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Examining Airspace Structural Components and Configuration Practices for Dynamic Airspace Configuration

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Dynamic Airspace Configuration (DAC) is a new operational paradigm that proposes to migrate from the current structured, static airspace to a dynamic airspace capable of adapting to user demand while meeting changing constraints of weather, traffic congestion and complexity, as well as a highly diverse aircraft fleet (Kopardekar et al., 2007). To understand how the air traffic system can transform from current airspace structures and operational practices to what is envisioned in the NextGen operations, current airspace structures and configuration practices are cataloged in this paper. The purpose of this paper is twofold. The first purpose is to introduce and summarize current airspace structures to researchers who may not be familiar with them and describe specific examples on how these structures are currently used in the operational contexts at different facilities. The second purpose is to describe the near to mid-term operational implementations planned by the Federal Aviation Administration (FAA) to researchers whose focus is on far-term concepts but may not be aware of the transition pathway to the far-term concepts. These near to mid-term implementations modify and/or extend the current airspace structures to provide greater flexibility and efficiency in air travel. The paper explores how the proposed airspace structures may be extended further to the NextGen timeframe with fully dynamic airspace and a mixture of highly equipped aircraft fleet.

Nomenclature

ARTCC = air route traffic control center
ARTS = Automated Radar Terminal System
ASDO = Airspace Super Density Operations
ATC = air traffic controller
ATCT = Air Traffic Control Tower
ATM = air traffic management
ATOP = Advanced Technologies & Oceanic Procedures
BA = Big Airspace
CARS = Controller Acceptance Rating Scale

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DAC = Dynamic Airspace Configuration
DME = Distance Measurement Equipment
DRVSM = Domestic Reduced Vertical Separation Minimum
DSR = Display System Replacement
FAA = Federal Aviation Administration
FPA = Fix Posting Area
HAR = High Altitude Redesign
IFR = Instrument Flight Rules
JPDO = Joint Planning and Development Office
LDR = Limited Dynamic Resectorization
LOA = Letter of Agreement
MNPS = minimum navigation performance specification
MOA = Military Operations Area
NAR = National Airspace Redesign
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NextGen = Next Generation Air Transportation System
NGATS = Next Generation Air Transportation System
NOTAM = Notice to Airmen
NRR = Non-Restrictive Routing
NRS = Navigational Reference System
RNAV = area navigation
RNP = Required Navigation Performance
SID = Standard Instrument Departure
SME = subject matter expert
STAR = Standard Terminal Arrival Route
STARS = Standard Terminal Automation Replacement System
SUA = Special Use Airspace
TFM = Traffic Flow Management
TMC = Traffic Management Coordinator
TRACON = Terminal Radar Approach Control
TSD = Traffic Situation Display
UPS = United Parcel Service
VOR = VHF (Very High Frequency) Omni-directional Radio-range

I. Introduction

The National Airspace System (NAS) is an interconnected system of airports, air traffic facilities, equipment, navigation aids, and airways. The NAS is designed to provide safe and efficient transport. Airspace design engineers and air transportation policy makers are continually adjusting system parameters in an attempt to anticipate changes in system demand that result as a consequence of foreseen (e.g. time of day) and unforeseen factors (e.g. weather systems that disrupt the NAS), or because of changes in air traffic management (ATM) policies that govern the operations in the NAS. One key element in guiding the safe and efficient operations of the NAS is airspace management. Airspace management requires predicting the load that is being placed on the NAS and henceforth, the capacity possible in the NAS. The current NAS architecture is reaching the limits of its ability to accommodate increases in traffic demand. Today's sector boundaries are largely determined by historical use profiles that have evolved slowly over time. Consequently the sector geometry has stayed relatively constant despite the fact that route structures and demand have changed dramatically over the years.

Both the FAA and NASA are studying the safety of the NAS associated with greater throughput by looking at system redesign concepts and new technologies (e.g. automation) to improve air-to-air and air-to-ground communication, situation awareness and aircraft control. These efforts are partly in response to the operational concepts proposed by the Joint Planning and Development Office (JPDO), who is charged with developing a vision for the 2025 Next Generation Air Transportation System (NextGen). The JPDO is also defining the research required to transform today's system into a 21st century system in order to accommodate the threefold increase in traffic demand by 2025 (JPDO, 2007).

An essential element of that transformation concerns the efficient allocation of airspace as a capacity management technique. The NextGen concept calls for a future system in which daily operations are managed with four-dimensional (4D) aircraft trajectories while the airspace structure and controller resources are continually adjusted to meet user needs. The airspace structural adjustments needed to manage traffic demands and capacity issues are being examined at NASA as part of a set of research activities called Dynamic Airspace Configuration (DAC) under the NGATS ATM-Airspace project.

DAC is a traffic management concept intended to improve the capacity of the NAS given the projected increase in airspace demands by allocating airspace as efficiently as possible (Kopardekar, Bilimoria, & Sridhar, 2007). DAC requires that the NAS undergo a shift away from the rigid airspace structures that characterize current operations to more fluid and dynamic airspace structures that are able to accommodate changes in both traffic and user demands. DAC research consists of three major components: 1) the overall organization of the airspace; 2) dynamically changing airspace to meet the demand; and 3) a generic airspace characterization. The first component relates to a strategic organization of airspace and the creation of new classes of airspace to take advantage of concepts and technologies that are expected to be available by 2025. The second component relates to the dynamic airspace reconfiguration that is needed to accommodate a fluctuating demand. The third component relates to "generic" airspace designs that could promote interchangeability among facilities and controllers by removing structural and functional components of the airspace that would require site-specific training of the airspace.

Some early objectives of DAC research are to conduct an initial assessment of potential benefits of resectorization, to identify the impact of automation on airspace configuration, to develop a playbook of airspace configurations (Klein, Kopardekar, Rodgers, & Kaing, 2007) that would complement the National Severe Weather Playbook[7], and to examine the feasibility of new airspace concepts such as the "tubes" concept (Sridhar, Grabbe, Sheth, & Bilimoria, 2006). In order to fully understand all the aspects associated with the new airspace designs, a review of some of the airspace concepts that have undergone recent research efforts will be explored. These include dynamic sectorization, dynamic density, airspace sectors and how they are combined, processes for airspace design and evaluation, and identifying temporal and spatial distribution of airspace complexity for air traffic controller (ATC) workload-based sectorization.

In the NextGen timeframe, a new organization of airspace could be introduced to facilitate anticipated future growth in the air transportation system. This airspace redesign could encompass many new technologies and capabilities both on the ground and in the air. For near-term operations, the FAA has already introduced various new airspace and route structures, such as "generic" waypoints called the Navigational Reference System (NRS), Non-Restrictive Routing (NRR), and route spacing based on Required Navigation Performance (RNP). Analogously, the FAA has also proposed some DAC-related operations in the near-term timeframe, such as the Big Airspace (BA) concept which allows dynamic allocation of traffic flow directions and the associated airspace configuration change depending on the traffic demand (FAA, 2007).

The main goal of this paper is to provide a link between current airspace structures and configuration practices, airspace structures/practices that are planned in the near future, and the far-term structures/practices that will be relevant for DAC research. The paper discusses how these structures may evolve gradually over time to accommodate the far-term NextGen operations.

The paper is divided evenly between two major themes/purposes and organized by sections. The first theme is an introduction/summary of current airspace structures and airspace configuration practices. Section II introduces and summarizes current airspace structures to ATM researchers who may be less familiar with the current ATM operations. In section III, specific examples are given on how these structures are currently used in the operational context at different facilities. Since most of the airspace configuration practices are not well documented anywhere, the examples in this paper were gathered from discussions with subject matter experts (SMEs) at various facilities and pieced together with notes from prior research (e.g. Taber et al., 2000). Specific examples from the facilities were chosen to highlight how the configuration practices "play out" in particular operational contexts since the practices were both facility and operational context-dependent.

The second theme is to extend the current airspace structures and practices to DAC-relevant NextGen operations. In section IV, each subsection examines the current airspace structures described in section II and (1) describes the near to mid-term operational implementations planned by the FAA and (2) explores how these components may

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[7] The National Severe Weather Playbook is a compendium of standardized alternative routes intended to avoid specific regions of airspace that are commonly impacted by severe weather during certain times of the year, based on historically validated data. The Playbook also contains alternative routes for circumventing closed airway segments, non-operational navaids, and airports that are impacted by weather or runway closures (National Severe Weather Playbook, 2001; Sridhar et al., 2003).

evolve further in the far-term NextGen timeframe. The connection between the near and mid-term implementation plans to the far-term research is to incite the researchers who focus solely on far-term concepts to reflect upon the transition pathways from near/mid-term to far-term concepts.

The sections described below are a culmination of literature reviews, discussions with SMEs, and authors' domain knowledge of the current and NextGen air traffic system. SMEs gave us insights and information supplemental to the literature review on airspace redesign.

II. Airspace Structures for Current Operations

The capability of the NAS to accommodate increases in traffic demand is significantly hindered by the current airspace and route structures, as well as how human resources are distributed across the NAS. For example, current sector boundaries, which are largely determined by historical use profiles that have since evolved over time, and rules governing how traffic is managed within and across the sectors, severely limit the amount of traffic that can be handled due to ATC workload limitations (Kopardekar et al., 2007).

These sectors and other components of airspace structures that are used in current operations have remained relatively constant over the years and have not fundamentally changed to meet the current and future traffic needs. Both the FAA and NASA are examining ways to introduce new airspace structures and operational concepts that can result in greater throughput and more efficient operations. As a part of these efforts, DAC research aims to determine the future airspace structural components and how they can be incorporated into the NextGen concepts to create an optimal use of system resources while gaining greater system efficiency. In discussions with SMEs from the air traffic operations domain, it became evident that airspace redesign and/or reconfiguration will often be driven by the need for new routes driven by various factors, such as weather, runway maintenance requirements, or temporary periods of increased or changed demand.

The descriptions of the current airspace structures in this section were compiled from various pilot and/or air traffic control handbooks and textbooks (e.g. Jeppesen, 1996; Nolan, 2004) unless otherwise noted. For the purpose of this paper, the structural components are described briefly, but in enough detail to identify them as pertinent and/or potential candidates to be modified or replaced in the future airspace design.

A. Airspace and Air Traffic Facilities (En Route, Terminal, Tower, and Oceanic)

In the U.S., the nation's airspace is assigned to different facilities with different assigned aircraft separation responsibilities. Each of these facilities manages air traffic across different airspace classes, each with its own flight rules and interactions between aircraft and ATC. There are airspace classes A through E, controlled by ATC, and classes F and G, which are uncontrolled. Class B airspace is used around most of the major airports which contain commercial aircraft operating generally under Instrument Flight Rules (IFR).

Within domestic U.S. airspace, the airspace is assigned to 20 air route traffic control centers (ARTCCs, or Centers) which have the responsibilities of detecting, displaying, and separating aircraft during the en route phase of the flight (e.g. high altitude above 10,000 ft). The separation requirement in the en route airspace is five nautical miles of lateral separation and 1,000 ft of vertical separation. ARTCCs use radar displays called the Display System Replacement (DSR), which track all aircraft position and other data in en route airspace.

