, the controller handed it off before PMM.
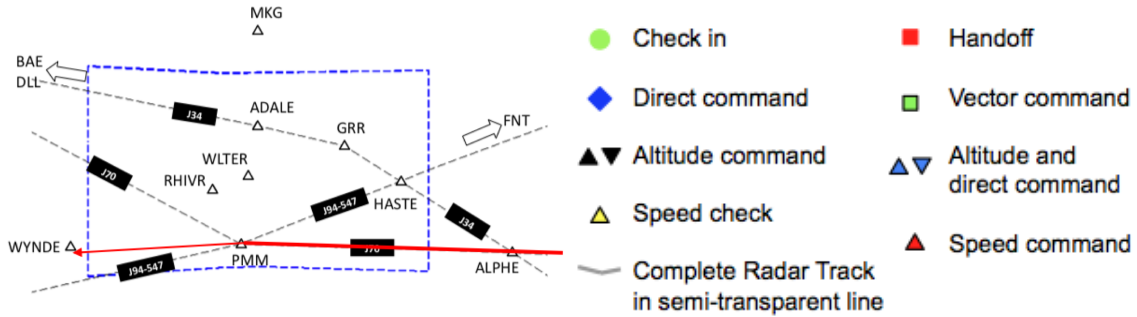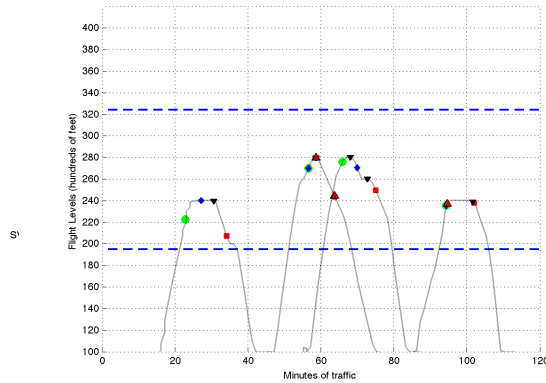
(a) Planned trajectory for group 5

(b) Legend of commands
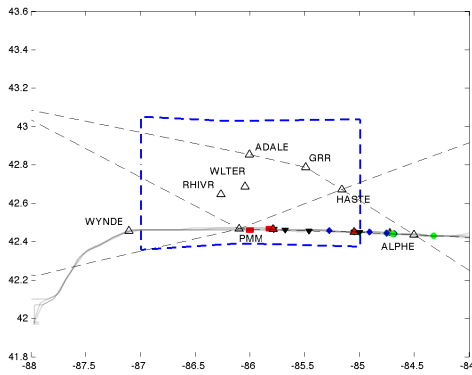
(c) Top view

(d) Side view

Figure B-6: ZAU25: Results for 4 flights in group 5 on 06/17, 05:00 – 07:00 PM

Group 6: northeast bound traffic

Flights in group 6 have the exact opposite planned route of group 2 inside ZAU25: ALPHE – HASTE – GRR – ADALE – BAE or J34 westbound. There were no predominant origin or destination in this group. This pattern could only be seen in the morning traffic. Therefore, for the purposes of this analysis, group 6 was considered a minor group. Further investigation would have to be done to assert if this is due to time variations of the traffic, weather or wind.

Figure B-7 presents the 5 flights observed in this group. None of them received any command. Moreover, flights in this group didnt necessarily follow the planned route. All of the flights entered and exited at level flight and, except for one, all the flights were already directed to a downstream destination. As such, the controller did not issue any command to any of these flights. Also there was no pilot request
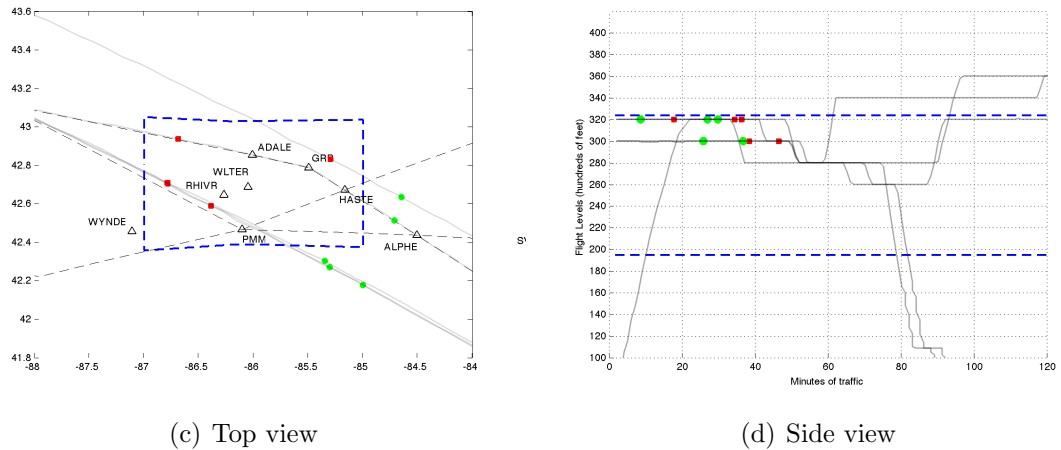
(a) Planned trajectory for group 6

