

# A Geometric Approach Towards Airspace Assessment for Emerging Operations

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**Abstract**—Emerging Urban Air Mobility (UAM) operators propose to introduce extensive flight networks into metropolitan airspace. However, this airspace currently contains complex legacy airspace constructs and flight operations that are perceived as safe, efficient, and generally acceptable to the overflowed public. Hence, Air Traffic Management (ATM) concepts to support UAM may be constrained to cause little to no interference with these legacy operations. The identification of airspace that is non-interfering and potentially “available” to these new operators is therefore a critical first step to support UAM integration. This paper introduces a geometric airspace assessment approach that considers seven existing airspace constructs. Four hypothetical ATM scenarios are developed that prescribe different degrees of UAM integration. An alpha-shape topological method is refined to process geometrically complex airspace construct polygons over an expansive geographic area and develop 3D mappings of airspace availability. The approach is demonstrated in the San Francisco Bay Area and is readily extensible to other locations. It is envisioned to be useful in identification of viable takeoff and landing sites, evaluation of the sensitivity of airspace availability to separation or trajectory conformance requirements, and flight route design, throughput estimation and risk analysis.

*Keywords*—Urban air mobility; unmanned aircraft systems; airspace assessment; alpha-shape method

## I. INTRODUCTION

UAM refers to a group of emerging concepts that aim to provide point-to-point passenger and cargo transportation in metropolitan areas using small aircraft with conventional, remote, or autonomous piloting systems. These concepts may introduce a significant number of new aircraft operations to metropolitan airspace, especially at altitudes below

915m (3000ft). The number of operations anticipated, their use of infrastructure in dense urban settings, and the low altitudes at which they may operate present significant challenges for safe and efficient flight [5], [22], [29].

Any future metropolitan airspace management approach will need to evolve from today’s system as a clean-sheet re-architecting of airspace and Air Traffic Control (ATC) will likely be infeasible. In particular, current commercial operators (and to a lesser degree general aviation and business operators) will stay on procedures with Concept of Operations (ConOps) similar (if not identical) to those with which they currently operate [13], [28]. UAM operations must therefore contend not only with surface-based obstacles, terrain, and intra-system interactions (e.g. small Unmanned Aircraft Systems (sUAS) mixing with larger passenger or cargo UAM aircraft) from below their flight altitude, but also with incumbent operations and airspace constructs from within and above their flight altitude.

The integration of UAM operations necessitates addressing three key questions:

- 1) What airspace volumes may the operators fly in?
- 2) How should traffic be structured in this airspace?
- 3) How are ATC services provided in this airspace?

Traffic structure concerns trade-offs in system performance between structured airspace concepts with defined procedures and unstructured airspace concepts with highly dynamic routing. Similarly, provision of ATC services concerns trade-offs between a centrally managed system similar to today’s and a distributed system where each aircraft provides its own services. The traffic structure and ATC service model required in low altitude, urban airspace would directly depend upon airspace availability considerations. Therefore, identifying the specific airspace volumes that emerging operators may potentially fly in is an important preliminary research step and the focus of this paper. This work is timely as EUROCONTROL

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recently outlined their plan to develop a risk-based airspace assessment methodology and highlighted the need for approaches to "model new UAS environments", "generate route topologies", and "examine the associated air and ground risks" of flight in specific airspace volumes [12].

The airspace assessment approach introduced in this paper identifies seven airspace constructs perceived by the researchers as potential constraints for UAM. Various levels of UAM access to these airspace constructs are represented through four notional ATC integration ConOps scenarios. Each integration scenario is evaluated through a topological analysis. The approach is appropriate to support the design and testing of novel ATC concepts in a city of interest.

The paper is structured as follows. Section II reviews the literature this work complements or expands upon. Section III introduces the proposed airspace assessment approach. Section IV demonstrates an application of the approach to the San Francisco Bay Area and discusses key results. Section V then proposes how the approach may be used to support investigations related to ATC design including separation minima, vertiport placement, trajectory conformance requirements, and noise. Finally, Section VI concludes the paper.