Once an aircraft is at a lower altitude (e.g. below 10,000 ft) and near an airport (e.g. between 30 – 50 nautical miles from an airport), it typically enters the control of a Terminal Radar Approach Control (TRACON) facility. The separation requirement in the TRACON airspace is typically three nautical miles of lateral separation and 1000 ft of vertical separation. However, a pair of aircraft may be closer than these limits and still be considered safe if certain other criteria are met (e.g. the aircraft are on divergent paths). TRACON facilities generally use variations of Automated Radar Terminal System (ARTS) or Standard Terminal Automation Replacement System (STARS) displays. When an aircraft reaches an airport, an Air Traffic Control Tower (ATCT) assumes the control of the aircraft. The ATCTs generally rely on their out-the-window view along with a Traffic Situation Display (TSD) screen and flight plan information on Flight Progress Strips to locate and identify the aircraft.

Finally, some Centers have responsibility for airspace located over an ocean, or Oceanic airspace. Because substantial volumes of oceanic airspace lie beyond the range of ground-based radars, oceanic airspace ATCs have to estimate the position of an airplane from pilot reports and computer models rather than observing the position directly. Aircraft flying in Oceanic airspace generally fly in parallel tracks with little or no intersections or merge points, which significantly reduces the traffic complexity. The separation in these types of airspace with little or no radar coverage is typically 10 – 15 minutes of separation. In the U.S., Oceanic facilities have installed the Advanced Technologies & Oceanic Procedures (ATOP) system, which can display aircraft position information as well as detect conflicts.

B. Navigational Reference Points (VORs and Waypoints) and Fixes/Fix Posting Areas

A typical commercial airliner often flies established Airways which are connected by a series of intersections and merge points defined by VORs (short for VHF Omni-directional Radio Range) which are part of a radio navigational system first installed in the 1950's. An alternate and more flexible navigational reference system, called waypoints, can be defined by a VOR radial and a Distance Measurement Equipment (DME) to fly under a method called area navigation (RNAV).

Fixes are points in space by which some action is needed. Different fix types include outer fixes, meter fixes, initial approach fixes, final approach fixes, and departure fixes. For example, in many TRACONs, multiple airports depart through common departure fixes by coordinating which departing aircraft need to be merged and sequenced prior to crossing the departure fix. The final approach fix is a fix that marks the initiation of the last leg in an aircraft's approach to the landing phase of flight. The meter fix is a fix used in time-based metering operations to space arrival aircraft by time.

Sectors are structured according to the fix posting area (FPA). Certain fixes that have a number of intersecting airways are chosen as posting fixes. Flight progress strips are printed and organized by the posting fixes as a way to form strategic planning for the sector team. The strip has the current altitude and the current estimated time of arrival for the subject aircraft at that fix. By scanning the strips, the team can identify potential future conflicts (Meyer, et al, 1998).

C. Routes – Airways, Navaid Routes, Oceanic Tracks

In order to fly from point A to B, a flight plan is generated for an aircraft that includes the route of flight. Aircraft routing types used in flight planning are Airways and Navaid routes. Airways occur along pre-defined pathways, often along VOR ground stations. Most airways are eight nautical miles wide, and the airway flight levels keep aircraft separated by at least 1000 vertical feet from aircraft on the flight level above and below. An aircraft can craft a route that consists of multiple Airways by switching from one Airway to another at Airway intersections. VOR airways, designated by numbers preceded with V for low altitude (Victor Airways) and J for high altitude (Jet Routes), are often filed initially in the flight plan.

Within the continental U.S., aircraft are also allowed to fly "point-to-point" between Navaids, consisting of VORs and waypoints, instead of flying along established airways. Navaid routes allow greater flexibility in route choices, giving airlines the ability to create user-preferred routings.

Oceanic or other large airspace with no radar services fall under the category of minimum navigation performance specification (MNPS) airspace, in which aircraft need to be properly equipped with accurate area navigation equipment. Without radar service, the separation requirement has been increased significantly and the traffic is organized into a system of flexible tracks that significantly reduces traffic complexity while maintaining throughput. These tracks change their locations daily, as they are developed 24 hours in advance with considerations for the daily winds, weather, and traffic situation.

D. Standard Instrument Departures (SIDs) and Standard Terminal Arrival Route (STARs)

SIDs are published/charted departure procedures that specify a published route with a series of lateral, altitude, and speed constraints that an aircraft must fly as it departs from an airport. Similarly, STARs are published/charted arrival procedures that specify waypoints and altitude/speed constraints along an arrival route.

E. Sectors

An airspace controlled by a Center is further divided into sectors. A sector is a fundamental unit within which one or more ATCs "own" the separation responsibility of that sector. Each sector has a distinct set of communication frequencies and an aircraft passing from one sector to another requires coordination overhead for hand-offs and frequency changes. Due to the current sector structure, the maximum aircraft per en route sector is limited by the workload that the sector ATC(s) can handle rather than the physical capacity limits.

It is important to design the sectors correctly to manage traffic efficiently without excessive coordination or workload. Some of the design guidelines from RTCA SC192 committee recommendations (Timmerman, 2007) are:

- Sector boundaries should not be constrained by regional or local boundaries within the NAS.
- Sector boundaries should be a function of flight profiles and trajectories. To the extent possible, sector boundaries should facilitate coordination and promote overall system flexibility to support user preferred trajectories.
- Sector boundaries should not be located in proximity to major conflict points, in order to prevent the need for excessive coordination.

- Sector dimensions should be designed to accommodate such air traffic control functions as radar vectoring, offset routes, or additional procedures that are deemed necessary.
- Sector design should address the establishment of holding patterns without requiring coordination with other sectors or facilities. This will maintain a reservoir of available aircraft for the approach control facility.
- Sector design should afford optimum flight profile procedures that enable flights to reach desired altitudes, optimum speeds, and climb/descent rates without interruption for air traffic control operational or organizational reasons.
- Sectors and routes should be designed to take into consideration a mix of aircraft with different performance characteristics.

III. Airspace Configuration Practices in Current Day Operations

In this section, current airspace configuration practices in today's NAS are described, along with some of their inefficiencies and constraints. Different trigger events and subsequent ATC actions for each event are outlined. Four types of airspace reconfiguration practices common in today's NAS are described: (1) airport runway configuration changes in response to weather, (2) consolidation of sectors in en route facilities to adapt resources to changes in demand, (3) adaptive airspace strategies, and (4) the development and use of exceptional configurations for special events.

The descriptions of the airspace reconfiguration practices were gathered from the Limited Dynamic Resectorization (LDR) report (Taber, Woodward, & Small, 2000), which categorized the different types of trigger events that could lead to airspace reconfigurations. Since these practices vary significantly for different operational contexts, specific examples were gathered from SMEs at different facilities to supplement the general descriptions given in the LDR report. The examples were developed from discussions with a traffic specialist at the San Francisco International Airport (SFO) Air Traffic Control Tower (ATCT) and the Jacksonville Center, as well as some observations of the night time operations at the Kansas City Center.

A. Airport Configuration

Every airport in the NAS has a unique runway layout, and a set of varying environmental and fixed geographic constraints that determine the preferred directions of use or configurations for those runways. Accordingly, the unique constraints at each airport lead to different configuration practices. The following description of airport configuration constraints and the triggers and processes for changing configurations was selected from SFO to allow a more detailed description of the trigger events and the reconfiguration practices at a particular airport. Although the exact details of the constraints that lead to the reconfiguration and the actions taken by the air traffic facility may differ, the general process is expected to be common with other facilities. The following description was developed from discussions with a traffic specialist at the SFO ATCT.

1. Reconfiguration Triggers

Weather is the main driver for reconfiguration – more specifically, winds and runway conditions (wet or dry). The maximum cross wind component on a dry runway is 20 knots, reduced to 15 knots on wet runways. Maximum tailwind components are 10 knots on a dry runway, and 3 knots on wet runways. Changes in runway direction or availability within a given configuration can occur for a number of reasons, including:

- Scheduled or unscheduled runway maintenance.
- Taxiway closure – blockage in the taxiway might be resolved by new paths to runways or runway configuration change. For example, every morning until 7 am, taxiway Alpha at SFO is closed for maintenance.
- Special events – e.g., a Blue Angels air show in San Francisco blocks departure paths from runway 1L over the city. As a consequence, some planes take off on 1R while others use 28 (Figure 1).
- Finally, reduced visibility may force reduction to single runway operations for parallel dependent runways whose centerlines are less than the 4300 feet minimum required allowable under IFR conditions. Reduced visibility from fog or a low cloud layer could interfere with a regulation that requires ATCs to be able to see the parallel departures turn away from each other. This occurs routinely at SFO, and can prompt coordination with the ATCSCC, who can execute a ground delay program if needed to reduce airport demand.

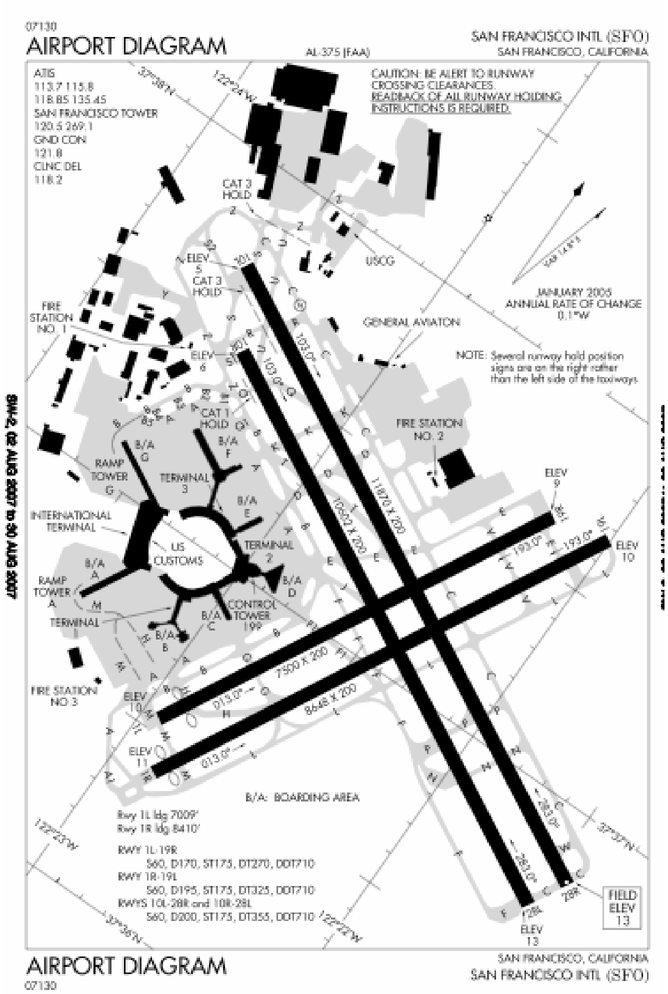

Figure 1. San Francisco International Airport. Thresholds for runways 28L and 28R (heading 283°) are at lower right; thresholds for 1L and 1R (shorter runways, heading 013°) at left.