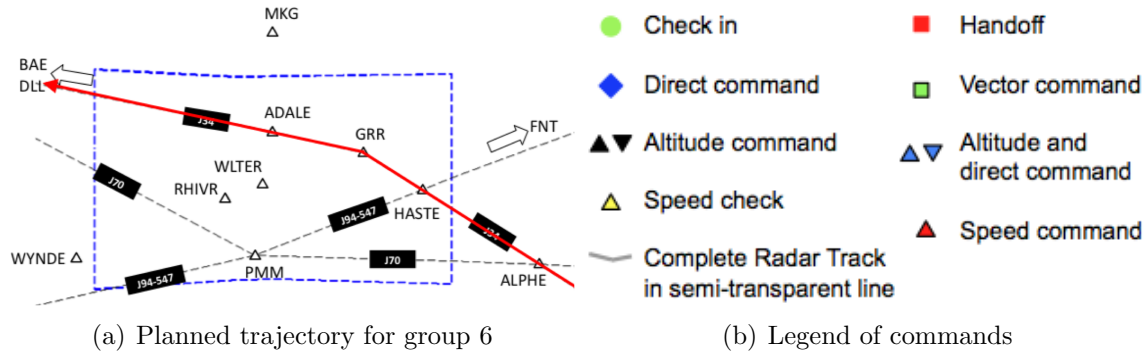(b) Legend of commands

(c) Top view

(d) Side view

Figure B-7: ZAU25: Results for 5 flights in group 6 on 06/17, 09:00 – 11:00 AM

from flights in this group. Therefore, the controller only monitored these aircraft that crossed the sector.
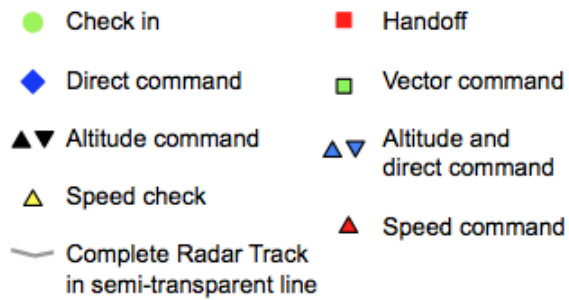
Background Traffic

Figure B-8 presents 12 flights that could not be categorized in any specific flight plan pattern. 7 (1 in the morning, 6 in the evening) of which did not receive any commands. 3 flights received climbing commands and 2 received descending commands. Both evening and morning traffic had a fair mix of short and long haul flights. Some takeoffs within sector boundaries were also observed. For instance, FFT253 climbed from Gerald R. Ford International Airport (KGRR), thereby receiving climbing instructions and speed command to resume normal speed. None of the commands issued to the background traffic were pilot initiated.
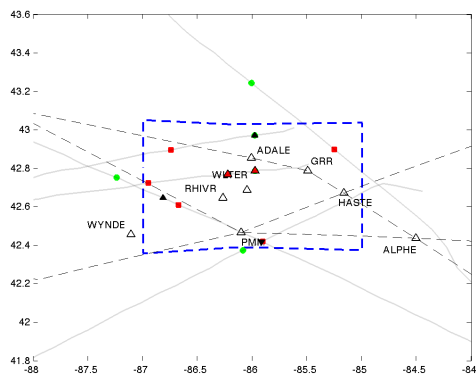
(a) 06/17, 09:00 – 11:00 AM
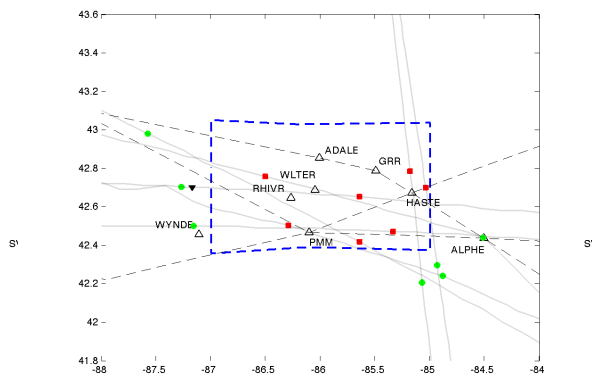
(b) 06/17, 05:00 – 07:00 PM

