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Initial Concepts for Dynamic Airspace Configuration

Parimal Kopardekar[1], Karl Bilimoria[2], and Banavar Sridhar[3]
NASA Ames Research Center, Moffett Field, CA, 94035-1000

Future airspace needs to be flexible, dynamic and adaptable based on traffic demand, equipage, and weather. Initial concepts focus on three core areas: 1) restructuring airspace, 2) adaptable airspace, and 3) generic airspace. The paper presents mid-term and long-term airspace configuration concepts. These concepts were developed based on literature reviews, workshops, subject matter expert discussions, and field trips. The mid-term airspace configuration concept includes high altitude airspace where user-preferred routes will be predominant and low altitude airspace divided into regions for super density and metroplex areas and remaining portion. Subsequently, the long-term airspace configuration may include four primary regions: 1) airspace for automated separation assurance, 2) high altitude airspace, 3) super density and metroplex operations airspace, and 4) structured classic airspace.

I. Introduction

CURRENT airspace has three main limitations. First, it is not clear if the current airspace and its structural elements such as sectors, routes, and fixes will support future concepts such as automated separation assurance operations and 4D trajectory operations. The partitioning of current airspace into sectors is largely based on controller workload limitations. Automated separation assurance operations will remove the workload limitation. Additionally, some structural elements of airspace (e.g., fixes and routes), which help controllers anticipate conflicts, may not be necessary. Second, current demand-capacity imbalances are addressed by traffic flow restrictions such as rerouting and ground delay. These restrictions often result in delays. To adjust the capacity portion of the imbalance requires airspace flexibility, but that flexibility does not exist due to lack of decision support tools, and coverage limitations of radio frequency and radar. Third, the demand is not uniform in the entire airspace. Under-utilized controller resources cannot be used for an airspace from a different facility or an area within the same facility, because the controllers are not familiar with the airspace. Therefore, current airspace adjustments are very limited to the airspace that controllers are familiar with. Such practice limits capacity adjustments.

A few concepts have been proposed to make future airspace more efficient. These concepts include corridors-in-the-sky and dynamic resectorization. The tubes, highways, or corridors-in-the-sky concept suggests creating an efficient highway network in the sky.[1-3] These papers suggest an initial potential for tubes/corridors based on traffic volume that can be covered through these tubes. Eurocontrol proposed an airspace concept that splits the air traffic in dense areas according to the air traffic control issues (e.g., short haul airport traffic, and long haul cruise traffic).[4] The proposed airspace consists of a freeway structure that is isolated at high altitudes with special rules. However, the corridors-in-the-sky concept may be too restrictive for the use of advanced concepts such as automated separation assurance, therefore airspace reorganization is still necessary. Additionally, researchers have examined initial concepts and algorithms for dynamic resectorization as a result of changes in demand.[5-7] Their research shows initial promise of how changes in airspace can accommodate changing demand. However, most of the dynamic resectorization research has been focused on limited resectorization and still conforms to current airspace divisions based on facilities and controller areas of specialization. Concepts and algorithms for large-scale allocation of airspace and controller resources to balance overall demand and capacity are still needed.

The objective of this paper is to describe initial airspace configuration concepts and associated research issues. Section II introduces these concepts, Section III describes the approach used to develop them, Section IV provides detailed concept descriptions, Section V discusses the evolution from current to future airspace configurations, and Section VI provides conclusions.

[1] Research Scientist, Automation Concepts Research Branch, MS 210-10, Moffett Field, CA, AIAA Senior Member.
[2] Research Scientist, Automation Concepts Research Branch, MS 210-10, Moffett Field, CA, AIAA Associate Fellow.
[3] Branch Chief, Automation Concepts Research Branch, MS 210-10, Moffett Field, CA, AIAA Fellow.

II. Background

NASA is conducting research and development to determine how to strategically organize airspace and efficiently allocate it tactically and dynamically under the Dynamic Airspace Configuration (DAC) technical area. DAC contains three parts: first, restructuring airspace; second, adaptable airspace; and third, generic airspace. The first part restructures airspace to take advantage of technologies such as self-separation and 4D-trajectories. The second part changes the airspace to accommodate the fluctuating demand. The third part defines airspace in a generic manner to promote interchangeability among facilities and controllers. DAC will address the technical challenges of migrating from the current structured, static homogenous airspace to a dynamic, heterogeneous airspace capable of adapting to user demand while meeting changing constraints of weather, traffic congestion, and a highly diverse aircraft fleet. In the future, Air Navigation Service Providers (ANSPs) will employ airspace adjustments to increase capacity (by manipulating airspace and controller resources) while leveraging Traffic Flow Management (TFM) techniques cooperatively to manage demand (by manipulating departure times, ordering adaptive speed control, modifying routes, etc.). The key challenge of this research effort is to design new airspace configurations to accommodate user-preferred trajectories while reconfiguring airspace daily operations in response to changing weather patterns and security and environmental constraints.