2. *Reconfiguration Process*

The reconfiguration process starts with an initial planning process with a conference call that include airlines, the airport's air traffic control tower (and adjacent airport towers if necessary), affected TRACON(s) and Center(s), and meteorologists from the different organizations. Participants in the telecon develop a shared picture of the weather and traffic situation and discuss plans for possible configuration change. This multi-party coordination is followed by one or more direct calls between the local facilities (tower and TRACON), with coordination done between the tower coordinator and facility traffic management coordinators (TMCs).

During the initial planning process, the participants identify an approximate time when the configuration change will occur. The airport tower tries to do this proactively by looking for a time when there is a gap in traffic. At SFO, they pick the last plane before the gap, and plan for the next plane to land at the new runway. They try to find a gap of more than about 50 miles (needed for rerouting arrivals in the air and departing aircraft still on the ground, which both require some time). Nominally they want 5 – 7 minutes for the last departure to clear the airspace before the first arrival in the new configuration. As the proposed configuration changeover time gets closer, they pick the last arrival to start implementing the plan. ATC/TMCs use the traffic situation display (TSD) to look for gaps in the traffic around the threshold time. They also develop a timeline guide that may be adjusted as the weather gets closer. One of the other constraints to consider in this process is ATC workload in the affected sectors. Although the workload is not a "show stopper;" they may need to start the change earlier than required by weather to manage their workload.

As the proposed changeover time approaches, they may tweak the final selection of the aircraft that will be first to arrive/depart the new configuration. When switching to a less optimal configuration, they try to maintain the more efficient configuration as long as possible. When an anticipated storm arrives, they will change to a new plan as close to the agreed upon (consensus) time as possible. If that is not possible, the change is implemented earlier at a logical break point. If the changeover is well coordinated, the last aircraft landing on the old runway (a previously active runway) is followed by the first aircraft landing on the new active runway with no significant gap in operations.

TMCs at the TRACON and Center make sure that the last planes arriving and departing on the original configuration are cleared out of the sectors, then change the sector maps and start taking aircraft in the new configuration. If the sectors cannot be cleared, TMCs need to coordinate with ATCs to vector or hold the planes to make this happen. Six or seven TRACON sectors may be affected by the runway changes. Supervisors need to check with each position to make sure that they are ready for change. When the sector map changes, the sector ATC stays with the "job" instead of the airspace (e.g. departure ATC stays with the departures, regardless of the physical sector location).

B. Sector Consolidation

In contrast to airport operations, airspace capacity is not determined by any physical capacity limits but by ATC workload. Airspace changes (e.g., sector consolidation or splitting) are driven by the need to balance resources to demand, and are accomplished by executing pre-defined solutions for changing the vertical and lateral boundaries for an ATC position. Some of the events that change the balance between resources and demand include changes in traffic volume, weather, SUAs, oceanic track change, and equipment outage (Taber, Woodward, & Small, 2000). This section describes the infrastructure that supports these sector configuration changes, the process itself, and some inefficiencies or limitations in the current system. This description was developed from observations of the night time operations at the Kansas City Center and the descriptions of the sector consolidation trigger events from Meyers et al. (1998).

Meyers et al. (1998) describe how a Center's "initial state" is specified through use of a *sector plan*. The sector plan specifies an initial configuration of a facility via adaptation data. During initialization, a sector plan is defined for a facility. It may be either a "basic" sector plan or some other sector plan that Meyers et al. denote as a "derived" sector plan. A derived sector plan specifies only the modifications to the basic sector plan. They note that during the course of operations, it is possible to change the sectorization of a facility by applying a different sector plan, known as resectorization. When this happens, the appropriate changes to the current sectorization are performed, resulting in ATC controlling different airspace geometries. An important situational consideration that impacts the NAS sector plans includes the occasions when it becomes necessary to combine the sectors given forecasted and non-forecasted changes in NAS demand.

For the context of sector combinations, it is important to note that sectors can either be active where an ATC is currently providing control of aircraft, or passive where the ATC is not currently providing control of aircraft. A number of considerations, both geometric and non-geometric, go into the decision to combine airspaces. Meyers et al. (1998) present a good description of the events that accompany a change in the sector boundaries from two (or more) sectors into one larger sector.

When a sector is combined from two sectors to one sector, a determination is made that the two sectors need to be combined to balance the workload of the ATC. The choice is procedural in nature and initiated by a Supervisor. One of the initial sectors is chosen to be the active sector for the resulting combination; the other sector will become the inactive sector. A message is sent to the affected consoles indicating that the sectors will be combined. The transfer of this message is initiated by a system management function. Upon receipt of the message, the operational consoles that received the message initiate processing to transition to the indicated state. This means that the active sector will assume control of aircraft in the sector(s) designated to be inactive. Correspondingly, the sector(s) designated to be inactive will no longer perform control of aircraft in their airspace.

Sector combination is commonly used when there are changes in traffic volume. When the traffic volume in a sector is predicted to exceed capacity due to ATC workload limitations, one way to mitigate the overload may be to split the sectors. This type of splitting/combining sectors in response to the traffic volume happens frequently in Jacksonville Center. The main north-south traffic flows that connect Miami and other Florida airports to Northeast cities (such as New York and Boston) are funneled daily through a highly concentrated airspace directly over the state of Florida. During the peak traffic hours, there are so many aircraft that fly along the same set of jet routes at different altitudes that they exceed the maximum aircraft that an ATC can handle, as well as create a significant datablock clutter on the radar display. Under these conditions, the sectors are split vertically to manage both the aircraft count per sector and ease the datablock clutter.

Sector combination is the counterpart to sector splitting. Sector combination is commonly used during periods of light traffic such as night-time flow shifts. Figure 2 illustrates how the daytime sectors are combined in the night time operations to create larger sectors in the Kansas City airspace. The nighttime sectors are typically combined both laterally and vertically. One of the sectors that we observed combined parts of eight high and low altitude sectors into a single sector that was controlled by a two person ATC team.

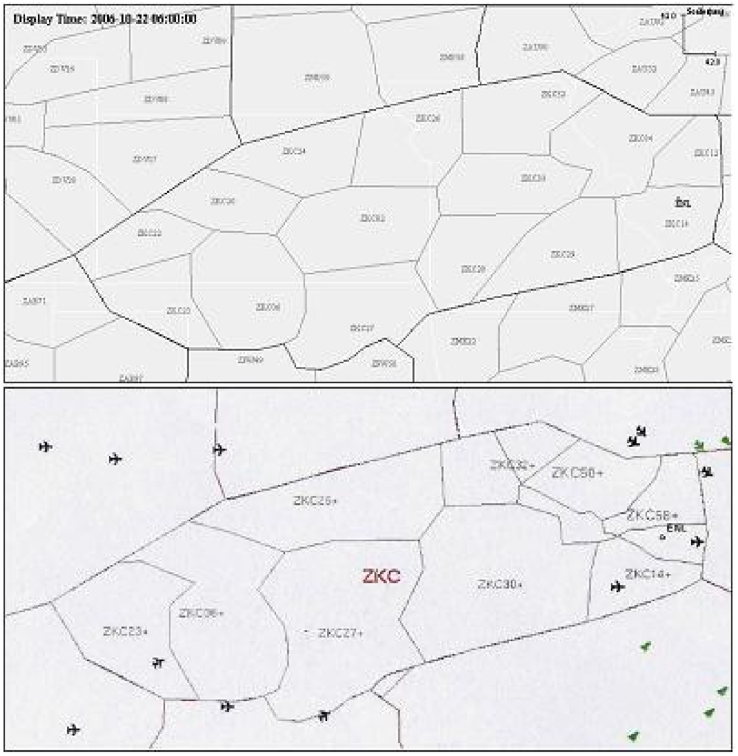

Figure 2. Basic Kansas City Air Route Traffic Control Center (ZKC) sector plan (above) and typical night-time consolidation of sectors (below). Sector ZKC30+ is formed by combining adjacent high altitude sectors ZKC28, ZKC29, ZKC30, and low altitude sector ZKC31. Sector ZKC14+ combines ZKC14 with sectors below it. daytime (above) and nighttime (below).

C. Adaptive Airspace Strategies

Sometimes adaptive airspace strategies are taken between sectors or between facilities to accommodate changes in traffic without officially moving the sector boundaries. In certain weather storm situations, for example, airspace can be delegated from one sector or one facility to another to allow re-direction of traffic flows around the storm. Other adaptive airspace strategies include dynamic changes in restricted areas related to SUAs/MOAs (Special Use Airspaces/Military Operations Areas), oceanic track changes, and equipment outages. The descriptions of adaptive airspace strategies were taken from the LDR report (Taber et al., 2000), supplemented by specific examples gathered from the Jacksonville Center site visit.

1. Weather-Related Strategies

In some parts of the NAS, weather can have a significant impact on traffic as aircraft deviate around storm cells. The deviations, in turn, can significantly redirect the traffic flow, affecting the workload of the neighboring sector ATCs. In these situations, the affected sector can work in cooperation with the neighboring sectors to temporarily and unofficially “redefine” the airspace boundaries to better accommodate the displaced traffic while minimizing the workload (Taber et al., 2000).

An example of a weather-related strategy was described by a traffic specialist at Jacksonville Center. When Jacksonville Center has significant weather storms, it may need to redistribute airspace across internal sectors, or may need additional airspace from the adjacent Centers. If it needs to “borrow” airspace from Miami Center, they can delegate the airspace procedurally by allowing Jacksonville ATCs to manage the traffic in the Miami Center via arrival and departure routings that have been previously agreed to by the two Centers. The airspace boundary changes are done without actually changing the physical boundaries in the host adaptation.

The ability to "borrow" airspace is done more easily and flexibly between sectors within a Center. A sector ATC can coordinate with an adjacent sector ATC to temporarily use a part of his/her airspace to route some of the aircraft around weather. This type of coordination can be commonplace in Jacksonville, which has a number of sectors that are thin, vertical rectangular shapes with heavy north-south traffic flows. The thin shape leaves little maneuver room laterally for the north-south flows, especially when weather cells block the path. Depending on the size and the location of the weather cells, an ATC may need to deviate significantly, forcing him/her to re-direct the traffic through an adjacent sector.

2. *SUA-Related Strategies*

SUAs are prevalent in the airspace in some parts of the NAS. There are several types of SUAs, including Restricted, Warning, Prohibited, Alert, and MOAs. Under certain weather and other conditions that may severely limit the flight path choices, flights may be funneled into highly congested airspace, thereby increasing ATC workload and traffic complexity.

In Jacksonville Center, there are many such MOAs and warning areas that can periodically block the traffic through the designated areas. Instead of being forced to funnel the traffic through congested airspace, Jacksonville Center has negotiated with the military a set of "corridors" that are safe to fly through the MOAs. These corridors through the warning areas can be procedurally released or made active. The corridors are not part of the host adaptation but they can be drawn on the ATC displays and saved so that the outline of their locations could be brought up visually whenever the corridors are active.

