User-Efficient Airspace Boundary Specification for Air Traffic Control Facilities

ABSTRACT

The most efficient size and shape of air traffic control facility airspace boundaries in the Next Generation Air Transportation System will not necessarily be the same as in past organizations of the system. As limitations of communications and surveillance technology become less important for drawing boundaries, operational efficiency will take a greater role in defining the airspace allocated to each facility. This paper presents an objective, repeatable method for defining airspace boundaries, derived from the rules of air traffic control, simulations of efficient air traffic operation, and principles of enterprise engineering.

INTRODUCTION

The purpose of the air traffic management system is to ensure a “safe, orderly, and expeditious flow of traffic.” (Office of Management and Budget 2013) Safety is assured by maintaining separation among aircraft and obstacles. Orderliness is assured by organizing aircraft with similar plans into flows. Expeditious flows are those in which the first two requirements impose the fewest constraints (e.g., delays or altitudes) on the efficient operation of each aircraft. The system’s airspace is divided into sectors controlled by a single person or a small team, whose maximum size is set by human cognitive limits. The sectors are organized into facilities, each of which is located in a physical building. Each facility is responsible for a defined geographic area with defined altitude limits.

The Next Generation Air Transportation System proposes to replace the current infrastructure of communications, navigation, surveillance, and automation with new technology that potentially changes the size and number of sectors, the responsibilities of controllers, and the routes of the aircraft in the system. The allocation of airspace to facilities is likely to change as a result. This paper presents a method for setting the airspace boundaries of a given facility to maximize the efficiency of aviation operations, while maintaining safe and orderly air traffic management.

BACKGROUND

Facility boundaries were dictated by technological limits in the past. Towers controlled airports, terminal facilities controlled airspace defined by the effective range of their surveillance systems, and Air Route Traffic Control Centers (ARTCC) were responsible for the rest. The boundaries of each ARTCC were set by the limitations of communications, surveillance, and automation systems. As technology improved, ARTCCs were consolidated, combining two or more facilities into one. The large-scale question of defining the boundaries did not occur.

Where major airports are close together, so that their airspace overlaps, Terminal Radar Approach Controls (TRACON) were established, beginning with New York City in 1968. (Federal Aviation Administration 2011) These new facilities were formed by consolidating existing facilities, so in this case, too, their boundaries preceded them.

Small-scale adjustments of boundaries happen constantly, as changes to operating conditions lead to new demands on the airspace, but these changes are negotiated between two or three facilities, *ad hoc*, with reductions in air traffic control complexity as the primary goal. Movements of boundaries among more than two facilities are rare.

As the national airspace is transformed into the Next Generation Air Transportation System (Joint Planning and Development Office 2010), the older methods of establishing facility boundaries lose their relevance. Satellite-based communications, navigation, and surveillance have few geographic limitations, and air traffic control automation systems will have much higher capacity than the twentieth-century computer infrastructure allowed. In this new environment, facility boundaries may be set by other criteria.

METHODOLOGY

Reducing air traffic control complexity is the key to improving efficiency. The primary contributor to air traffic complexity is the number of flights that must be issued clearances, which implies that splitting the job among many controllers yields a more efficient system. However, coordination among controllers is the second-largest contributor to air traffic control complexity. (Mogford, et al. 1995) This implies that the number of control boundaries should be minimized. Defining boundaries for efficiency is a process of balancing these competing requirements.

Finding a balance between the advantages of division of labor and the costs of coordination is a common problem in enterprise engineering. In the enterprise view, the air traffic management system can be understood as an enterprise whose “product” is safety, which is accomplished by the separation of aircraft trajectories. The “actors” in the enterprise are the air traffic controller teams that have responsibility for each sector. The actors are combined into “business units”, which correspond to facilities. The “price” of safety is deviation from the trajectories that aviators would prefer in the absence of other traffic.

This approach has one difficulty. The actors are identified by sectors, and sectors can only be defined in the context of their facilities. Defining the facility is the objective here, so sectors may not yet exist. The solution is to represent sectors in terms of their abstract function, not their detailed geography, using an enterprise ontology. (Dietz and Hoogervorst 2008) It is useful to consider enterprise ontology for another reason, as well: As technology improves, information relationships within the system are simplifying, so business relationships may come to dominate the process of managing traffic in the future.