(c) Legend of commands

Figure B-8: ZAU25: Background traffic

B.2 Flight Plan Groups: Miami 40 (ZMA40)

Group 1: traffic to KMIA

Group 1 is characterized by arrivals to Miami International Airport (KMIA). Flights had FLIPR2 STAR at the ending of the flight plan (see Figure 5-25). Figure B-9 shows trajectories and position of commands for group 1.

All of 34 flights were assigned final altitude to FL240 before handoff. As presented in Figure B-9, the descending commands were given shortly after crossing the sectors boundary. 10 of the flights were directed to FLIPR, a point in the FLIPR2 STAR. 8 flights received speed commands. The speed commands varied depending on the traffic situation, such as " do not exceed 290 knots for spacing" or " when able main-
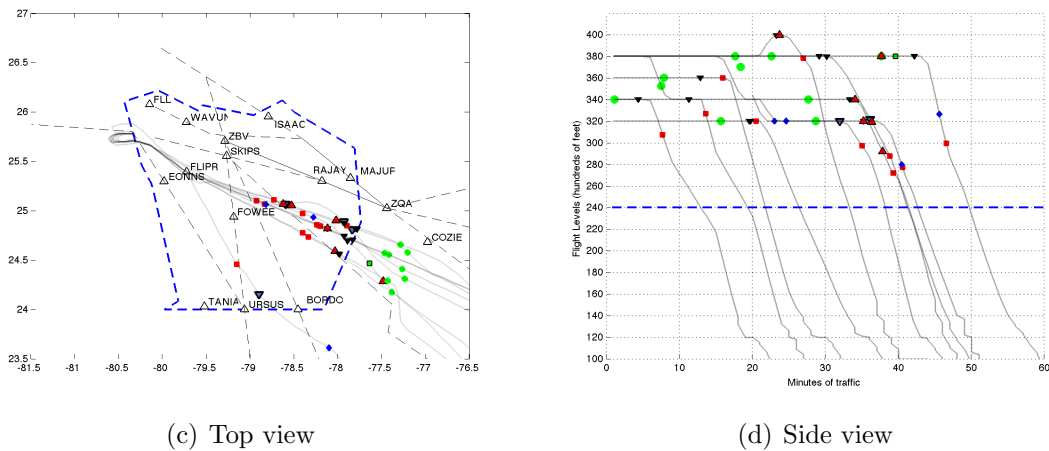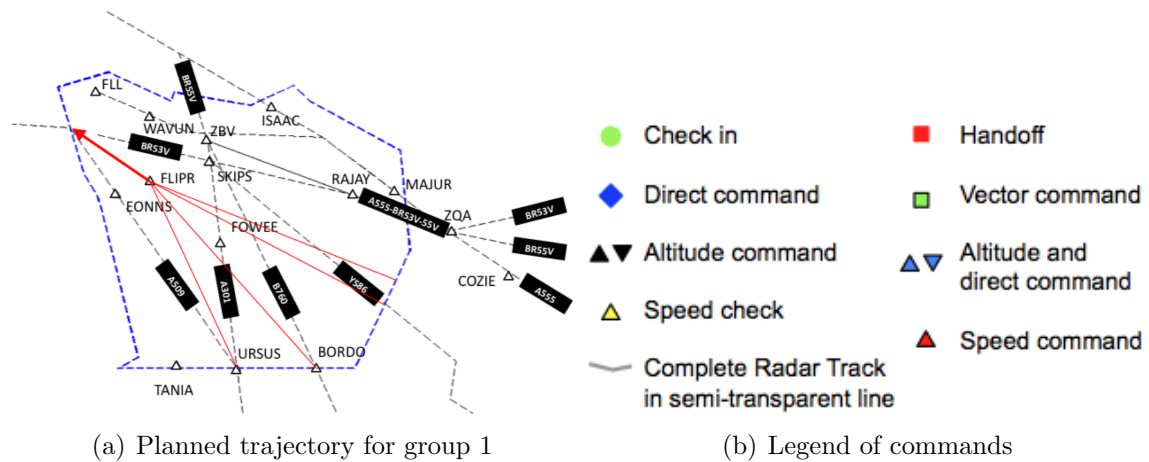