3. *Oceanic Track Change*

Aircraft over the Oceanic airspace fly along parallel tracks. The tracks may be "fixed" following the same path daily, or they may be flexible (as in "Flex Tracks") which change their locations daily to make the best use of prevailing winds for flight planning.

In the Oakland Center oceanic environment, the tracks across the Pacific Ocean originally intersected a series of static sectors, requiring frequent coordination for each flight (Taber et al., 2000). To reduce the amount of coordination, the sectors were redesigned along each track such that an ATC would control one or more tracks all the way across the ocean. To adapt to Oceanic track shifts in Flex Tracks, the sectors are also dynamically defined to follow the tracks. These oceanic sectors are called "dynamic work areas", defined by a track's north-south position along the lines of longitude at which the flights are required to report. The dynamic work areas are defined by a series of very thin FPAs along the reporting lines. The FPAs are just wide enough to ensure that flights in the neighboring tracks could not both enter the same FPA.

Prior to the ATOP system, ATCs had no graphical display, using only a relatively basic set of tools, such as an FPA assignment chart based on the Dynamic Ocean Track System Plus (DOTS+), which generated wind optimum routes on a daily basis. With the ATOP system, ATCs can see the sectors, tracks, and aircraft positions visually, similar to the Center ATCs in domestic airspace.

The oceanic tracks have some structural similarity to flow corridors described in DAC research. The dynamic nature of the tracks and the sector definitions are potential mechanisms to explore in defining flow corridor operations.

4. *Equipment Outage*

When radar is off-line, either due to unplanned outage or maintenance, the control of the traffic may be delegated to other sectors or air traffic facilities. For example, if radar near the northern part of Miami Center is off-line, the traffic that can be seen from Jacksonville Center's radar can be procedurally delegated to a Jacksonville sector ATC who controls the flights in Miami Center's airspace (Taber et al., 2000). To facilitate these types of interactions, Jacksonville Center developed a set of maps near its border with Miami Center so that those maps can be quickly switched on when an outage occurs. A similar incident was observed in an unrelated visit to the Command Center involving Southern California TRACON (SCT), who temporarily lost all radar coverage in its airspace. Until SCT recovered their radars, Los Angeles ARTCC "expanded" their sectors to control the aircraft in SCT's airspace.

D. Special Configurations

Special events (e.g., the Kentucky Derby or the Super Bowl) or seasonal traffic changes (e.g., summer traffic around Cape Cod) occasionally require special sector solutions. These may involve weeks of planning, including development of special procedures or temporary workforce assignments. Greater flexibility in sector reconfiguration to match workforce with demand could reduce the cost of accommodating these special cases.

IV. Airspace Structures and Configurations for Future Operations

Problems with current airspace structures and configuration practices include limited sets of options, timing and need-determination issues. New methods are needed to improve need-determination, increase the flexibility of solution development and selection of the optimal solution, and to develop systematic processes for implementing those solutions. A DAC workshop was conducted at NASA Ames in February 2007 with European and U. S. airspace configuration researchers to discuss the current state of the art in airspace design and management, as well as current relevant research on advanced concepts, algorithms, tools, and human factors considerations. The workshop provided interesting ideas for flexible airspace, optimal configuration development, and new airspace components and reconfiguration methods.

At the workshop, airspace designers from FAA and European ATM community who work on near and mid-term changes to the airspace structures discussed their implementation plans for various new airspace and route components. These new structures, described in this section, provide a glimpse of near and mid-term airspace structural components, the motivation and the design rationale for the new structures, and the human factors and other implementation issues associated with them. The information from the workshop was supplemented with additional literature review and by further discussions with the airspace designers and other operational SMEs.

Finally, there is a brief discussion at the end of each section on how the current and the near to mid-term changes to the airspace structures may further evolve to fully support the dynamic airspace changes that are being envisioned for the far-term NextGen concepts. Whenever possible, the discussion centers on the far-term structures that have already been proposed under DAC and other projects.

A. Airspace and Air Traffic Facilities (En Route, Terminal, Tower, and Oceanic)

1. Near and Mid-term Changes to the Airspace and the Facilities

In near to mid-term future operations, there may be new categories of operational airspaces, such as high altitude and super density metroplex airspace. These new types of airspace may replace current classes of airspace but more likely, these airspaces are likely to overlay on top of the existing airspace classes. The FAA has already taken some initiatives to implement airspace concepts and the necessary changes to airspace components to facilitate an evolutionary implementation towards the NextGen operations. The proposed airspace components and redesign efforts have many parallels with DAC research in both their purpose and the associated constraints/issues in their implementation, except that they are designed for near to mid-term timeframe with fewer equipage and system requirements than assumed in DAC research. Understanding these efforts provide greater insights into designing DAC-related airspace components and potential challenges to their implementations.

Two current airspace redesign activities outlined in this document are High Altitude Redesign (HAR) and Big Airspace (BA). Both activities are FAA initiatives under National Airspace Redesign (NAR). The goal is to review, redesign, and restructure the NAS to successfully manage the increasingly demanding operational environment. NAR encompasses both domestic and oceanic airspace and its overall goals are to decrease delays, improve efficiency, increase flexibility and predictability for the end users while balancing the access needs of all users and maintaining a high level of system safety. Many NAR projects have safety, efficiency, and environmental consequences. The national NAR projects include HAR and Domestic Reduced Vertical Separation Minimum (DRVSM) and the regional NAR projects include the BA concept for the New York/New Jersey area, the Chicago terminal airspace project, the Potomac and Boston consolidated TRACONs..

The HAR project was established in 2000 to improve en route airspace capacity and flexibility by introducing new airspace structures in the high altitude en route airspace that take advantage of new technologies to maximize efficiency and maintain a flexibility of routes (Timmerman, 2007). A general philosophy for modernizing U.S. airspace is to gradually migrate from constrained ground-based navigation (e.g. VOR-based) to a more flexible RNAV RNP-based system. The implementation focuses on optimizing and redesigning key airports and associated airspace elements to realize potential benefits as soon as possible while redesigning the national airspace in parallel to make sure that the necessary infrastructures are in place for the future. A follow-up activity to the HAR project may be to review and reorganize high altitude airspace and the associated en route facilities to maximize the system efficiency and flexibility by taking advantage of new technologies and route structures.

In this context, facilities themselves can be viewed as airspace components. How the future airspaces are distributed in future facilities will have significant capacity, efficiency, and human resources impact due to different assumptions at various facilities about separation requirements, operational rules, traffic patterns, geographical characteristics, ATC display requirements, etc. Some of the future airspace redesign that proposes a radical reallocation of airspace between the facilities may have a significant impact on the throughput, safety, and efficiency of the affected area. For example, the New York Integrated Control Complex (NYICC) operational concept (FAA, 2007) calls for the expanded use of TRACON rules (e.g. 3 mile separation standards and current minima for diverging courses) to 100 nm from the major airport and up to FL270 and also the use of visual separation standards above 18,000 feet. These changes combine the existing En Route and TRACON facilities in order to streamline the traffic by reallocating facility rules and redesigning the airspace to various air traffic facilities. This concept has been expanded to other major metropolitan areas, such as Atlanta, Baltimore/Washington, D.C, Central Florida, Chicago, Northern California, Philadelphia, and Southern California. This expanded concept was called the Integrated Arrival/Departure Control Service, or alternatively called the BA concept.

The results from the NYICC/BA study (FAA, 2007) suggested that an integration of En Route and TRACON sectors to strategically control arrivals and departures reduced the overhead of traffic control and management. Under high demand or complex traffic situations (e.g., weather), the amount of routine coordination transfer of communication/control events was reduced. These reductions seemed to be due to better situation awareness on the part of ATCs due to the co-location of ATCs who were managing traffic in adjacent airspace and a better redesign of the airspace, as well as the timely and accurate transmission of the traffic conditions, which in turn contributes to better situation awareness. It is unclear from the study if the benefit is mostly due to the co-location of the ATCs or a better airspace design. This distinction will be important in a NextGen environment, in which ATCs may be more geographically distant compared to current day operations. Ability to gain efficiency in the operations without the necessity of physical proximity would reflect the ultimate flexibility in the NextGen operations that do not depend upon the physical airspace and the reflection of that physical airspace in the ATCs' locations.

2. *Changes to the Airspace and the Facilities for DAC*

Although the assumptions behind NYICC/BA are very near-term in nature and are not particularly revolutionary, they nevertheless provide some insight into how airspace redesign could be applied for DAC. Operating with today's constraints in terms of available technology, operational practices, and business models in mind, the BA concept takes advantage of recent advances and capabilities that would remove obstacles that stem from legacy practices and equipment. How these changes are applicable to a future NAS in which DAC would be expected to operate is yet to be determined. Under NextGen networking and information sharing assumptions, the need for physical separation of facilities must be reexamined; there could be collaborative advantages to personnel working in a shared location. Indeed, even the ideal number of facilities should be reconsidered. DAC resectorization techniques can be applied to bundle traffic flows and patterns into large regions with balanced workload, which would indicate how en route facility boundaries might be formed (Yousefi 2005).

In NextGen operations, there may be segregated airspace for highly equipped aircraft (e.g. airborne spacing or automated separation capable). Kopardekar et al. (2007) proposes four categories of airspace for NextGen operations: automated operations airspace, high altitude airspace, structured classic airspace, and super density metroplex operations airspace. These new types of airspace may replace current classes of airspace. If the current airspace redesign efforts provide any insights into this process, however, these new types of airspace are likely to overlay on top of the existing airspace classes.

B. Navigational Reference Points (VORs and Waypoints) and Fixes/Fix Posting Areas

1. *Near and Mid-term Changes to Navigational Reference Points and Fixes*

User-preferred routing is a key component of future NAS operations, which can be facilitated by the availability of a greater number of waypoints that are easy to reference. The Navigation Reference System (NRS) is an example of a "generic" waypoint concept that provides a greater number and more uniform distribution of waypoints across the NAS (Borowski, Wendling, & Mills, 2004).

The NRS is an organized set of regularly spaced waypoints across the NAS that uses a unique naming convention that is a systematic way to easily find the waypoint without prior knowledge of the local airspace. These way points are not based on NAVAIDS tied to ground stations, and they require advanced RNAV capabilities with an updated FMS database to include NRS waypoints. The NRS waypoints overlay latitude and longitude positions and are placed every 30 minutes of latitude and every 2 degrees of longitude (see Figure 7). The naming convention of the NRS waypoints is as follows: It has five characters in its name with the first letter identifying the country (in U.S., it is "K") followed by the second letter which identifies the ARTCC where the point is located. The next two spaces are designated for latitude increments as two digit numbers, followed by a letter designated for longitude increment. Therefore, “KD54W” is a unique waypoint in the U.S. (“K”), in Denver Center (“D”), with latitude designated by “54” and longitude designated by “W,” located in the center of Denver Center’s airspace.