Enterprise Ontology

Splitting an enterprise into well-functioning sub-units according to its ontology has been accomplished for a variety of enterprises. Basic organization construction rules have been identified (Op 't Land 2008, p. 67) that apply to enterprises in general. These form the foundation of a set of criteria for drawing efficient boundaries for a facility’s airspace. Most of the rules are re-written here in air traffic management terminology. A few that are specific to business enterprises were discarded. In addition, air traffic management has unique features that required the creation of several mission-specific organization construction rules.

All flights but the shortest involve several air traffic control facilities. A flight between large airports within the United States is handled by two to eleven facilities, excluding towers. Long flights typically communicate with two approach/departure controls, plus the intervening airspace controlled by one or more ARTCCs. As recorded by the Traffic Flow Management System archive at MITRE, the median is six facilities for main-line carriers and four for regional carriers and general aviation. In an environment where information and control are constantly being transferred among so many facilities, business relationships affect the performance of the whole system.

Relationships between facilities exist on two time scales. On the longer time scale, letters of agreement between facilities are analogous to service-level agreements in a business enterprise, codifying mutual obligations and expectations. These letters are very rigid; they are intended to provide simple, predictable fallback procedures in case of a loss of communication between the facilities. On the shorter time scale and under normal conditions, facilities coordinate altitudes, speeds, and required spacing between aircraft by voice or data communications. These negotiations usually involve two facilities. They typically require five to thirty minutes to complete, so a single coordinated traffic restriction is generally put in place for hours at a time. Negotiated spacings are generally limited to 10, 15, 20, or 30 nmi in trail; finer precision is not predictable hours in advance, and therefore would be difficult for controllers to implement.

Within a facility, such formality is often unnecessary and a third, shorter time scale is available. Spacing between aircraft is decided case by case. When an aircraft needs to cross a sector boundary in an unusual place, controllers can quickly look at each other's displays, or simply turn and ask permission. The distinction between intra- and inter-facility coordination is at the root of many of the criteria.

Construction of the Criteria

The criteria describe air traffic control from an enterprise-ontological point of view, in very abstract terms. The criteria form a checklist. Each criterion is to be satisfied by the airspace boundary. The checklist is intended to ensure that no important considerations are missed; a certain amount of overlap among the criteria is therefore present.

Air Traffic Criteria

Criteria specific to air traffic are the first items to consider for two reasons. First, they are the most intuitively related to the question of drawing facility boundaries. Second, the process of obtaining the supporting data necessarily provides information that will be useful in checking airspace against other criteria.

Drivers of Complexity: Air traffic control becomes more complex when the controllers have to respond to unpredicted changes in the system. Controllers should be kept together in a facility when they deal with the same events. Conversely, it is frequently useful to separate actors who usually respond to different events. When a facility has a single, clearly-stated purpose, there is little danger of conflicting goals requiring contradictory actions. For example, in terminal areas, the predominant events are changes in the status of the hub airports. In enroute facilities, the predominant events are the formation of flows, and avoiding convective weather.

High Internal Cohesion: The boundary should be drawn to focus the airspace on the mission of the facility. The controllers who will eventually work the airspace will benefits from a sense of common purpose. Cohesion is readily quantified by enumerating the flows of traffic inside the possible boundaries, identifying those related to the facility's purpose, and maximizing their fraction of the total traffic. Note that keeping aircraft safely separated involves interactions among flows: where a flow mentioned in the facility's purpose crosses an oblique flow, both flows are related to the purpose.

Low External Coupling: The converse of high internal cohesion is low coupling to other facilities. Where it is possible to exclude flows of traffic that are not related to the purpose of the facility, the boundary should be drawn there. However, complete exclusion of external flows could come at a high cost, such as excess route mileage. Zero external coupling is therefore not generally desirable.

Geometric Criteria

These criteria are derived from fast-time simulation results. Common features of the relationship between air traffic efficiency and the shapes and sizes of airspace have been abstracted from these simulations, and verified with working air traffic controllers. The first of these criteria, Sequencing Efficiency, provides the characteristic length scales in the method.

Sequencing Efficiency: Once separation is assured in their own airspace, the second responsibility of a team of air traffic controllers is to create orderly flows to minimize the chance of unacceptable complexity in sectors downstream. Controllers need the appropriate space to build sequences of aircraft. Sequences can be built to an airway or to a runway.