(a) Planned trajectory for group 1 (b) Legend of commands

(c) Top view (d) Side view

Figure B-9: ZMA40: Results for 10 flights in group 1 on 07/05, 05:30 – 06:30 PM

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tain 310 knots or greater for spacing". Pilot requests were either to start descending to KMIA or, in July 5th, to deviate for weather. Table B.4 illustrates the requests.

Table B.4: ZMA40: Pilot requests from aircraft in group 1.

Traffic	Call Sign	Request	Approved
07/05 EVEN	AAL1078	deviation for weather	yes
07/05 EVEN	AAL1830	to FL400 before start down	yes, in 20 sec
07/05 EVEN	AAL1880	deviation for weather	yes
07/11 EVEN	AAL1832	lower	yes
07/11 EVEN	TAM8094	descent	yes
07/23 MORN	AAL464	lower	yes, in 100 sec

The origins of the traffic in this group were very diversified and not within the United States. For instance, there wasnt a single Origin repetition in the same traffic period being analyzed. Not surprisingly, group 1 presented a merging pattern with focal point at FLIPR.

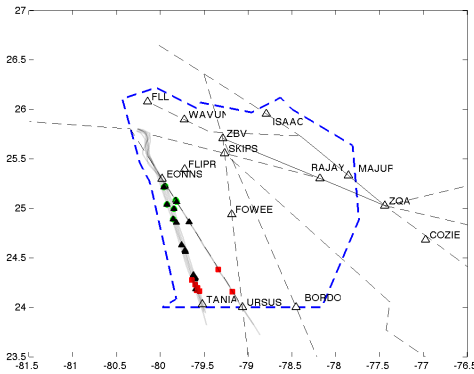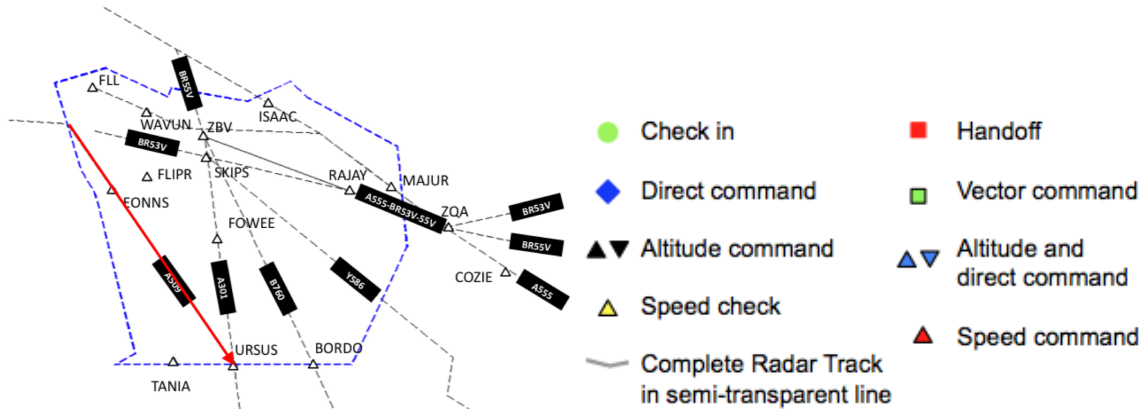**Group 2: traffic from KMIA, EONNS ONE Departure**

Group 2 is characterized by departures from Miami International Airport (KMIA) that had EONNS1 Standard Instrument Departure (SID) and then EONNS – A509 – URSUS (or equivalent route) in their flight plan (see Figure 5-25). A total of 13 flights were observed, 10 going to South America and 3 going to Central America. All of them received climbing instructions to flight levels ranging from 290 to 370. No speed or vector commands were given.

It can be seen in Figure B-10 that these flights checked in around FL180. Despite planned to pass through URSUS, the flights were consistently crossing TANIA instead, without controller interference. The upstream controller had most probably directed them, in order to allow for a shorter route or to avoid head to head conflict with flights in group 1 and 6 that enter via URSUS.