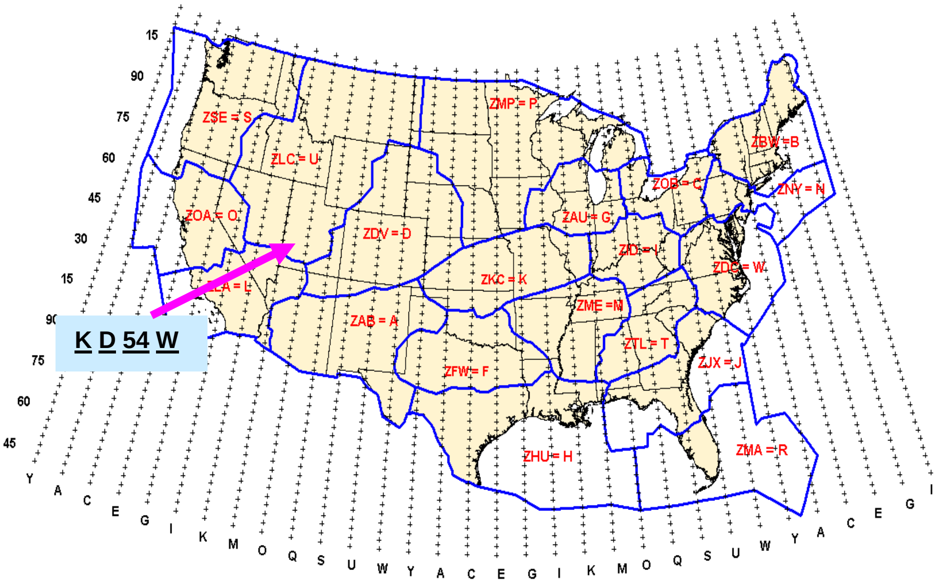

Figure 7. Navigation Reference System – waypoint naming convention from the HAR briefing (Timmerman, 2007) at DAC workshop

NRS waypoints provide an enabling mechanism for flexible, efficient routings that the users can construct. By using NRS waypoints, routes can be constructed to follow wind-optimal paths or to avoid weather cells with minimum deviations. In the next section, we describe how UPS is using NRS to create optimum user-preferred routes. A secondary goal of NRS waypoints is to make them more “generic” such that no training is required to locate the waypoint within a sector. The current waypoint naming system is arbitrary, requiring the ATCs to have a good knowledge of any particular sector to know where all of the waypoints are located in the vicinity of that sector. NRS has been implemented in all 20 domestic ARTCCs at FL180 and above. To take advantage of the NRS grid, airlines also need to update their databases to include these waypoints. At the time of this report, UPS has updated their aircraft navigation databases to include NRS waypoints and American Airlines has begun this update process as well.

Borowski, Wendling, and Mills (2004) examined the usability of the NRS conventions, using groups of ATCs from Memphis Center (ZME) and Albuquerque Center (ZAB). Operationally, ZME is likely to control more traffic than ZAB, and is also a current user of CCLD/URET (Core Capability Limited Deployment/User Request Evaluation Tool), while ZAB is still using flight progress strips. Overall, the findings were that adequate training, practice, and experience should make the NRS conventions usable by ATCs. There was a learning curve in using them and ATCs also needed to understand the philosophy behind how the grid was structured.

Some of the issues with the NRS that remain despite training efforts were:

- unfamiliarity with waypoints outside their normal airspace
- having to type in both alphabetic and numeric characters on the keyboard, which is more time-consuming (and likely more prone to data-entry errors)
- if NRS is used as an adjunct tool in addition to the current system, its use is likely to drop in preference to the original non-NRS system as the workload and/or the traffic complexity increases

Another way that HAR allowed more efficient routing was to publish a number of waypoints near SUAs to efficiently and safely plan a route around the perimeter of the restricted areas. SUAs are areas that commercial aircraft are generally expected to avoid. SUAs can create significant challenges to commercial aviation and can also severely restrict flows in certain areas of the United States, such as in Albuquerque and Jacksonville Centers, in which there are large portions of airspace occupied by military SUAs. Some of the HAR airspace redesign activities that are designed to maneuver around SUAs create SUA-related waypoints and customized routes that can fly right up to, and "thread" between, SUAs. In the future NAS there are expected to be a greater number of SUAs/MOAs, creating challenges to flexibly and dynamically route around the SUAs and maintain efficiency in NextGen operations.

NRS provides generic waypoints for user-preferred NRRs. Users can craft flexible "point-to-point" NRR routes using both regular and NRS waypoints and connect them to existing SIDs and STARs using "pitch and catch" points. Pitch and catch points are fixes that link the user preferred routes to structures at the beginning and end of a filed NRR flight plan. They are generally NAS waypoints located at or near common top-of-climb (TOC) and top-of-descent (TOD) points, respectively, often at the transition points for SIDs and STARs. Pitch and catch points are listed in Airport Facility Directories.

In Europe, the Maastricht ATC New Tools and Systems (MANTAS) program has a similar element called "focal points" that connect STARs to routes in the en route airspace. There will be further discussion of the MANTAS project in the following sections to describe how the focal points are used in the dynamic resectorization process using "gateways".

2. Changes to Navigational Reference Points and Fixes for DAC

Dynamic reallocation of airspace and flexible routings identified in DAC research indicate that the NRS and/or other "generic" reference systems would need to be developed and/or refined for NextGen operations. One option would be to extend the NRS conventions to a finer level of granularity. The current NRS is limited in its granularity due to the five-character limitation on the waypoint designation, in conjunction with the required use of the first two characters for the country and the center designation, leaving only three characters for designating the geographic location within the NRS grid. Much of the database limitations on the waypoint designation may disappear in the NextGen timeframe, as the cockpit and the ground systems evolve with better equipage. With an extension of one or two characters on the waypoint names, one can greatly increase the granularity of the NRS grid. The need for the grid may also disappear altogether with the proliferation of data link since trajectories using latitude and longitude coordinates can be constructed and uplinked from the ground to the cockpit.

In addition to generic waypoints, NextGen airspace may also need generic fixes. For example, current pitch and catch points are generally selected to be the transition points to SIDs and STARs. These points are currently named waypoints but they may need to have generic naming conventions in the future where SIDs and STARs are replaced by more dynamic RNP procedures. In fact, all entry and exit points to dynamic terminal routes/procedures would need to have a sensible generic naming convention to easily generate them and allow the ATCs to quickly identify them. NRS and other generic naming conventions may provide a good starting point for the naming conventions for fixes.

C. Routes – Airways, Navaid Routes, Oceanic Tracks

1. Near and Mid-term Changes to the Route Structures

One of the main objectives of HAR was to balance flexibility and structure to obtain maximum system efficiency. To achieve this goal, HAR introduced new routes called Q-routes where the system may benefit from better route structures around merge points and other traffic congestion points. For the airspace where flexibility was the goal, HAR introduced user-preferred NRRs to facilitate point-to-point navigation.

Q-routes are RNAV RNP routes that can be placed anywhere, independent of the Navaid ground station locations. The current route structures (e.g. jet routes) connect from VOR to VOR, and thereby inadvertently create routes that cross and converge, resulting in conflict points between routes. Q-routes, if properly designed, can significantly reduce conflict points by designing parallel routes with minimal flow crossings. Since Q-routes can be constructed independent of Navaid locations, additional routes can be added to previously unused airspace, thereby potentially increasing capacity use and creating greater efficiencies in traffic flows.

Based on discussions with a HAR expert, many Q-routes are designed and available across the NAS. They serve different functions for different regions. For example Q-routes in the Pacific Northwest, used by Alaska Airlines and others, have three parallel tracks to the San Francisco Bay Area to separate the traffic for San Francisco, Oakland, and San Jose airports so that weather-related delays at the San Francisco airport do not affect the other traffic (see Figure 3). In contrast, Albuquerque Center has a large number of SUAs in their region and Q-routes there are mainly designed to "thread" between SUAs that currently block most jet routes, and therefore require flight plans that deviate completely around the SUAs. In the Gulf of Mexico, Q-routes are being used by UPS and other airlines as a direct passage between Texas and Florida over the ocean, where there are no existing jet routes, providing more efficient paths that also relieve traffic congestion in those airspaces. Jacksonville Center regularly controls traffic on the Q-routes over the Gulf of Mexico and analogous routes over the Atlantic Ocean called "AR routes."

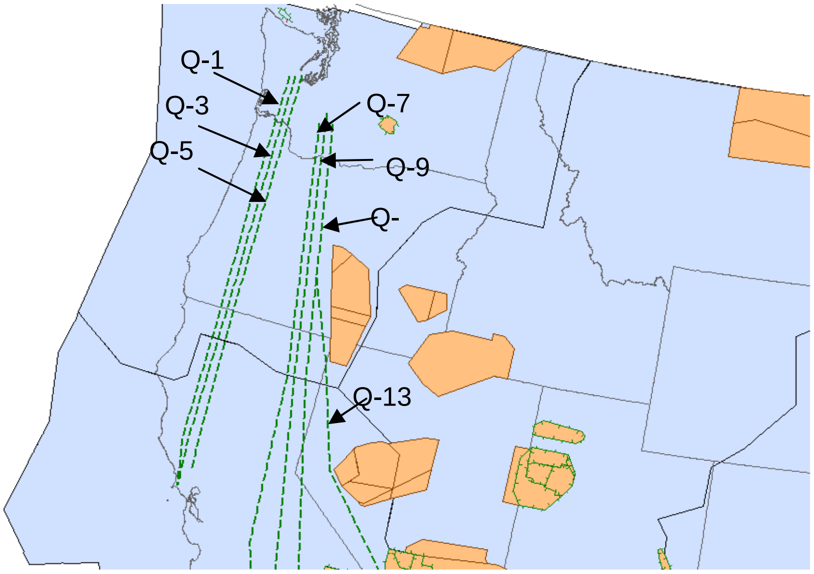

Figure 3. Q-routes in the Pacific Northwest from the HAR briefing (Timmerman, 2007) at DAC workshop

Boetig, Borowski, and Wendling (2004) evaluated Q-routes at Oakland Center (ZOA). Q-routes were rated by the ATC participants as being highly acceptable (M = 9.2 on 10 point scale) on a modified Controller Acceptance Rating Scale (CARS), adapted from the original CARS developed at NASA Ames Research Center (Lee, Kerns, Bone, & Nickelson, 2001). The average rating was in the category of "safe, manageable, satisfactory without improvement and with negligible deficiencies." The ATC participants also responded to workability questions related to the overall effect of the HAR design. When they were asked about their assessments of HAR design elements (i.e. NRR, Q routes, SUA waypoints, and NRS), they responded that NRR and Q routes in general were not significant changes from current operations while the SUA waypoints and NRS was better than what they use in current day operations.

NRR is an enhanced version of the North American Route Program (NRP) that began in the mid-90s. NRP allows the user to file preferred routing based on Navaid routes to give more flexibility in flight planning above FL290, and is identified by the acronym "NRP" in the remarks section of the filed flight plan. ATCs leave NRP flights on their filed route and flight levels unless needed for "weather, traffic, or other tactical reasons" (7120-3U Chapter 17, Section 14; more details on requirements can be found there, and in FAA Advisory Circular 90-91H). NRP originally started at or above FL390 and was later lowered to FL290 as is today.