To extract the relationship between sequencing delay and the space available to construct the sequence, fast-time simulations using the Total Airport and Airspace Modeler (TAAM) (Jeppesen, Inc. 2013), for 54 different combinations of aircraft flow and inter-aircraft spacing requirements were conducted. Each flow was built of un-coordinated streams of traffic from at least three starting points. Required inter-aircraft spacings varied from 10 to 15 nautical miles in trail. In analyzing the simulation results, the total delay imposed on aircraft was modeled as the sum of an unavoidable fixed amount due to the number of flights and the spacing requirement, plus an exponentially decreasing excess delay that depends on the amount of airspace available. Figure 1 shows the average delay per flight, with the fixed amount subtracted. Across the simulations, excess delay shows very similar dependence on distance, as measured along the aircraft's flight-planned track to the spacing point. The error bars are the standard deviation of ten iterations of each simulated flow with randomized flight-start times.[1]

For distances above 100 nmi, the excess delay is indistinguishable from zero. From this, we infer that any space above 100 nmi supports the most efficient sequencing quality when aircraft are climbing or level.

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[1] The distances begin at 30 nmi because putting aircraft ten nautical miles in trail less than 30 nmi from departure leads to simulation errors. Discussion with air traffic control subject matter experts confirmed that this would be an impossible task in practice as well.

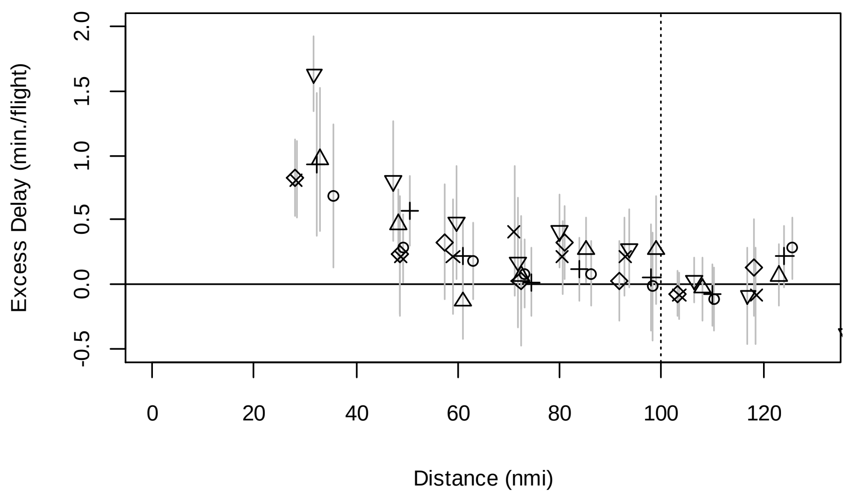

Figure 1. Excess delay from sequencing as a function of flying distance

Sequencing to runways is, after weather disruptions, the largest source of delay in any air traffic management system. Arrival sequences are most efficiently done on the basis of time (Idris, et al. 2004), but distance-based metrics are necessary to draw facility boundaries that are fixed with respect to the ground. In a simple model, omitting uncertainties in winds, controller technique, and pilot actions, the total amount of delay caused by sequencing arrivals to a runway is a function of the separations required and the pattern of demand, and is relatively insensitive to the space available for sequencing. When limited amounts of space are available for sequencing arrivals, efficiency losses appear not in the total delay, but in the mechanisms available to delay aircraft.

The most desirable way to delay an aircraft (both to controllers and to pilots) is for the controller to issue a reduced-speed instruction. The time that can be absorbed with a speed-control instruction increases almost linearly with the available space. When speed control is insufficient, then the aircraft's path must be stretched via some lateral maneuver. The time that can be absorbed with lateral maneuvers increases stepwise with the number of sectors in the available space, since each sectors' controller typically issues only one such instruction per flight. If the required delay exceeds the amounts that can be absorbed by speeds and path stretching, the aircraft must hold. Holding is least desirable, first because of the communication time required to initiate and terminate the hold, and second because following aircraft frequently must hold as well. A holding pattern can cause delays that are not needed by any downstream part of the system.

The balance among these effects was estimated from a suite of ten TAAM simulations at each of six airports. The simulations showed similar results; one example is shown in Figure 2. This airport is operating near its maximum capacity, so more than half the arrivals are delayed. One flight may have any or all of the delay mechanisms applied to it. In the smallest viable space, within 50 nmi of the destination, holding is the most likely method of delay. Holding decreases as the space available for other mechanisms increases. By 100 miles, speed control is the most common delay mechanism, used for almost all delayed flights. The likelihood that a flight will be delayed with lateral maneuvers ("Vectoring" in Figure 2) is not strongly dependent on the available distance from the destination, since lateral maneuvers gain effectiveness with lateral space, and lateral space is constrained by the presence of other routes, not usually the facility boundary. Ground delay, the lowest-cost of all delaying maneuvers, is hardly used at all in small spaces. It becomes important above 150 nmi.