Requests in this group were mainly for higher altitudes and not associated with weather conditions, as presented in Table B.5.

Table B.5: ZMA40: Pilot requests from aircraft in group 2.

Traffic	Call Sign	Request	Approved
07/11 EVEN	AAL917	to FL350	yes, in 216 sec
07/11 EVEN	AAL927	to FL370	no
07/11 EVEN	AVA7	to FL410	no

(a) Planned trajectory for group 2

(b) Legend of commands

(c) Top view
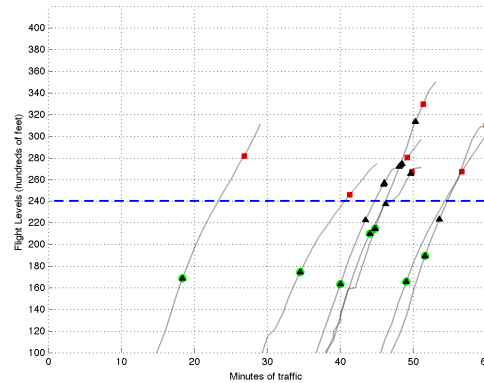
(d) Side view

Figure B-10: ZMA40: Results for 7 flights in group 2 on 07/11, 05:00 – 06:00 PM

Group 3: traffic from KMIA, SKIPS ONE Departure

Group 3 is also composed of KMIA departures, but they follow the SKIPS1 SID, and then they take either BR53V or Y586 (see Figure 5-25). Figure B-11 presents trajectories and estimated position of commands for traffic in group 3 in July 23. Table B.6 presents the pilot requests, which were mainly meant for expediting the
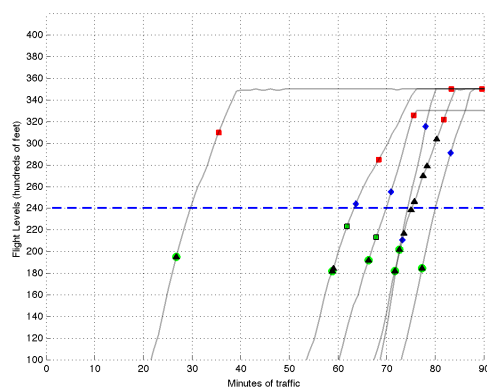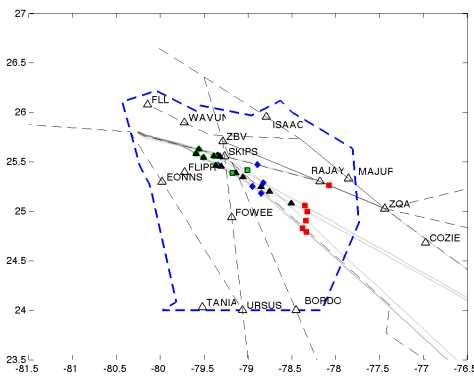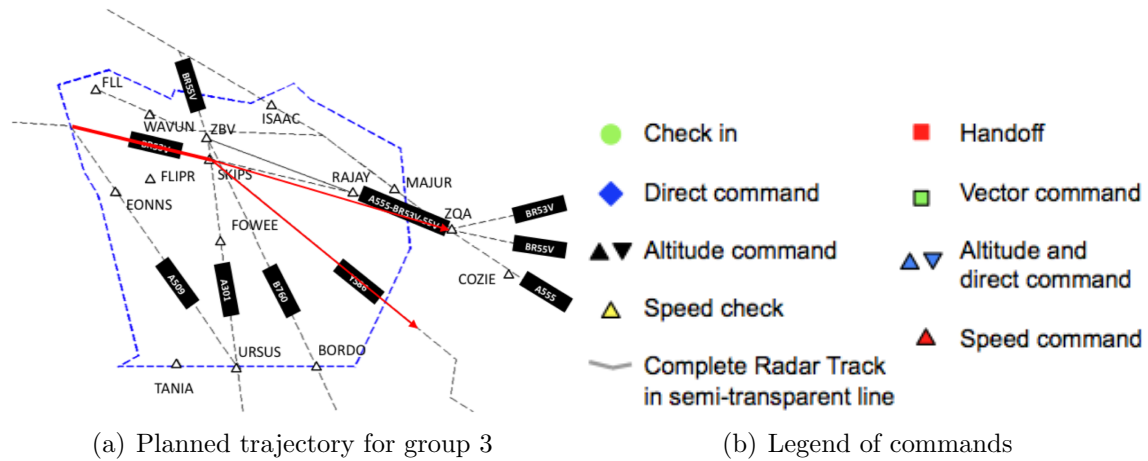
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(a) Planned trajectory for group 3

(b) Legend of commands

(c) Top view

(d) Side view

Figure B-11: ZMA40: Results for 6 flights in group 3 on 07/23, 09:00 – 10:30 AM

Table B.6: ZMA40: Pilot requests from aircraft in group 2.