## II. LITERATURE REVIEW

UAM operations could be constrained from flight in specific airspace by a number of constructs such as terrain and obstacle clearance requirements, airport procedures, or Special Use Airspace (SUA). Previous research has shown that minimally structured airspace architectures that create altitude layers with prescribed heading restrictions maximize network performance [5], [20], [26], [27]. However, these studies assume that aircraft can access any airspace within the study region. Because low-structure airspace architectures minimize conflicts by spreading aircraft throughout the available airspace, the presence of unavailable volumes may result in congestion points that degrade performance [27]. Researchers have considered optimal traffic structure in the presence of obstacles in urban canyons [14] and at rooftop height [11], [21], however, a repeatable approach to identify available airspace from the surface up to cruising altitudes has not been developed.

The trade-off between centralized or distributed provision of ATC services also depends upon airspace availability, however previous studies [7], [10], [18], [24] also did not consider this. The performance of both service approaches may be influenced by airspace availability. For example, the concentration of flights at vertiports or around inaccessible airspace could increase flight density and necessitate longer planning horizons for sequencing and scheduling, a challenging aspect for distributed services [13], [28]. Terrain or obstructions could also limit Communication, Navigation, and Surveillance (CNS) capabilities and affect where ATC services could be provided through each approach.

The NASA UAS Traffic Management (UTM) [16] and

TABLE I: Availability implications of airspace constructs.

Airspace Construct	Entry Implication for UAM
Obstacle\terrain clearance	Physical constraint to flight
Airport controlled airspace	ATC clearance required to access
sUAS part 107 airspace	Increased interaction with sUAS
Airport procedures	Prioritized for legacy operators
Special use airspace	ATC clearance required to access
Min. vectoring altitudes	Increased interaction with aircraft
Special flight rules areas	Accessible airspace

European U-space [25] programs represent approaches envisioned to manage unmanned flights in metropolitan areas. They propose unstructured airspace except in congested flight areas or in proximity to manned operations. Furthermore, they propose a hybrid ATC service model with strategic traffic flow management conducted by an automated, centralized provider and tactical detect and avoid handled by the aircraft. The identification of airspace availability is essential for these proposals in order to delineate regions where congestion is likely to occur, where greater airspace structure may be necessary, and where ATC services may become overwhelmed.

Various authors have previously attempted to characterize airspace availability for emerging low altitude operators. References [19] and [30] displayed how surface-level controlled airspace and commercial flight operations may exclude new operators from significant proportions of major cities. Reference [21] demonstrated how terrain and obstructions (such as buildings) may affect traffic structure. A list of relevant airspace constructs was compiled by [22] and included terrain/obstructions, controlled airspace, airport procedures, and SUA. Finally, [8], [9] introduced a topological analysis framework to identify airspace free from obstructions for sUAS operations. The work displayed how keep-out geofences around surface obstructions and terrain limited viable flight routes and affected feasible infrastructure locations. The analysis was limited in its application, however, as it did not consider the influence of airspace constructs other than obstructions/terrain, was computationally intensive, and was not applied above 122m (400ft) Above Ground Level (AGL).

This paper expands upon these previous studies by developing an approach to identify potentially accessible airspace for UAM operations in a given metropolitan area.

## III. AIRSPACE AVAILABILITY ANALYSIS

### A. Modelling Airspace Constructs

The safety and efficiency of air traffic is managed through the designation of various airspace volumes with specified properties; we call these volumes "airspace constructs". Each construct may or may not support UAM flight depending upon equipage, performance, or integration requirements set by ATC. Airspace outside of all constructs is automatically assumed to be accessible to UAM aircraft. Table I displays seven constructs that are frequently present in low altitude airspace; a short description of their potential impact on airspace availability is provided.

1) *Obstacle and Terrain Clearance (OTC)*: Aircraft are protected from flight into obstacles or terrain through vertical and lateral separation requirements specified through §91.119 of the Federal Aviation Regulations (FARs) in the United States (US). Terrain and obstacle geometries were retrieved from public databases for the case study.

2) *Airport Controlled Airspace (ACA)*: Entry into Class B, C, & D controlled airspace in the US requires, at a minimum, that two-way communication is established with the tower controller. UAM operations could therefore be excluded from these airspace volumes by a controller (e.g. for workload or safety reasons). Controlled airspace volumes were generated from the FAA 28 Day National Airspace System Resource, effective Jul 1, 2018.