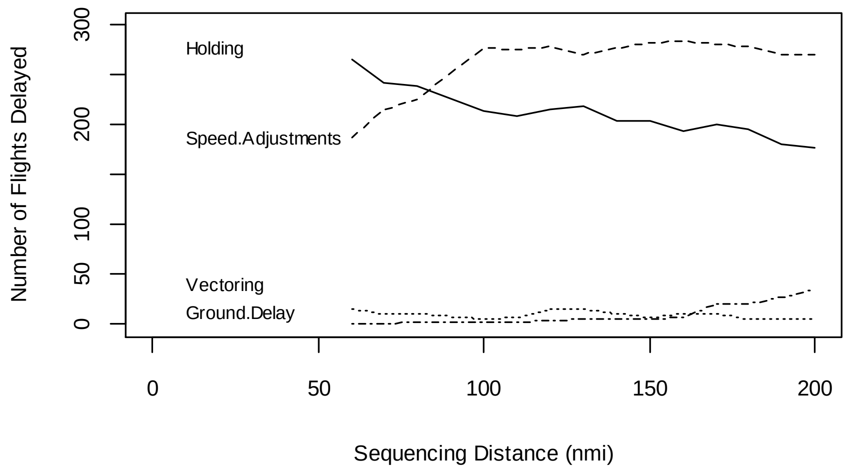

Figure 2. Sequencing actions as a function of space available

Note that these were simplified simulations, intended only to establish a generally applicable criterion for the minimum effective size. Local details will dominate any particular airspace; these are addressed by other criteria.

The criterion resulting from the two kinds of sequencing is that a properly-sized facility should have at least 100 nmi of space, measured along a geodesic, in which to construct each of its flows. Airspace that is responsible for sequencing to a runway improves its efficiency further, as space available increases up to 200 nmi.

Altitude Restrictions: Altitude restrictions have three roles in air traffic control. First, they are used to separate crossing flows without the need for delay maneuvers. Second, when communication fails at a facility boundary so that it is not possible to coordinate trajectories, altitude restrictions are put in place to which all parties can revert, to ensure handoffs are done in an orderly manner. (The third is part of the next criterion.) Altitude restrictions come at a cost in fuel efficiency, so airspace designers try to minimize their use. A well-placed boundary enables a single restriction to be used for both purposes. These frequently appear as changes to the cruise altitude of a flight. A flight that is cruising at an inefficient altitude is not always as discernible from trajectory analysis as an interrupted descent can be.

Vertical Extent: The third important use of altitude restrictions is to force flights in a common direction to merge early, in a sector where the controller can manage the workload. Figure 3 shows a case where two differently-climbing aircraft may create a complex situation in the downstream airspace. The trajectory marked with an "X" complicates the operation of Sector A. Facility 2 would usually impose an altitude restriction to force both aircraft to enter Sector B directly. Relocating the facility boundary to either dashed line in Figure 3 would eliminate the altitude restriction and improve the efficiency of the operation.

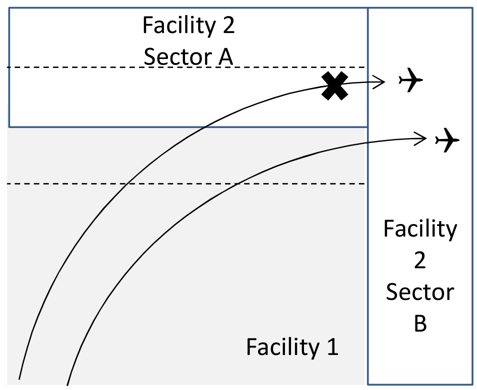

Figure 3. A facility boundary with incorrect vertical extent.

The general principle is that the lateral and vertical extent of the airspace are linked through aircraft climb and descent performance. When this criterion is satisfied, interruptions to climb and descent profiles are minimized.

Boundary complexity: Controllers should be placed together when their airspace interface is too complex to be standardized well. Severe weather (the most common cause of off-normal operations) is the test of interactions across any interface. A boundary with many sharp angles may restrict the options for controllers to reroute traffic. The shape of the boundary should confine unavoidable sharp angles to places where they are irrelevant to the flows, or internal to a facility.