A discussion with a HAR expert provided insight into the rationale for creating NRR, which is similar to NRP. NRP had limited success in spite of its inherent route flexibility because aircraft were often ("90% of the time") taken off of NRP routes for one reason or another, so airlines stopped requesting them. Currently, the number of aircraft that fly NRP is lower than during the earlier years of its implementation. One problem contributing to its lack of use was a lack of suitable routes through congested terminal areas, creating problems for ATCs – i.e. many of the NRP-filed aircraft were taken off their routes due to incompatible entry and exit points near the SIDs and STARs. NRR addressed this by using pitch and catch points (described in the previous section) to facilitate exit from / entry into congested terminal areas.

NRR flight plans include a different flag in the remarks section: "HAR" or "PTP." The "HAR" flag denotes an NRR flight that is equipped with NRS database and the "PTP" flag denotes an NRR flight without NRS capabilities. NRR routes are adapted from the ICAO definition of "air traffic service routes" that go from waypoint to waypoint. NRR routes also require one fix per ARTCC traversed. Figure 4 illustrates an NRR routing from SFO to EWR.

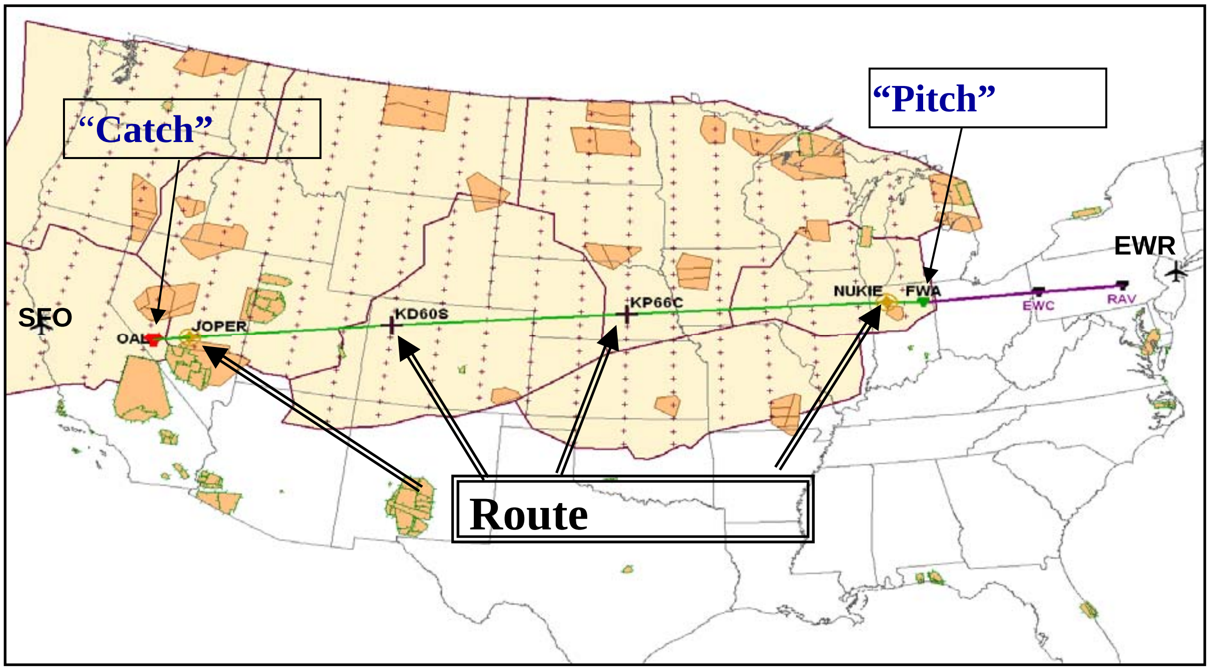

Figure 4. Non-Restrictive Routing from SFO to EWR from the HAR briefing (Timmerman, 2007) at DAC workshop

To get a better understanding as to how an airline operator would use NRR and NRS to create user-preferred routings, an informal interview was conducted with a dispatch operator from the United Parcel Service (UPS). UPS uses a dispatch support tool called Lido Flight Planning Services, which considers all valid aeronautical restrictions (e.g. NOTAMs or "Notice to Airmen", restricted airspaces, weather minima, etc.) in creating flight plans that are optimized for various factors such as winds. UPS has incorporated NRS into its database and Lido has the ability to create NRR flight plans using NRS waypoints. A discussion with dispatch operators from UPS provided insights into how current-day airline operations are managed, and also included feedback on some of the newer elements of the HAR project.

Currently, UPS uses Lido to calculate the most efficient route between two points, while considering weather, wind, terrain, and all valid aeronautical restrictions. Filing a flight plan with the FAA used to require at least one VOR per traversed airspace sector. UPS originally tried to file a fix-radial-distance from a VOR to gain more flexibility in the kinds of routes they could file, but the FAA did not accept these kinds of flight plans. In the last few years, after the HAR project introduced the NRS grid, UPS has incorporated the NRS grid into Lido and is using them very successfully to build flight plans.

When the HAR elements were first introduced, UPS also started filing flights with pitch and catch points, but was not able to gain any benefit from them, as it was very common for the ATC to cancel the flight plan and re-route the aircraft. These re-routes potentially delayed the aircraft and created more work for the pilots while losing any optimization expected from the original flight plan. Because of this, UPS decided to stop using these more-direct routes, and worked closely with the ATC facilities to understand what procedures, both official and unofficial, could be expected and planned. UPS found that for their operations, it was most efficient to file their flights in line with what the ATCs were least likely to cancel.

This knowledge base is very valuable to UPS since it is now also a part of their Lido system. For example, any procedure, e.g., "always expect 'FL290' as early as ZOB when going to any airport in ZNY" and "we typically prefer arrival procedure 'XYZ' during our morning rush" was documented and integrated into the Lido system as "fixed route" objects. With all this information integrated into the Lido system, UPS dispatch operators can create a flight plan by checking for any fixed-routes for a given city-pair, and can file the most optimal routing. If no fixed-route constraints exist, then flight plans are optimized for winds. Due to the nature of traffic patterns in the NAS, flights in the Northeast corridor mainly use flight plans based on fixed-route constraints, whereas flights in the western part of the country typically use more wind-optimal routing.

When asked what would be the ideal way to file flight plans for their operations, the UPS dispatchers put forward the idea of filing a wind-optimal route with only three points, a start, middle, and end. They believed that if

ATC had reliable real-time wind information, such a flight plan would be workable since ATC would know where the aircraft is going. They also acknowledged that such operations would be more prevalent for the western part of the country where the volume and traffic complexity is less of an issue than in the East.

Re-filing a flight plan for an aircraft already in mid-flight is one of the more dynamic aspects of flight planning. Sometimes dispatch operators need to re-file for weather, a proactive process that tries to avoid ATC re-routes, which can sometimes be less efficient for the airline's particular needs. In the example of convective weather, UPS uses their Lido system to compute a new route around the constrained area, and then files it with the FAA.

2. *Changes to the Route Structures for DAC*

In the HAR project, NRR and Q-routes are two types of new route structures with differing goals. NRR allows less routing structures to let the users fly their preferred routings. In contrast, Q-routes provide better route structures to replace existing jet routes to fly more efficient paths with potentially fewer merge points, less traffic complexities, and/or the ability to fly between tightly spaced SUAs.

The route structures in far-term NextGen concepts are likely to have similar goals as above. New airspace and new routing types are likely to be introduced to facilitate user-preferred routings, greater capacity, and better efficiencies. However, with the advanced tools in the air and on the ground, the new route structures may be far less constrained than what has been imagined so far. In an airspace that has enough capacity to allow flexible user-preferred routings, an extension of NRR would be needed in the far-term. The user-preferred routes may be supported by supporting a finer NRS grid and/or the flight crews may be able to request an amended flight plan in mid-flight via data link.

For the new types of structured routings, one of the key exploration in DAC research is to see if aircraft with advanced avionics and automation can be grouped together in new route and/or airspace structures to allow greater throughput with potentially less ATC workload. One such proposed route structure is flow corridors, or "tubes". At the network or system level, tubes have a great potential to augment the existing airspace with a parallel system of multi-lane airways or jet routes, free from cross traffic. If properly constructed, this could greatly decrease traffic complexity and increase throughput by adding parallel traffic lanes (where today there is only one) and by adding rules for prioritizing traffic flows. This may also allow for specially equipped aircraft to travel in close proximity to each other. Tube activation times and tube locations could vary over time, even throughout the day, to accommodate changing user needs and weather conditions. Initial studies have shown that tube implementation and development of associated procedures will be highly involved. Interaction with existing airspace, e.g. how tube traffic merges in and out of existing airspace, is particularly problematic (Wing et al. 2008, Hoffman and Prete 2008). Though there does not appear to be sufficient demand today to warrant a tube network, tubes that operate under ordinary separation and equipage assumptions could certainly be implemented today.

D. Standard Instrument Departures (SIDs) and Standard Terminal Arrival Route (STARs)

1. *Near and Mid-term Changes to SIDs and STARs*

The arrival and departure procedures are pertinent structural components that may need to be altered in response to the dynamic reconfiguration of airspace. In the near future, they are likely to be flown by highly equipped aircraft much more accurately and efficiently using the RNP routes. In addition, flexible airspace reconfiguration may require more flexible and generic arrival and departure procedures. Such mechanisms have been proposed in the BA concept (FAA, 2007).

One of the key features of the airspace structure that is described includes the ability to dynamically move the sectors or the directions of the flows within the sectors, according to demand and presumably in response to weather changes. In the recent BA simulation study (FAA, 2007), RNAV routes within and around a "generic" airspace were created to expedite the flow of arrival and departure aircraft to and from the simulated airports. Figures 5 and 6[8] depict the RNAV routes or the baseline and BA condition, respectively. Compared to the current day baseline condition, the BA condition allowed for more RNAV routes, which can be seen in Figure 6. Both the increased number and better flexibility in the new RNAV routes allowed for better weather avoidance and higher efficiency. For example, certain routes in the simulation study were bi-directional; that is, they were utilized as either arrival or departure routes depending on the traffic situation and the location of the severe weather. The bi-directional flows drove the dynamic airspace changes between arrival and departure sectors.

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[8] Figures 5 and 6 were taken from the Big Airspace concept validation report (FAA, 2007).