III. Approach

The DAC operational concept is in a formative stage. Initial DAC concepts are undergoing development based on analysis of information obtained from scientific literature surveys, current practices, field observations, interviews with subject matter experts and various stakeholders, brain-storming sessions, and from national and international workshops. Researchers will refine the initial concepts using fast-time modeling and simulations, human-in-the-loop simulations, and benefits assessments. These preliminary concepts will evolve with further research.

IV. DAC Concepts Overview

DAC is a new paradigm for airspace. The goal of airspace design is to provide flexibility where possible and provide structure where necessary. Unlike today's system, DAC does not only rely on fixed geographic features such as fixes, airways, and sectors but rather allocates airspace as a resource to meet user demand while also addressing weather, safety, security and environmental constraints.

Restructuring Airspace

The fundamental hypothesis behind restructuring airspace is that advanced concepts that make use of higher performance capabilities of aircraft and ground automation, and more accurate trajectory modeling and prediction may need new classes of airspace. These classes of airspace are meant to promote the efficiency and safety of air traffic management operations. The benefit mechanisms may include fewer TFM restrictions, ability to self-separate, and priority for arrivals. Concepts proposed to support these classes of airspace include, but are not limited to:

- Airspace sectors used in current operations
- Tubes, corridors, or "highways in the sky"
- "Gaggles" and "platoons"
- Airspace blocks assigned to specific operations (e.g., automated separation assurance operations)

Corridors will serve in two areas:

- First, corridors may serve where high-density operations are possible without interference from other traffic in high altitude airspace. In such cases, aircraft inside the corridors may be able to conduct their self-spacing or separation operations depending on equipage. The number of controllers per aircraft that are required to manage the corridors may be lower compared to current operations.
- Second, corridors could serve as dedicated arrival and departure pathways to connect busy airports and high altitude airspace. The arrival corridors may begin at top of descent and departure corridors may end at top of climb.

In both cases, the corridors will be dynamic and will be based on the traffic demand and wind. The start- and end-time of the corridors will be dependent upon the demand profiles, and the exact profile (route and size) of the corridors may depend on the demand profile, wind, equipage, and weather conditions.

A gaggle is a group of aircraft traveling in the same direction and could be treated as a single unit by the controller. Inside gaggles, properly equipped aircraft may be permitted to conduct self-spacing and separation operations. The shape and size of a gaggle and the relative position of aircraft within it may vary with time; aircraft may join or leave as per their origin and destination.

Platoons may be considered when at least two aircraft fly in formation so that they will be treated as one unit for air traffic management operations. The same controller or manager may operate these aircraft regardless of the airspace in which they travel.

Adaptable Airspace

The fundamental hypothesis behind adaptable airspace is that demand and capacity imbalances could be reduced by dynamically changing airspace. It would be useful to determine if, under nominal conditions, an en route capacity constraint can be relaxed completely or partially by modifying the airspace boundaries. Fundamentally, as the routes change based on wind or severe weather, the airspace has to change to accommodate the routes. If the airspace is not changed with the changing route, additional demand-capacity imbalances may occur. Researchers have proposed the "airspace playbook" concept in which the airspace will adjust according to the National Severe Weather routes playbook. The airspace playbook will complement the routes playbook currently used in the NAS.[8] The airspace will be adjusted to accommodate the route playbook so additional demand management constraints may not be necessary to reduce sector congestion problems.[9]

Airspace configuration will be tightly coupled with TFM. In some cases, TFM will be *proactive* where new and optimized routes will be developed based on poor weather. In other cases, the TFM will be *reactive* where changes to the airspace will be attempted first to balance demand and capacity prior to demand management.

Generic Airspace

Generic airspace is defined as an airspace managed by any controller from any facility with supporting procedures, structure, and automation levels. The fundamental hypothesis for developing generic airspace is that the interchangeable airspace will lead to better utilization of controller resources. For adaptable airspace, it has to be sufficiently generic so that any controller can manage that airspace. Additionally, the airspace characterization (also known as referencing or indexing) should be generic so that it will be easy to understand and use by any operator (e.g., traffic flow managers, pilots, and controllers).