Facility Isolation: Blocks of airspace within a facility should be large enough that a sector does not find itself both accepting traffic from another facility and handing traffic off to third facility. A volume passes this criterion if its inclusion in the facility does not isolate it, or other small volumes. ("Small" in this context is relative to the 100-nmi scale of sequencing efficiency.)

An example (admittedly unlikely) of facility isolation could arise where a facility's purpose is to manage traffic to a major airport. Figure 4 shows Chicago ARTCC at 24,000 feet, with the sectors colored according to the fraction of the traffic arriving or departing from Chicago O'Hare International Airport. If internal cohesion were the only criterion for inclusion, the resulting facility would have a hole in the middle, since very little of that traffic is so high, directly over the airport. The isolated sector would be too small to provide any help with sequencing the overhead streams of traffic. Excluding that airspace would, in addition, mean that when looping over the airport is necessary, it would be difficult to coordinate. This criterion ensures that such facility shapes are avoided.

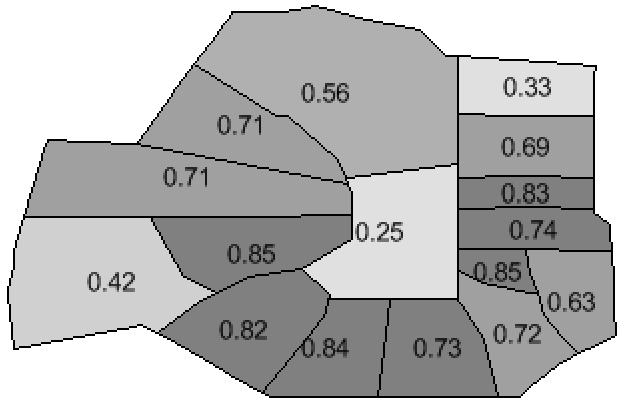

Figure 4. Density of O'Hare airport traffic in Chicago ARTCC

Human Factors Criteria

Criteria derived from human factors are intrinsically less quantitative than those derived from counting aircraft or measuring polygons, but are often the most important considerations in facility design. These three criteria relate to the need for communication of various kinds.

Information Sharing: Some channels of communication, face-to-face interaction for instance, can carry large amounts of information in a short period of time. These channels should be kept available for pairs of control positions that need them. Lower-speed communications, a telephone for instance, are sufficient between positions that rarely interact, or whose interactions take place without time pressure.

A symptom that results where this criterion is not followed can be found in the FAA Order concerning facility administration. In case of excess demand or inclement weather, "Because of the unique situation of the New York TRACON having three centers, the New York TRACON must coordinate directly with the [System Command Center] and have the [System Command Center] conference the appropriate [centers]." (Federal Aviation Administration 2012, p. 17-2-3) A situation of this kind is ideally managed on a scale of five to ten minutes. In most large terminals, these matters are dealt with directly between the terminal and one center, for which five minutes is sufficient. Around New York, the boundaries of three centers meet over the TRACON, so at minimum a three-way conference call is necessary and five-party negotiations are common.

Interface Variability: A boundary should keep controllers together when their interface changes too frequently to be standardized well. An example of excessive interface variability is where approach control airspace is so small that the enroute center must use procedures for different airport configurations. A properly-sized facility will be able to manage highly-variable conditions internally, with no need to involve surrounding facilities.

One example of this criterion is explicitly called out in the FAA Order governing air traffic control. Controllers must coordinate with any receiving facility before the departure of an aircraft if the departure point is less than 5 minutes flying time from the transferring facility's boundary, assuming appropriate automation support. (Federal

Aviation Administration 2013, s.4-3-8) Departure times are the most variable part of the system. To avoid the need for constant updates to the ARTCC, large terminal facilities typically encompass 7-10 minutes of flying time from their hub airports.

Shared Competencies: When controllers have similar responsibilities, they should be kept together in a single facility. Over the long term, best practices can easily be shared and institutional memory preserved among people in physical proximity. In day-to-day operations, unexpected situations can be handled most effectively when coordination can happen among controllers who are familiar with each other's responsibilities and working conditions. (Air traffic control subject matter experts dubbed this criteria "empathy of operations".)