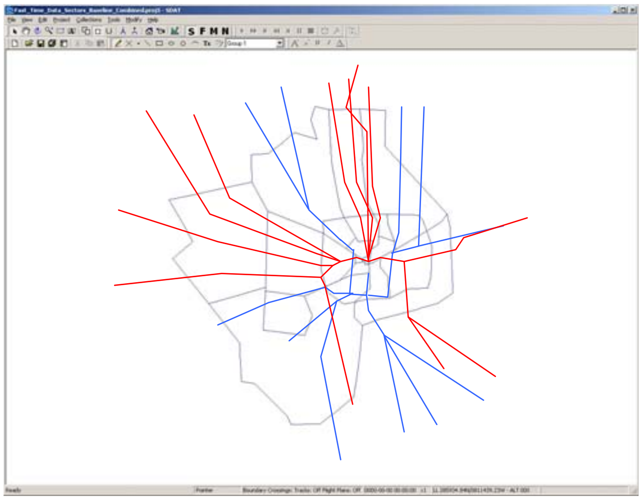


Figure 5. Baseline RNAV routes
Note. Arrivals = Blue, Departures = Red

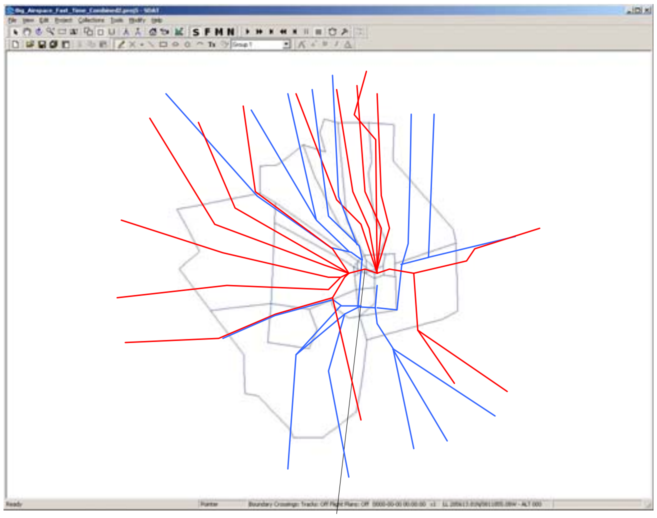


Figure 6. BA RNAV routes
Note. Arrivals = Blue, Departures = Red

2. *Changes to SIDs and STARs for DAC*

For DAC research, flexible airspace reconfiguration ideas from BA and other near-term concepts may be expanded to create even more flexible route and airspace structures that can dynamically match the traffic demands. For example, the Airspace Super Density Operations (ASDO) program at NASA envisions that increased demand at the busy metroplex areas will increase the utilization of regional airports around the large airports to absorb the expected increase. To meet the demand for high capacity, the operations are expected to handle tight scheduling with high precision in sequencing, merging, and spacing while maintaining flexibility to navigate around weather and other disturbances. NextGen operations at the busiest airports and terminal airspaces are likely to require dynamic RNP routes and flows into the airports that can keep aircraft on high precision 4D trajectories under the off-nominal circumstances (SLDAST, 2007).

The relationship between NextGen analogs of SIDs/STARs and DAC is less about how SIDs and STARs will need to be changed to accommodate future dynamic airspace than about how flexible airspace reconfiguration can accommodate the dynamic RNP routes that are likely be a part of NextGen terminal operations. As highlighted in the example of runway configuration changes at SFO in response to a weather event, changes in the routes near the airport requires significant coordination and planning between multiple sectors and facilities to change the appropriate sector configurations. Further research is needed to understand the benefits and feasibility of airspace reconfiguration in response to dynamic routes in the terminal operations.

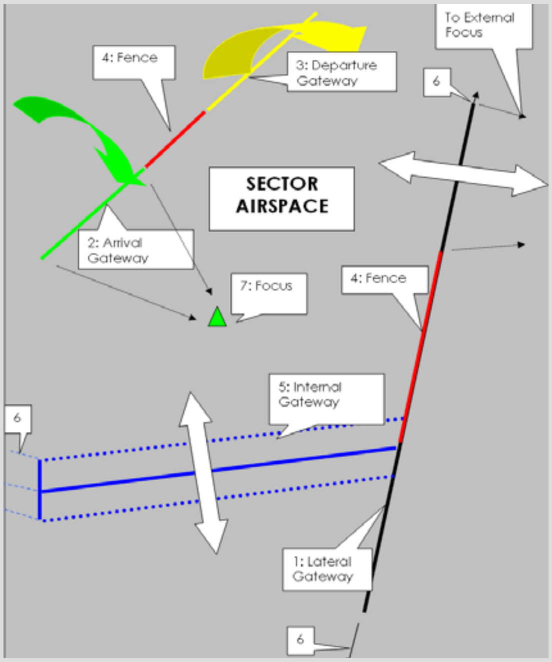
E. Sectors

1. *Near and Mid-term Changes to Sectors*

In DAC research, the “airspace playbook” concept has been proposed as a mid-term change for dynamic sectorization to complement the existing route playbook (Klein, Kopardekar, Rodgers, & Kaing, 2007). The playbook contains pre-formulated TFM responses (rerouting strategies, or “plays”) to the most common weather scenarios that occur with each severe weather season. Familiarity with the rerouting strategy in advance allows traffic managers and airspace users to have a common view of objectives and options. The ATCSCC is not limited by the fixed set of plays in the playbook (refer to www.fly.faa.gov/ PLAYBOOK/pbindex.html for the list of plays) but the specific routes from different plays could be selected to create a new customized play (FAA, 2000).

The playbook essentially funnels the NAS-wide traffic onto a few pre-defined routes, which can potentially result in creating significant traffic congestion in the affected sectors. In the airspace playbook concept, the airspace will be adjusted to accommodate the route playbook so that additional demand management constraints (e.g. miles-in-trail) that aim to lessen sector congestion problems can be reduced or eliminated.

An important consideration for changes to sectors is how they relate to other airspace elements, such as arrival/departure corridors and fixes. For example, MANTAS introduces arrival and departure “gateways” which are volumes of airspace associated with the focal points, derived from the Letter of Agreement (LOA) on how transfer of aircraft control is managed (Hickson, 2004). In MANTAS airspace design algorithms and gateway properties (e.g. separation levels, activation criteria) are varied to achieve different behavior. Relationships between gateways and fixes are then used to determine sector size and location (Hickson, 2004). Sectors can be created and moved or modified by adding or removing gateways, or by changing their properties. For example, special use airspace can be activated by changing a gateway’s throughput to zero (i.e., making it a “fence”). See Figure 8.



1: A **Lateral Gateway** represents a boundary between Maastricht’s and adjacent units’ Areas of Responsibility. Gateway conditions are derived from Letters of Agreement.

2: **Arrival Gateways** provide the link from Mixed Route Airspace to the fixed Focus (and hence to Standard Arrival Routes). Associated conditions are derived from the Letter of Agreement with the relevant unit.

3: A **Departure Gateway** links fixed standard departure routes with Mixed Route Airspace. Conditions are derived from the Letter of Agreement with the relevant unit.

4: A **Fence** is a Gateway with particular conditions that relate to an allowed though-put of zero. They will be used both tactically and strategically to provide flight profile separation.

5: An **Internal Gateway** bounds distinct sectorisation within Maastricht’s Area of Responsibility. Attached conditions include all properties of silent radar hand-over procedures.

Figure 8. Definition types of “gateways” from MANTAS Operations Manual (Hickson, 2004).

2. *Changes to Sectors for DAC*

An active area of DAC research has been methods for dynamic *resectorization*, in which sector boundaries can be reset in response to changing demand, weather, or user preferences. Dynamic sectorization provides a means to supply airspace capacity where it is most needed. Eliminating overload situations that typically lead to airborne delay is the major benefit of dynamic sectorization. Benefits can be measured in terms of reduced delay, reduced workload, increased capacity, or airspace complexity. Reducing workload can also lead to a reduction in the number of ATCs needed in the NAS. Also reducing the number of functional sectors by combining low-workload sectors during off-peak periods can greatly decrease the required workforce and result in significant cost reduction. The benefit gained by resectorization is a function of frequency of resectorization. Theoretically, if we can change the sector boundaries for every significant change in traffic characteristics, the most benefit will be delivered.

Mathematical techniques for determining an optimal sectorization based on forecasted traffic patterns range from heuristics to cell clustering to optimization and even to genetic algorithms (Wyndemere 1996, Yousefi 2005, Klein 2005, Xue 2008). Most of these are ‘clean slate’ design approaches; future research will consider transition from an existing airspace to a new airspace design, and the associated cost of transfer. Dynamic changes to the sector boundaries also have other human factors issues, such as how ATCs can keep track of changing communication frequencies as well as the dynamic sector boundaries themselves. Key enablers for dynamic sectorization will be the elimination of facility (ARTCC) boundaries, replacement of radio-based communications with data-link, aircraft surveillance via ADS-B or similar technology, and possibly new console display concepts for ATCs that allow 3D views.

V. Discussion

Airport configuration and runway changes occur in response to external factors, with more routine reconfigurations driven primarily by weather. Since configuration changes have a direct impact on airport capacity, the information used to base reconfiguration decisions needs to be as timely and accurate as possible. The reconfiguration process itself can also affect airport throughput. Use of automation to improve coordination of the runway changes or trajectory reassignment process could reduce that impact.

Since the airport configuration change requires significant changes in arrival and departure flows, the impact of the change encompasses multiple facilities (e.g. multiple towers, TRACON, and Center), making effective inter-facility coordination essential. Steps are taken to reduce the coordination workload whenever possible. For example, the configuration change could mean that the departures could not complete its turn prior to entering the Center airspace (thereby requiring additional coordination) if the arrival and the departure sectors in the lower altitudes remain the same. However, this problem is mitigated by reconfiguring both the TRACON and en route sectors to accommodate the new arrival and departure flows (Taber, Woodward, & Small, 2000). To keep the ATCs’ mental model as constant as possible, the ATCs continue to work the “same” problem – e.g. arrival ATCs continue to control the arrival problem in the new sector/flow configuration. Whenever possible, the radio frequency is also maintained for the ATCs despite the physical changes in the airspace.

In DAC research, we should preserve some important human factors considerations in designing reconfigurable airspace that are in practice today. For example, the design should

- continue to assign ATCs to functions rather than the airspace – i.e. let the arrival/departure ATC continue to work the arrival/departure problem in spite of significant changes in the flow location and characteristics
- keep as many elements of the airspace constant in spite of significant changes in the physical characteristics of the airspace

External factors determine the set of available airport configurations and set limits on the capacity that can be achieved within each configuration. Airport throughput is determined by selection of the best available configuration, and the ability of pilots and service providers to realize that configuration’s maximum capacity through efficient, well-coordinated, precise and timely operations.

By contrast, airspace resectorization is usually triggered by predicted changes in demand. As traffic density decreases, ATCs can work much larger airspace volumes and sectors can be combined. Conversely, as traffic density (or complexity) increases, sector size is reduced by recombining FPAs in predefined ways in order to better allocate resources (workforce). There are costs associated with reducing sector size however, that limit the effectiveness of these solutions. Control transfers and frequency changes are needed each time an aircraft moves from one sector to the next. Additionally, a small sector size limits the ATC’s ability to solve sequencing and spacing or separation problems. Any control instructions that involve another sector’s airspace must be pre-coordinated and also adds workload. Beyond a certain point, the cost of these control transfers and coordination tasks outweigh the workload reduction of a smaller sector size.