The FAA has proposed the Navigational Reference System (NRS) as part of the high altitude airspace redesign initiative. The NRS is a system of waypoints developed for flight planning and navigation without reference to ground based navigational aids. The NRS waypoints are located in a grid pattern along defined latitude and longitude lines. The initial use of the NRS is in the high altitude environment in conjunction with the FAA's High Altitude Redesign initiative. The NRS waypoints are intended for use by aircraft capable of point-to-point navigation. Initially, to minimize the database requirements of aircraft navigation and flight management systems, the NRS is populated with waypoints every 30 minutes of latitude and every two degrees of longitude. In its final version, the NRS waypoints will have a grid resolution of 10 minutes of latitude and 1-degree of longitude. Although it is a great improvement over the current referencing system that employs ground based navigational aids, its resolution could be improved to allow user-preferred routes. Even the proposed NRS may not be fine enough for user-preferred routing.

The current operational paradigm implies that the more familiar a controller becomes with airspace, the more efficiency is gained. This is because of the abundance of local, site-specific, and airspace-specific procedural and airspace referencing knowledge a controller must learn and master to be efficient. Such practice increases efficiency but limits interchangeability. It is possible that parts of the NAS could be created using generic characterization or referencing that could promote interchangeability while maintaining a desired level of efficiency, particularly with higher automation on the ground and in the cockpit. It is possible that such a generic system may not apply to heavily congested areas such as New York Center.

With the emergence of Required Navigation Performance, ADS-B, and Global Positioning System (GPS) technologies, a different airspace referencing system, which is much finer, may be needed to accommodate user-preferred routes. Obviously, such a system must be easy to comprehend and communicate among pilots, traffic flow managers, and controllers.

V. Airspace Configuration Evolution from Current Operations to Future Operations

The following sections provide an evolution of airspace configuration and design. First, today's operations are described to illustrate the current practices. Then, mid-term and far-term operations are described to illustrate the desired concepts and capabilities. The time frames provided here are notional and may vary depending on the technological, policy, and procedural considerations.

A. Current Operations

Current airspace boundaries are rigid and static for the most part. The purpose of current airspace management is to ensure that the controllers are not overloaded. Controllers are responsible for separation assurance duties within sectors. The traffic management coordinators (TMCs) examine the flows and sector overload situations before aircraft enter the sectors. If necessary, the TMCs create restrictions (e.g., miles-in-trail, aircraft holding on ground) to alleviate capacity-demand imbalances. The current sectors are designed, and occasionally redesigned, based on changes in the flows and aircraft mix to ensure that sector workload is manageable by the controllers while promoting efficiency. To the extent possible, the sector shapes are aligned with the major traffic flows. Each sector has an aircraft count threshold, called the Monitor Alert Parameter (MAP) that sets an approximate complexity and capacity limit as to the number of aircraft that can be safely managed by the controllers. MAP values are roughly based on average sector flight time.[10]

The primary building blocks of the current airspace are sectors, routes, fixes, and different airspace classes. Figure 1 shows the classes of airspace. Class A airspace is from FL 180 to 600. All pilots who fly through Class A airspace are required to file an instrument flight rules (IFR) flight plan. Class B airspace is generally the airspace from surface to 10,000 feet around the busy airports. This airspace is individually designed to meet the needs of the particular airport. Class C airspace is from surface to 4,000 feet. This is found at medium-sized airports that have an operational control tower and radar capabilities. Class D airspace is from the surface to 2,500 feet and surrounds airports that have an operational control tower. Class E airspace is all controlled airspace that is not Class A, B, C, or D. It extends upward from either the surface or a designated altitude to other classes. It is used by aircraft transiting to and from the terminal or high altitude en route environment. It also makes up most of the current low altitude en route environment. Class G airspace is uncontrolled airspace where IFR aircraft are not controlled.[11]

Terminal operations offer interesting cases for making airspace changes on a tactical basis. As the airport configurations change, with changes in the wind conditions, corresponding routes also need to change. This creates a need to change sectors and thus creates a cascading effect from terminal to en route operations. Currently, these changes are done manually based on prior experience; operators find an appropriate time (e.g., gap in the traffic) to change the airport configuration and subsequent changes. No automation is available to change the airspace configuration based on changes in demand and weather.