Traffic	Call Sign	Request	Approved
07/05 EVEN	AAL1267	to FL370	no
07/11 EVEN	AAL729	heavy, stay at FL350	yes
07/23 MORN	AAL645	to FL350	yes

climbing process.

A total of 11 flights were observed, 9 of them going to the Caribbean and 2 of them to Central America. All flights received climbing commands, some receiving multiple altitudes in the climbing process. The final climb altitudes were FL330, FL350 and FL370. 6 flights were directed to scattered destinations.

In July 23rd, airplanes did not follow Y586 precisely. It is evident that these flights conflict with group 1, as both cross the southeast boundary of ZMA40 with ZMA60. The separation is assured via early descend and climb commands being issued to groups 1 and 3, respectively. Directing arrivals to FLIPR also cleared them out of the way of the departures. There was, however, one time-critical event involving AAL1647 (group 3) and ALL748 (group 1), where the controller had to hold the group 1 flight at FL360 while the group 3 departure exited at FL350. Traffic advisories were issued for potential conflict:

10:21AM, ATC: *"American 748 company traffic at your 12-o-clock and 20 miles opposite direction at FL350 maintain FL360."*

10:21AM, AAL748: *"American 748."*

10:21AM, ATC: *"American 1647 company traffic 12-o-clock 18 miles at FL360."*

10:21AM, AAL1647: *"Yeah we're looking thanks American 1647."*

10:22AM, AAL748: *"Traffic in sight American 748."*

Minor Groups

Six minor groups (Figure 5-25(c)) were identified in the analyzed traffic, due to fluctuations of traffic volume across traffic intervals (specific criteria explained in Section 5.1.2. These minor groups are presented in Table B.7 below, with the respective traffic count (complete data and complete voice communication). In the interest of brevity, trajectories and estimated position of commands for the minor groups are not presented.

Members of group 4 had WAVUN1 or DEKAL2 standard arrival procedures, depending if they were going to Fort Lauderdale/Hollywood International Airport (KFLL) or Lauderdale Executive Airport (KFXE), respectively. Group 4 received a series of descending commands, being handed off with final altitude to FL240.

Flights from KFLL (group 5) had BEECH2 SID in their flight plans, they received directs to UCA (south of ZMA40, specific location not found on the available data sources) and climbing commands up to FL330.

Group 6 consisted of traffic from Sangster International Airport (MKJS), in Mon-

Table B.7: ZMA40: Minor flight plan groups and traffic count for each traffic period.

Group	07/05 EVEN	07/11 EVEN	07/23 MORN	Description
4	3	4	-	to KFLL / KFXE
5	1	2	-	from KFLL
6	2	5	-	mainly from MKJS
7	-	1	5	mainly to MKJS and MKJP
8	1	1	2	from MYNN
9	1	1	-	to MMUN

tego Bay, Jamaica (Figure 5-25(c)). Flights in this group entered the ZMA40 area of responsibility either through TANIA (1), URSUS (4) or BORDO (1). Group 6 presented scattered destinations in the United States and Canada and, as such, its flights received direct commands to varied points, shortly after checking in. Airplanes entered in level flight, mostly at FL340 and then received small altitude amendments, being handed off with final altitude either of FL350 or FL370.

Group 7 was predominant in the morning traffic (Table B.7). The traffic in this group had dispersed origins, converging to A301 usually at ZBV. Aircraft had flight plans that were equivalent to A301 – URSUS – UCA – UG437. Note that past URSUS the common trajectory (UCA – UG437) is outside ZMA ARTCC. The destinations were either to MKJS or to Norman Manley International Airport (MKJP), also in Jamaica. Group 7 received climb command to an odd flight level: FL350, FL370 or FL390 and were directed to UCA prior to handoff.

Group 8 was composed of departures from the nearby Lynden Pindling International Airport (MYNN) in Nassau, Bahamas. These flights fanned out following one of two lateral trajectories: ZQA – BR54V – ISAAC or MAJUR – BR22V – FLL, depending on the destination. Climb commands were observed at the check-in. Directs to FLL were observed for the subgroup with the latter flight plan.