Criteria Considered and Excluded

A few organization construction rules do not translate into boundary criteria because of the unique conditions of air traffic control. Issues of common language and culture, common regulatory regime, and legal authority do not arise when all air traffic control facilities are under the umbrella of a single air navigation service provider. Assessing the risk of failure at the boundary is redundant, since every change to the system must take place within the Safety Management System. (Federal Aviation Administration 2010) As a result, these organization construction rules were excluded from the checklist.

Process of Application

The criteria for an efficient facility boundary are applied in three steps of a six-step process. The process begins with a statement of the purpose of the proposed facility, and finishes with sectorized airspace within a definite boundary.

Definition of Purpose and Constraints

Many of the criteria described in the previous section refer to the purpose of the facility whose boundary is being determined. This purpose does not come from within the process; it must be defined by the authority that establishes the evaluation team and will be building the facility.

The purpose should be expressed in ontological terms, without too much detail. An example purpose for an Air Route Traffic Control Center might be, "Create flows of arrivals that meet requirements from the designated hub approach controls. Efficiently integrate departure traffic into orderly overhead flows. Cross flows to different destinations with the greatest efficiency to hub traffic. Expedite organized flows, keeping them free of delays due to interactions with unstructured traffic." An example purpose for a TRACON might be, "Support best throughput on runways via arrival sequencing and departure management. Expedite traffic on approach and departure procedures. Enable efficient use of emerging traffic management technologies."

At this stage, any inviolable constraints on the expanse of the facility must be noted. Constraints may come from national boundaries, military airspace, or limitations of the communications, navigation, and surveillance infrastructure.

Partition of the Airspace

The airspace meeting the specifications in the first step is divided into parts. Each part should ideally have a single function. If the routes to be used by aircraft in the facility are not too different from current routes, data processing is simplified if groups of one or two current sectors can be used. Where the routes have no close analogue in historical traffic databases, the airspace should be divided between the routes, encompassing at most one major route merge or crossing point, if possible.

Triage of Parts

An initial scan of each part against the criteria causes the various parts of the airspace to fall into one of three groups. Some parts obviously belong to the facility in question, and pass all criteria by a simple inspection. Others fail many criteria, and may be immediately excluded. The remainder are ambivalent cases, where a few criteria fail. These are defined as “Focus Areas”.

Reduction of Focus Areas

The included parts from the triage step form a kernel of airspace. To test each Focus Area, the airspace under consideration is temporarily added to the kernel of airspace, and a detailed evaluation against the criteria is performed. If there are enough positive results that inclusion of the volume would be desirable, but failures on some other criteria, the boundaries of the Focus Area are moved horizontally or vertically until the volume can be made to pass on all criteria. The volume that passes is kept to form part of the new kernel. If it is not possible to pass on all criteria, the volume is excluded.

The analysts should simultaneously evaluate the airspace inside the new boundaries for inclusion and the airspace outside the boundaries for exclusion. The purpose is to avoid induced failures in surrounding facilities. Note that Low External Coupling on the inside of a volume and High Internal Cohesion outside it are usually the same judgment, and vice versa.

Since moving a boundary will necessarily improve satisfaction of some criteria while diminishing others, a simple pass/fail evaluation is no longer sufficient at this stage. A criterion that is better satisfied by inclusion of the Focus Area is rated “Improvement” on the checklist. If inclusion of the Focus area neither improves nor reduces satisfaction of a criterion, it is rated “No Effect”. A criterion for which a possible improvement has been forgone to mitigate a failure in some other criterion is rated “Trade-off”. Irreconcilable failures remain “Fail”. Recording the trade-offs among criteria is important, so that future airspace design efforts in the same vicinity can begin with an explanation of all the competing interests that were balanced to produce the current organization of the airspace.

Quantitative evaluation of improvement comes from counting aircraft and analyzing historical records of trajectories (where they are relevant) or simulated trajectories (in proposed airspaces). Signs of poorly-located boundaries appear as level segments in climb or descent phases, routing around boundaries, holding or path-stretching maneuvers, or ground delays due to traffic-management requirements. Quantitative measurement of geographic criteria is still to be developed. Qualitative criteria are evaluated from the expert judgment of the application team.

A volume is marked for inclusion if it is rated “Improvement”, “No Effect”, or “Trade-off” on all criteria. An excluded volume may be included in the eventual facility design based on other factors (e.g., industrial issues or implementation cost), but it will not be included on the basis of airspace efficiency.