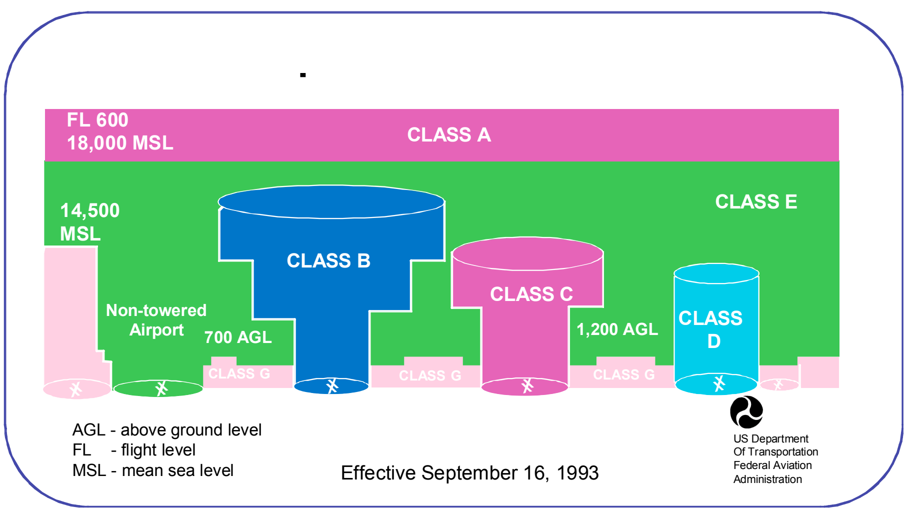

Figure 1. Current U.S. Airspace Classes

Strategic changes to the airspace are based on operational experiences of airspace congestion, changes in the flows, and workload. Recently, the FAA implemented a High Altitude Redesign program based on RTCA SC192 committee recommendations that included non-restrictive routing (NRR), Area Navigation (RNAV) and closely spaced parallel RNAV routes, and NRS in the high altitude airspace.[12] The NRR is available from FL350 and above; other elements are available from FL180 and above. MITRE has developed a suite of tools to conduct a strategic large-scale airspace redesign for current operations.[13] Their design process involves airspace partitioning based on clustering algorithms and then evaluation of redesigned airspace using fast-time modeling and human-in-the-loop simulation. Additionally, decision support tools, such as the Sector Design and Analysis Tool, are used to redesign airspace based on controller experience with increased complexity within the sectors. These tools are useful for strategic airspace planning. On a tactical basis, such as day-to-day or hour-to-hour, the airspace changes are limited to combining and de-combining sectors mostly during shift change operations when the traffic demand drops off significantly. Currently, no automation assists in determining the best airspace sectorization scheme for a projected traffic demand and weather on a day-to-day basis.

B. Mid-term Operations (2010-2025)

The airspace may be divided into high altitude airspace and two low altitude airspace categories: Super Density Metroplex areas and remaining low altitude airspace. The purpose of airspace management will be to begin providing more efficiency based on aircraft equipage and performance capabilities. The primary emphasis of airspace management will remain on limiting human workload. Figure 2 provides a notional airspace operations concept.

High Altitude Airspace
- Larger and simplified sectors – greater interchangeability of controllers
- Increased user preferred routing/non restrictive routing
- Dynamic RNAV routes where structure is necessary
- Aircraft with higher performance mostly use this airspace – datalink, RNP

Conventional Low Altitude Airspace
- Routine use of dynamic resectorization based on demand and weather
- Routine use of airspace playbook to match the routes based on severe weather
- Contain largely climbing and descending traffic
- Controller manages all traffic with decision support tools
- Mix of high and low performance equipage
- Increased dynamic RNAV routes for overflights

Super Density Metroplex Areas
- Spacing and merging operations
- Static arrival/departure RNAV routes into busy areas
- Resectorization based on demand
- Airspace playbook to match the routes based on severe weather
- Controller manages all traffic with decision support tools
- Airport configuration and subsequent changes in routes and airspace will be better supported by decision support tools

Note: The exact boundary may depend on the percentage of equipped and unequipped aircraft that are capable of automated separation assurance. In addition, Class B, C, and D airspace for tower operations may be required.

Figure 2. Mid-term Airspace Operations Concept

High Altitude Airspace

The primary building blocks of airspace will be sectors; RNAV routes; arrival, departure, and flow corridors; and certain applicable airspace classes currently in use. Fundamentally, the building blocks add homogeneity to the operations. To provide flexibility to users, there will be increased reliance on static and dynamic RNAV routes and non-restricted routing as aircraft equipage evolves. In the upper altitudes (e.g., FL290 and above), properly equipped aircraft may file and fly user-preferred routes. The RNAV routes may be generated dynamically on a daily basis or even more frequently. The airspace playbook concept may address demand-capacity imbalances due to weather-related rerouting. In these situations, airspace adjustments will be made to distribute workload and redistribute capacity. These airspace adjustments will react to the traffic-management-generated new routes around severe weather. Where a sector demand is expected to be over capacity, sectors will be redrawn to redistribute the workload. If the sector demand-capacity imbalances are not addressed by resectorization, TFM restrictions will be planned and executed. Clearly, there will be a tight coupling between airspace configuration and TFM. Nonetheless, dynamic resectorization will be routine and conducted a few times in a day.