Configuration options are also limited to the set of available, predefined sector plans, which may not be well suited for reducing workload associated with weather-related increases in local complexity (e.g., due to storm cells or turbulence), NAS-wide traffic flow patterns (e.g., Playbook routes), or special events. As new methods for dynamic route creation or activation are developed (e.g. tubes, flex tracks in domestic airspace), more flexible sector configurations will be needed to support those new route structures. As suggested by this last example, techniques for better adapting resources to demand could both enhance the effectiveness of user preferred routes as well as mitigate the impact of weather-avoidance routes.

Several new developments and ideas for airspace management suggest some promising approaches to addressing this need. The BA concept includes flexible transition corridors whose direction of flow can be changed to accommodate the ebb and flow of arrival and departure pushes observed at major hub airports. This kind of dynamic flexibility in airspace definition could be well-supported by the MANTAS idea of using Gateways as versatile building blocks for airspace configuration. By dynamically varying the properties of Gateways, an arrival corridor can become a departure corridor; sectors can be reconfigured; and new sectors or SUAs can be created with custom boundaries. How powerful this concept proves may only be limited by the effectiveness of ATC tools and displays in communicating gateway changes and the accompanying changes in airspace operations.

VI. Summary

DAC is a new operational paradigm that proposes to migrate from the current structured, static airspace to a dynamic airspace capable of adapting to user demand while meeting changing constraints of weather, traffic congestion and complexity, and a highly diverse aircraft fleet. DAC will do so by dynamically allocating both ATC resources and the airspace structure to meet real-time demand profiles (Kopardekar et al., 2007).

To understand how the air traffic system can transform from current airspace structures and operational practices to what is envisioned in the NextGen operations, this report has cataloged DAC-relevant airspace components and operations used in the present day, as well as research and near-term operational implementations that are currently being pursued. For example, the current day jet routes that are constrained by VOR locations are being supplemented by Q-routes which use RNAV capability to generate a greater number of available and potentially less complex routes. Q-routes, in turn, may evolve into flow corridors that are being investigated in DAC research (Kopardekar et al., 2007). Similarly, named VORs and waypoints of the current day system will be supplemented by NRS which provides a greater number of evenly distributed “generic” waypoints that could be used to create user-preferred flexible NRRs. The NRS, which has relatively coarse granularity due to current technical limitations, can evolve in the future to have finer granularity and the non-restrictive routings in NextGen operations may have a broader number of applications than is possible with NRR today.

Dynamic airspace reconfiguration is another key component of DAC research. Current operations have limited options in terms of how sectors and airspace can be reconfigured due to various technological and human factors issues. DAC envisions the future sectors to be substantially more dynamic, changing fluidly with the changes in traffic, weather, and resource demands. Understanding the limitations of the current reconfiguration practices – as well as some near-term solutions outlined in research like BA, LDR, and MANTAS – will be the necessary initial steps to designing effective airspace reconfiguration support tools and operational concepts in the DAC research focus area. In sum, a number of research issues remain to be addressed to test the feasibility of mid-term and long-term airspace configuration concepts, as well as to establish the overall benefits of airspace configuration concepts.

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References

Air Traffic Control System Command Center (2001). National Severe Weather Playbook, http://www.fly.faa.gov/Operations/Strategic_Planning/playbook_html/index.htm, November 1, 2001.

Boetig, R.C., Borowski, M., & Wendling V.S. (2004). ZOA HAR design and Q Route validation, MP04W0000236, The MITRE Corporation, McLean, VA.

Borowski, M., Wendling, V.S., & Mills, S.H. (2004). HAR NRS Usability Study, MP04W0000163, The MITRE Corporation, McLean, VA.

Conker, R.S., Moch-Mooney, D., Niederringhaus, W.P., & Simmons, B.T. (2007). New process for “clean sheet” airspace design and evaluation. Proceedings of the 7th USA/Europe Air Traffic Management R&D Seminar, Barcelona, Spain, June, 2007.

Delahaye, D., Schoenauer, M., & Alliot, J. (1998). Airspace Sectoring by Evolutionary Computation, Proceedings of the IEEE International Congress on Evolutionary Computation, Piscataway, NJ, IEEE Press.

Doble, N.A., Barhydt, R., & Hitt, J.M., (2005) Distributed conflict management in en route airspace: human-in-the-loop results. Digital Avionics Systems Conference, DASC 2005. The 24th Volume 1, Issue 30, Oct.-3 Nov. 2005 Page(s): 2.A.5 - 21-11.

Doble, N.A., Hoffman, R., Lee, P.U., Mercer, J., Gore, B., Smith, N., & Lee, K. (2008). Current Airspace Configfruation Practices and their Implications for Future Airspace Concepts, 8th Aviation Technology Integration Operations Seminar, AIAA, Anchorage, AK.

Egron, D., & Montoya, F. (2007). Validation of a European gate to gate operational concept for 2005-2010. Available from http://www.g2g.isdefe.es/home.html?overview, G2G-05-PCO-EUR-FinalReport-D052-V0200-PUBLIC.pdf, May, 2007.

Federal Aviation Administration (1997). Aviation system capacity plan. Washington, DC: FAA Office of System Capacity and Requirements.

Federal Aviation Administration (2007).Integrated arrival/departure control service (Big Airspace) concept validation. Washington, DC: FAA Office of Air Traffic Organization Operations Planning.

Flener, P., Pearson, J., Agren, M., Garcia-Avello, C., Celiktin, M. & Dissing, S. (2007). Air-traffic complexity resolution in multi-sector planning, Journal of Air Transport Management, doi:10.1016/j.jairtraman.2007.05.001.

Flynn, G., Leleu, C., & Hilburn, B. (2006). A complexity study of the Maastricht Upper Airspace Centre, EEC Report No. 403, Eurocontrol Experimental Centre: Brussels.

Hadley, J.A., & Sollenberger, R.L. (2001). Dynamic resectorization of airspace boundaries between adjacent air route traffic control centers. Intelligent System Applications to Power Systems (ISAP), Hungary.

Hickson, R. (2004). MANTAS Operations Manual, Maastricht UAC Operations Division. Version 1.2.

"High Altitude Airspace Design Phase I" (2003) FAA Advisory Circular 90-99, ATA-301.

Hoffman, R., Prete, J. (2008). "Principles of Airspace Tube Design for Dynamic Airspace Configuration," AIAA-ATIO Conference, Anchorage Alaska.

Jeppesen, (1996). Private pilot manual, Englewood, CO: Jeppesen Sanderson Inc.

Joint Panning and Development Office (2007), Concept of Operations for the Next Generation Air Transportation System, version 2.0.

Klein, A., (2005). "An Efficient Method For Airspace Analysis And Partitioning Based On Equalized Traffic Mass", Proceedings of 2005 USA/Europe ATM Seminar, Baltimore, MD, June 2005.

Klein, A., Kopardekar, P., Rodgers, M., Kaing, H., (2007). "Airspace Playbook" Dynamic Airspace Reallocation Coordinated with the National Severe Weather Playbook, 7th Aviation Technology Integration Operations Seminar, AIAA, Belfast.

Kopardekar, P., & Magyarits, S. (2003). Measurement and prediction of dynamic density. 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary, June, 2003.

Kopardekar, P., Schwartz, A., Magyarits, S., & Rhodes, J. (2007). Airspace complexity measurement: an air traffic control simulation analysis. 7th USA/Europe Air Traffic Management R&D Seminar, Barcelona, Spain, June, 2007.

Kopardekar, P., Bilimoria, K., & Sridhar, B. (2007). Initial concepts for Dynamic Airspace Configuration, 7th Aviation Technology, Integration and Operations (ATIO) Seminar.AIAA, Belfast, Northern Ireland.

Lee, K.K., Kerns, K., Bone, R., & Nickelson, M., (2001). Development and validation of the Controller Acceptance Rating Scale (CARS): results of empirical research, 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe, NM, December, 2001.

Majumdar, A., Ochieng, W., McAuley, G. & Lepadata, C. (2005). Factors affecting airspace capacity in Europe: a framework methodology based on cross-sectional time-series analysis using simulated controller workload data, 6th USA/Europe Air Traffic Management R&D Seminar, Baltimore, MD, June, 2005.

Meyers, B.C., Plakosh, D.R., Place, P.R.H., Klein, M., & Kazman, R. (1998). Special report: assessment of CORBA and POSIX.21 designs for FAA en route resectorization (CMU/SEI-98-SR-002). Pittsburgh, PA: CMU Software Engineering Institute.

Nolan, M.S. (2004). Fundamentals of air traffic control, Belmont, CA: Brooks/Cole.

Rowe, D.W., Borowski, M., Wendling, V.S., & DeSenti, C.T. (2003). Redesigning High Altitude Airspace in the National Airspace System: modeling, simulation, and assessment. Journal of Air Traffic Control, Vol. 45, no. 2, pp 17-23. Apr-June 2003.

SLDAST: System-Level Design, Analysis, and Simulation Tools (2007). NASA NextGen Air Transportation System ATM-Airspace Project SLDAST Technical Integration Report, November, 26. 2007.

Sridhar, B., Chatterji, G.B. Grabbe, S., & Sheth, K. (2002). Integration of traffic flow management decisions (Paper # AIAA-2002-3748). American Institute of Aeronautics and Astronautics.

Sridhar, B., Grabbe, S., Sheth, K., and Bilimoria K. (2006). Initial Study of Tube Networks for Flexible Airspace Utilization, AIAA Guidance Navigation and Control Conference.

Stein, E.S., Della Rocco, P.S., Sollenberger, R.L. (2005). Dynamic resectorization in air traffic control : human factors perspective, DOT/FAA/CT-TN05/19, Washington, DC: FAA Office of Air Traffic Organization Operations Planning..

Taber, N.J., Woodward, F., Small, D. (2000). Limited Dynamic Resectorization Casebook. The MITRE Corporation, McLean, VA.

TranDac, H., Baptiste, P., & Duong, V. (2003). Optimized sectorization of airspace with constraints, 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary.

Timmerman, J. (2007). Airspace management program: High Altitude Airspace: "Foundation to the future", presented at DAC Workshop in 2007, Moffett Field, CA.

Wing, D., Smith, J., and Ballin, M. (2007). "Analysis of Dynamic Multi-Track Airways Concept for Air Traffic Management," DRAFT NASA/TP-2008-215323, NASA Langley Research Center.

Wyndemere, Inc., (1996). "An Evaluation of Air Traffic Control Complexity," final report to NASA Ames in support of Advanced Air Transportation Technology (AATT) Program.

Xue, M., "Airspace Sector Redesign Based on Voronoi Diagrams", Proceedings of AIAA Guidance, Navigation, and Control Conference, Honolulu, Hawaii, August 2008.

Yousefi, A. & Donohue, G.L. (2004). Temporal and spatial distribution of airspace complexity for air traffic controller workload-based sectorization (Paper # AIAA 2004-6455). AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum. September 20-22, 2004, Chicago, Illinois: AIAA.

Yousefi, A., "Optimum airspace design with air traffic controller workload-based partitioning", Ph.D. dissertation, George Mason University, Fairfax, VA, Feb. 2005.