Integration of Parts

When all of the Focus Areas have been adjusted appropriately, the resulting aggregate volume should be re-checked against the criteria. A combination of parts is particularly vulnerable to failing on boundary complexity, even though each part passes individually. At this stage, disconnected shelves are joined and sharp angles and cusps are smoothed, usually by adding volumes that contained no traffic relevant to the stated facility purpose.

Sectorization

The candidate boundary is now complete, at the level of precision of the criteria. In the final stage of the process, the resulting three-dimensional volume is passed to local experts, who create the final division of the new facility into air traffic control positions and sectors. Sectorization is well understood, so it will not be explicated here. Sectorization requires fine precision, and accordingly is dependent on many more factors than have been considered in the first five steps of the process. As these new factors require it, the boundary can be adjusted in this phase by small amounts. A boundary adjustment that is not small is one that changes the inclusion of flows in the facility. Changes of this magnitude require re-evaluation of the affected region as in the Reduction of Focus Areas, to ensure that the airspace still passes on all criteria. Once the airspace has been sectorized, the process is complete.

OPERATIONAL VALIDATION

The FAA and the National Air Traffic Controllers' Association convened a team to conduct a joint validation of the boundary-definition process between January and March 2013. The team examined the process, explored the definition of each criterion, and conducted a test application of the process to a hypothetical Next-Generation Integrated Arrival/Departure facility. The team concluded that this method is a systematization of ideas that are intuited by airspace designers, and that with refinement could address both labor and management requirements. As a result of their input, the names of many of the criteria were changed, the definitions were clarified, the four-level classification scheme was developed, and the criterion related to failure risk was eliminated.

Visualization tools and traffic data support were found to be essential to developing a common understanding of the airspace volume under consideration. It was found that a team using this process will raise unexpected questions, so real-time visualizations and quantitative data capabilities need to be available during workgroup meetings. For traffic-based criteria, trajectory visualizations exist. For geographic criteria, a Geographic Information System that can operate in three dimensions works well. When using these tools, care must be taken not to let them make the criteria they support appear more important than those that are derived from human factors.

Note that unlike a simple pass/fail evaluation, "improvement" and "no impact" involve a comparison between two possible future organizations of the airspace. Applications of the process must take care that the comparison is applied between the proposed future alternatives with the volume in question inside and outside the boundary. Comparisons between familiar, current operations and a hypothetical future are tempting but irrelevant, and should be avoided.

CONCLUSION

The objective, repeatable method using a checklist of airspace-design criteria presented here has applicability in dense, highly-complex airspace. Initial applications and validation exercises with air traffic controllers have established that these criteria are sufficient, practical, and generate supportable answers to difficult, complex, and politically-fraught questions.

The future will bring radical changes to the roles and responsibilities of the various entities that make up the system. This method can support many different operational concepts, and can play a part in implementing the next generation of air traffic management facilities.

Op ‘t Land’s work (Op 't Land 2008, p. 62) suggests that there is good correspondence between theoretical results and “gut feelings” of the experts, when the criteria are chosen correctly. Discussion with air traffic control subject matter experts suggested similar correspondence with this methodology.

Limitations of the Method

The method is based on flows of aircraft. In high-density airspace, where flows are close together, the boundary can be drawn with fair precision. In less-dense airspace, where there may be no dominant flow, or the flows are far apart, the output of this process is correspondingly less precise.

A feeling of “ownership” of airspace assets is a sensitive point with facility personnel. This is not unique to air traffic control. (Op 't Land 2008, p. 88) It will rarely be possible to define an efficient boundary without detailed local knowledge. Local knowledge is inseparable from local interest, so a dispute-resolution process must be established along with the decision to define a new facility boundary.

The process involves balancing competing interests in a sensitive domain. Consequently, it is very time-consuming.

Future Directions

As it stands, the process is human-centered and slow. Many parts of the system are good candidates for computerization, once the criteria and methods are widely accepted. The next step in development of such a computerized tool is basic work on quantitative definition of the geographic criteria. After that, Op ‘t Land’s work (*ibid*.) in very different enterprises found utility in graph-theoretic methods for optimal splitting. Techniques exist for dividing airspace into sectors (Conker, et al. 2007). It is likely that they can be used at a higher level of abstraction for the problem of facility design.

ACKNOWLEDGEMENTS

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ACRONYMS

ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
FAA	Federal Aviation Administration
TAAM	Total Airport and Airspace Modeler
TRACON	Terminal Radar Approach Control

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