Where flexibility is possible, equipped users can fly user-preferred routes. Sectors in the upper airspace may become "generic." Generic sectors will promote interchangeability of controllers and facilities to improve the overall efficiency. These large generic sectors will be procedurally similar, since most of the traffic will be overflights. With the increased use of data link, the coordination workload may be reduced, and controllers may be able to handle larger sectors in the upper altitudes. Additionally, the performance characteristics of the aircraft that operate on these altitudes may be similar in terms of their speed, turn rates, and climb/descent rates, which will help reduce complexity and workload. Some airspace classes may continue. Controllers may also manage aircraft as a group (e.g., in gaggles or platoons). The management of aircraft by group is a way to add homogeneity of operations so that a group can be treated as one unit thereby significantly reducing the controller workload. It is anticipated that there will be more strategic and tactical decision support tools available to decide the best airspace configuration for a given demand and weather profile. These tools will examine and propose when and how the airspace should be configured. The redesigned airspace will provide enough notice to the controller before the configuration changes and try to distribute the workload as evenly as possible by adjusting the size of the airspace allocated to the controller positions.

The controller will be responsible for separation assurance duties within the sector, but decision support tools will aid in the detection and resolution of conflicts. Traffic flow coordinators and additional decision support tools will examine flows and sector overload situations before an aircraft enters a sector. Before creating any flow restrictions, airspace adjustments may be made to ensure that the airspace is utilized properly and workload is distributed. If necessary, traffic management coordinators will create restrictions (e.g., miles-in-trail, aircraft holding on ground) to alleviate capacity-demand imbalance situations. Additionally, concepts such as multi-sector planner (in which a multiple data entry position supports more than one radar controller) may be used based on traffic demands.[14] In high altitude sectors, controllers may be interchangeable due to homogenous equipage and flows (e.g., largely overflights) and a reduced need for local procedural knowledge.

The strategic airspace changes will be based on the evolving equipage profile of the aircraft. More automation will be available for strategic airspace changes, which will focus on the allocation of airspace for high altitude operations as well as busy terminal operations. As more aircraft are equipped with data link and RNP capabilities, the route structure will continue to change as needed and more altitudes may be available for user-preferred or non-restricted routing.

Super-density Metroplex Area Airspace

More automation will be available for managing terminal operations. The management of airport configuration and its cascading effect may be supported by decision support tools, which will indicate when and how the flows should be adjusted as a result of winds and planned changes in the airport configuration. The airspace size and shape may change based on the wind and weather conditions. An airspace playbook and dynamic resectorization will reduce demand-capacity imbalances. Where structure may be necessary (e.g., busy terminal areas) the users can use more efficient RNAV routes. High-density metroplex areas (e.g., Chicago and New York) will have RNAV routes and larger airspace than assigned currently. Such a structure will allow spacing and merging operations early on. The FAA is investigating a concept called "Big Airspace" that focuses on eight busy metroplex areas (e.g., Chicago and New York) where the arrival and departure routes will be redesigned to take advantage of RNAV capabilities. The concept elements include: expanded use of 3-mile-separation standards, use of visual separation standards above 18,000 feet, dynamic airspace reconfiguration using bi-directional arrival/departure routes, creation of additional RNAV routes, and improved TFM.[15]

Conventional Low Altitude Airspace

The conventional low altitude airspace is expected to be similar to current low altitude airspace operations where the controller will be responsible for separation assurance. There may be routine use of dynamic resectorization and airspace playbook concepts based on the demand and weather to improve efficiency. Additionally, the equipped aircraft may be able to take advantage of dynamic RNAV routes. The primary features of this airspace are expected to be transitioning traffic and mixed performance aircraft. These two factors are shown to be contributors to the controller workload and complexity of operations.[16] Therefore, managing complexity and controller workload will remain important.

C. NextGen Operations (2025 and beyond)

In this period, the purpose of airspace management will be to leverage aircraft equipage and performance characteristics to increase capacity, flexibility, and efficiency. For portions of the airspace, human workload will not be a limiting factor. Overall, there will be increased use of higher altitudes (i.e., super high altitudes) where properly equipped aircraft will be allowed to use automated separation assurance methods (via ground-based or distributed airborne systems) in addition to user-preferred routes. There will be an increase in the use of dynamic RNAV routes in the en route and terminal airspace, which will take advantage of RNP capabilities. Generally, the higher altitudes offer more flexibility and may require higher performance capabilities. This airspace is expected to be organized so as to provide maximum flexibility to aircraft where possible while maintaining the structure where necessary. The flexibility will be offered by automated separation assurance airspace. Higher structure in the form of static and dynamic routes may be necessary for low altitude airspace. Additional flexibility may be offered by airspace playbook and dynamic resectorization based on changes in the weather, routes, and traffic demand to promote efficiency. Dynamic RNAV routes may offer flexibility based on winds and provide a structure for departure and arrival flows. Dynamic corridors-in-the-sky may provide further flexibility. The controller may be responsible, with decision support tools, for separation assurance for low altitude airspace. The high altitude structure may remain similar to the mid-term operations. The generic nature of airspace in high altitudes may promote controller interchangeability and increase operational efficiency.