The analyzed flights of group 9 were composed of departures from Barajas International Airport (LEMD) in Madrid, Spain, to Cancun International Airport (MMUN). Flights from other origins in Europe were also identified to belong to this group, but

were not analyzed due to incomplete voice communication. The flights in this group checked-in above FL380 and did not receive any amendment from the controller.

Background Traffic

A total of 8 flights did not fit in any specific flight plan or Origin and Destination patterns. Figure B-12 presents the lateral trajectories of the background traffic for each analyzed traffic period. 6 flights of the background traffic were level flights and 2 were climbing flights. The issued commands appeared to be issued on a case-by-case basis and no pattern was found.

(a) 07/05, 05:30 – 06:30 PM
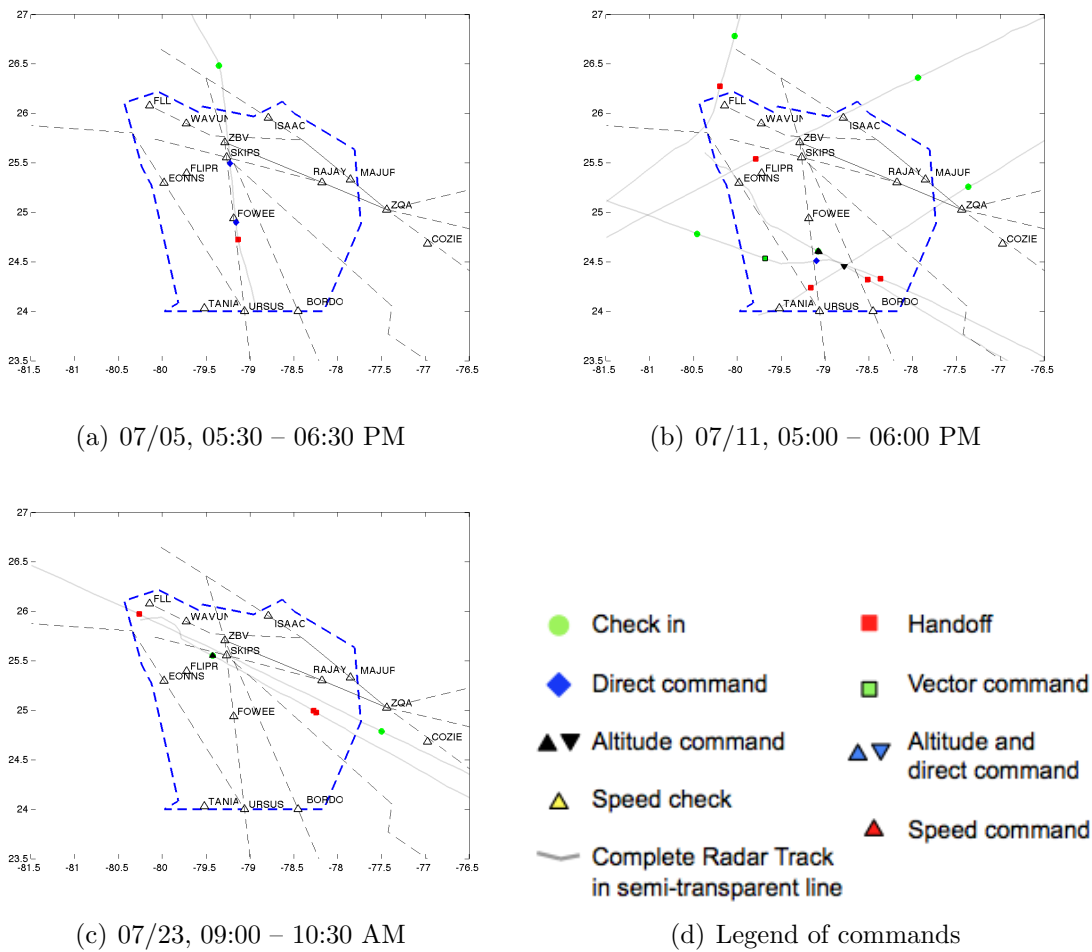
(b) 07/11, 05:00 – 06:00 PM

(c) 07/23, 09:00 – 10:30 AM

(d) Legend of commands

Figure B-12: ZMA40: Background traffic