The primary building blocks of airspace will be arrival, departure, and flow corridors; user-preferred routes; and gaggles and platoons. There will be increased reliance on dynamic RNAV routes and non-restricted routing as aircraft equipage evolves. Overall, the airspace will be separated into four elements (See Figures 3 and 4):

- Automated separation assurance operations airspace (FL350 and above),
- High altitude airspace (FL250-350),
- Structured, classic, or low altitude airspace (ground-250), and
- Super density metroplex operations airspace (ground-250) surrounding busy and multiple airport regions such as Chicago, New York, and Los Angeles.

Figures 3 and 4 are similar and only the top layer related to automated separation assurance operations airspace is different. Therefore, Figure 4 only presents that l

Automated Separation Assurance Operations Airspace (Exclusionary)
- Airspace building blocks may not be necessary
- Automation manages conflicts between aircraft
- All aircraft are capable of automated separation assurance
- Focus on Complexity management
- Arrival corridors begin at top of descent, departure corridors end at top of climb, overflight corridors may connect wind optimal user preferred routes
- All corridors will be dynamic based on demand and weather conditions
- Controller primarily manages flows

High Altitude Airspace
- Sector characteristics are similar promoting interchangeability of controllers and facilities (i.e., generic airspace)
- Dynamic RNAV routes
- Airspace playbook to handle weather and demand profile changes
- Mix of high and low performance aircraft operate in this airspace
- Arrival, departure, and overflight corridors may continue
- Spacing and merging operations may begin for busy metroplex areas

Structured/Classic/Low Altitude Airspace
- Mix of high and low performance equipage
- Routine use of dynamic resectorization and airspace playbook to match the routes based on weather and demand
- Climbing and descending traffic
- Limited use of dynamic RNAV routes
- Controller manages all traffic with decision support tools

Super Density and Metroplex Areas
- Spacing and merging operations
- Dynamic arrival/departure RNAV routes into busy areas
- Routine use of dynamic resectorization and airspace playbook
- Controller manages all traffic with decision support tools
- Airport configuration and subsequent changes in routes and airspace will be supported by higher levels of automation

Note: The exact boundary may depend on the percentage of equipped and unequipped aircraft that are capable of automated separation assurance. In addition, Class B, C, and D airspace for tower operations may be required.

Figure 3. Airspace Configuration Option 1 (Includes Exclusionary Airspace)

Automated Separation Assurance Operations Airspace (non-exclusionary)
- Some building blocks may be necessary (e.g., very large sectors)
- Automation manages conflicts for equipped aircraft
- Fewer unequipped aircraft, more automated separation assurance aircraft
- Focus on Complexity management
- Arrival corridors begin at top of descent, departure corridors end at top of climb, overflight corridors may connect wind optimal user preferred routes
- All corridors will be dynamic based on demand and weather conditions
- Controller manages flows and conflict between unequipped aircraft with decision support tools

Note: The exact boundary may depend on the percentage of equipped and unequipped aircraft that are capable of automated separation assurance. In addition, Class B, C, and D airspace for tower operations may be required.

Figure 4. Airspace Configuration Option 2 (Includes Non-Exclusionary Airspace)

It must be noted that these altitude strata are hypothetical at this point and the exact levels will depend on future aircraft equipage and performance characteristics and on new air transportation policy. It is also possible for a structured, or classic airspace to exist in the higher altitudes if the aircraft equipage so requires. Similarly, it is possible that the automated separation assurance airspace could exist in lower altitudes if all aircraft are capable of supporting such operations. Alternatively, they could be dynamic and vary based on the demand, weather, and equipage profile. A fundamental research need is to identify how much capacity improvement is possible with airspace configuration concepts. Another interesting research issue is to identify the relationship of airspace organization and different business models such as hub-and-spoke, or point-to-point operations.

Automated Separation Assurance Operations Airspace

In the upper altitudes (e.g., FL350 and above), automated separation assurance operations may occur. Such operations are expected to provide the flexibility to the users and increase airspace capacity by reducing the dependence on human controllers. These operations may employ ground-based or aircraft-based separation assurance methods. It is important to note that whether or not this airspace should be *exclusionary* (i.e., only automated separation assurance operations should be allowed in this airspace, as shown in Figure 3) or *non-exclusionary* (i.e., both automated separation assurance operations aircraft and other aircraft are allowed in this airspace, as shown in Figure 4) remains an open research issue. It is possible that at certain times of the day, depending on the demand and aircraft equipage characteristics, it could be exclusionary airspace and at other times it could be non-exclusionary airspace. Additionally, arrival corridors may begin at the top of descent, departure corridors may end at the top of climb, and flow corridors may be used on wind optimal routes where higher density is expected. Multiple levels of automation and decision support tools will be needed to support each type of operation and will include at the highest level either ground-based or aircraft-based separation assurance automation. In addition, RNP, datalink, and Automatic Dependent Surveillance Broadcast (ADS-B) may be required.

In such highly automated operational conditions, the goal of airspace management will be to manage complexity operations. The airspace design should be such that the maximum possible capacity is achieved while maintaining airspace complexity under a manageable threshold. A complexity threshold is considered manageable if an additional aircraft can enter the airspace without causing a safety-critical situation. Ideally, the entering aircraft may retain the flexibility to choose a flight path through the airspace and in a conflict situation have at least one degree of freedom available to resolve the conflict. If an entering aircraft has no flexibility in its flight profile and there are limited or no degrees of freedom available to resolve a potential conflict, then the airspace complexity is considered to be high and the capacity limit is reached. In highly automated operations (where conflict detection and resolution are conducted by automation), the complexity threshold is based on the degree of flexibility afforded to aircraft entering the same airspace; it is not based on controller workload. The exact complexity threshold may be different for different operations (e.g., corridors in the sky and gaggles), and setting up complexity thresholds continues to be a matter of research.[17] The role of the human in future systems has not been fully explored or identified. However, if the role of the human is to serve as the final backup, then the management of airspace complexity, airspace design, and grid structure design will have different implications. In such cases, an interesting area of research concerns how to safely gracefully degrade the system. If the human is to serve as the backup or manage degraded conditions and take over airspace operations, the issue becomes what is the complexity limit that can be managed by the human. On the other hand, if the role of the human is more of a monitor, and automation and redundancies will manage regular and novel situations, then airspace design becomes much simpler since complexity and capacity thresholds will be much higher.

In the exclusionary airspace option, only the aircraft that are capable of automated separation assurance will be allowed in this airspace. This will increase the capacity and flexibility. Alternatively, in the non-exclusionary option, most of the aircraft will be separated via automated separation assurance methods. A few unequipped aircraft (without data link and FMS) may be allowed in the non-exclusionary airspace. If unequipped aircraft are allowed then they will need to be managed by the controller. Fundamentally, the conflicts between managed and automated separation assurance aircraft may create procedural and automation challenges. Also, depending on the number of allowed unequipped aircraft, the controller workload may become a factor that limits capacity. Therefore, sectors may be required so that the controller workload may be partitioned. There will be arrival, departure, and overflight corridors in this airspace. The corridors will provide dedicated airspace for these operations. These corridors may vary based on demand and wind. Their start and end times, size and location will vary based on the demand and equipage. In the *exclusionary* option (Figure 3), human operators in the top level of airspace will function as flow managers. In the *non-exclusionary option* (Figure 4), human operators will use decision support tools to manage flows and maintain separation assurance between unequipped aircraft. More research is needed to investigate whether the non-exclusionary option is feasible, and if so, at what level of aircraft mix do such operations become feasible. For example, is a non-exclusionary operation feasible with 80% equipped aircraft and 20% non-equipped aircraft?

Strategic airspace changes will be made as aircraft equipage and performance characteristics evolve. It is expected that the first altitude layer will continue to reduce its floor (e.g., FL350) as more aircraft become capable of automated separation assurance operations either via ground-based or airborne automated separation assurance systems. It will be possible to routinely alter the ceiling of multiple levels of airspace based on the demand and weather profile as needed to maximize airspace capacity and efficiency. In addition, the classic airspace may continue to use capabilities such as dynamic resectorization and airspace playbooks to further maximize efficiency and balance demand and capacity. RNAV routes will be dynamic based on the winds for increased efficiency.

Related to airspace organization, it is important to determine when and where the corridors, platoons, and gaggles would be useful and at what levels of densities their implementation is desired. Additional research considerations include development of on/off structures for corridors, and entry and exit criteria for gaggles. The relationship of airspace organization and levels of mixed equipage needs to be understood which has implications on the non-exclusionary or exclusionary alternatives. Issues associated with segregated or integrated airspace operations must be carefully researched.

High Altitude Airspace

The second layer (e.g., FL250-350) will be similar to the high altitude airspace described in the mid-term concept section. It will make greater use of dynamic RNAV routes, airspace playbooks, and re-sectorization based on wind, weather, and demand profiles. Sectors in the high altitude airspace may be classified as generic. These large sectors will be procedurally similar. Related to generic airspace, the research issues include developing simplified functions, tasks, and airspace structures so that with the help of automation the controller may not need to rely on "local knowledge" nor memorize airspace specific details. Decision support tools will promote the interchangeability of controllers. With the increased use of data link, workload coordination may be reduced and controllers may be able to handle larger sectors. In high altitude airspace, a human operator will be responsible for separation assurance but will be supported by automation. Additionally, the performance characteristics of aircraft that operate on these altitudes may be similar in terms of speed, turn rates, and climb/descent rates, which will help reduce complexity and workload. In the second airspace layer, RNP and data-link capabilities will be required. It may also require capabilities such as airspace playbooks and dynamic resectorization to increase efficiency and flexibility.

Furthermore, the dynamic airspace adjustments and airspace playbook related research topics include: when, how much, how frequently, and where to resectorize the airspace and how much advance notice must be given to the operator. Research is also needed to develop and validate 3D airspace partitioning methods to support the dynamic resectorization and airspace playbook concepts.

Super Density and Metroplex Areas Airspace

In the third layer (e.g., ground to FL 250), there will be two options: one for non-metroplex areas and another for super density and metroplex operations. This airspace will be geographically close to super density airports and busy metroplex areas. More decision support tools will be available for managing terminal operations. The runway configuration and subsequent route and airspace changes will be planned and implemented in an automated fashion that resembles the airspace playbook concept. A more complex structure will be required to maintain operational efficiency. Dynamic RNAV arrival and departure routes and flow corridors will be operational in this airspace.

At the third layer, for super density and metroplex operations, an automation capability will be required to generate dynamic RNAV routes, assure separation, plan for spacing and merging, make airspace adjustments, and plan runway configuration changes. In the super density and metroplex areas, aircraft performance characteristics will probably need to be homogeneous to maintain operational efficiency (at least during the busiest periods). The human operator will manage flows. One of the research issues is to develop the automation capability that will plan and recommend flows and airspace change as a result of changing winds, which may require runway configuration changes.

Structure/Classic Low Altitude Airspace

Non-metroplex operations will apply to airspace that is not covered in super density and metroplex areas. This airspace may contain mixed operations where the controller, assisted by decision support tools, may still be in charge. This airspace may be the most challenging to manage because it will include a mix of aircraft performance operations. Structures such as sectors, predefined playbook options, and re-sectorization schemes may help operators maintain efficiency and familiarization.

This airspace may still contain sectors and other airspace "building blocks" and will make use of dynamic re-sectorization and airspace playbooks. Limited dynamic and static RNAV route structure may be present. There will be a mix of high and low performance operations in this airspace. Additionally, there will be transitioning traffic. This airspace may be the most complex and may therefore require a more complex structure than other two altitude layers. The need for classic airspace will drop as aircraft equipage becomes more advanced. An interesting research issue is to determine the capacity limits for this airspace. At present, this airspace is not utilized to its full extent. Interestingly, if point-to-point operations were to grow, this airspace may also become busier and may require strategies to balance demand and capacity. For classic airspace, decision support tools will be needed to detect and resolve conflicts since this area may see the largest aircraft performance variation. In addition, it may also need some RNAV routes for equipped aircraft and capabilities such as airspace playbook and dynamic resectorization.

VI. Conclusions

The structural elements of current airspace include sectors, routes, and fixes. Current airspace has significant limitations. It is not structured to accommodate automated separation assurance aircraft, airspace boundaries cannot be changed, and controller resources are not interchangeable. The goal of future airspace is to provide flexibility where possible and structure where necessary. The main airspace research areas are: restructuring airspace, adaptable airspace, and generic airspace. The airspace organization should support concepts such as automated separation assurance. The airspace should change based on demand and weather predictions. The airspace should be as generic as possible so that controllers and facilities will be interchangeable. Based on the current understanding, it now appears that new airspace building blocks may include dynamic sectors, gaggles, platoons, and corridors-in-the-sky. The mid-term airspace may be divided into high altitude and low altitude airspace. The low altitude airspace can be further divided into structured, and metroplex and super density airspace. The far-term airspace may be divided into four primary regions: airspace for automated separation assurance operations, high altitude airspace, super density and metroplex operations airspace, and remaining airspace. When all aircraft become capable of automated separation and spacing assurance, either via ground based or airborne based technologies, the airspace design can be further simplified. In such a case, only arrival-departure corridors may be necessary and the rest of the airspace can be generic and may not need much structure. However, there are a number of research issues that need to be addressed to test the feasibility of mid-term and long-term airspace configuration concepts.

VII. References

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