3) *Small UAS FAR Part 107 Airspace (sUAS 107)*: Part 107 of the FARs authorizes sUAS to automatically operate at up to 122m (400ft) AGL in Class G airspace. Furthermore, the FAA defined facility maps for every airport controlled airspace where sUAS may operate with permission from third-party service providers in the Low Altitude Authorization and Notification Capability (LAANC) program. This airspace may be unavailable to UAM aircraft due to the chance of an encounter with a sUAS or priority issues with LAANC reservations. Facility map boundaries were obtained from FAA Open ArcGIS data.

4) *Airport Approach and Departure Procedures (AP)*: The arrival and departure of aircraft at airports is the most common urban airspace operation today. Due to the volume and size of aircraft on these procedures, it is unlikely UAM aircraft will be able to access active procedures. However, when these procedures are inactive (due to airport configuration) or do not contain an aircraft, ATC may authorize crossings of the procedures.

To model airport arrivals and departures, it was assumed that large-scale UAM and UAS integration will require commercial aircraft to fly Instrument Approach Procedures (IAPs) or Standard Instrument Departure (SID) procedures irrespective of weather conditions. A data-driven flight procedure simulation technique from [15] was adapted to model the airport procedures for San Francisco International Airport (SFO) and Oakland International Airport (OAK). Procedure definitions were obtained from the FAA Coded Instrument Flight Procedures, effective Dec 6, 2018.

5) *Special Use Airspace (SUA)*: SUA protects aviation or surface activities of a unique nature. While most types of SUA are uncommon within cities, Temporary Flight Restrictions (TFRs) and prohibited airspace may significantly impact UAM airspace access. Prohibited airspace may permanently preclude access to specific areas. TFRs commonly appear in cities around large, open-air stadiums, but are generally active for less than 50 hours per year. However, TFRs around baseball stadiums may limit UAM flights for as many as 400 hours per year. TFR volumes were defined based upon NOTAM FDC 7/4319.

6) *Minimum Vectoring Altitudes (MVA)*: Air traffic controllers may vector aircraft off of established procedures subject to minimum altitude limits. These limits therefore represent the altitude below which a UAM aircraft is certain to not encounter a commercial aircraft in instrument conditions. Minimum vectoring altitude charts were obtained from the FAA Aeronautical Information Services.

7) *Special Flight Rules Area (SFRA)*: SFRAs are currently defined in three major US cities. In Washington, DC, the SFRA may exclude UAM operations all together. However, the New York and Los Angeles SFRAs enable aircraft to pass through airport controlled airspace without the need to receive clearance from controllers. This second type of SFRA has been proposed as a means to provide UAM aircraft access to more airspace [22], [28], [30].

## B. ATC Integration ConOps

Each of the airspace constructs presented above may or may not impact airspace availability for UAM operators. Their impact depends upon if and where they exist in an urban area, as well as the integration ConOps used by ATC. Four different ATC integration ConOps scenarios are defined in which UAM aircraft are constrained by different airspace constructs as shown in Table II. All scenarios exclude flight in proximity to terrain/obstructions and allow access to SFRAs that support small aircraft operations.

1) *ATC Excluded*: UAM operations are constrained to airspace that does not require any interaction with ATC. Access to airport controlled airspace and SUA is excluded. This scenario minimizes controller workload, requires no regulatory change, and enables UAM access to significant uncontrolled airspace in visual meteorological conditions.

2) *Fully Segregated*: UAM operations are constrained to operate in airspace that is not used by part 107 authorized sUAS or commercial aircraft on instrument flight plans. This scenario excludes access to all airport procedures, SUA, Part 107 sUAS airspace, and airspace above the minimum vectoring altitudes. This ConOps separates all airspace users into independent airspace volumes.

3) *Statically Integrated*: UAM operations may access airspace that is not contained within an active or inactive airport procedure. In this scenario, part 107 authorized sUAS and other UAM aircraft may simultaneously operate in low altitude airspace thus requiring some form of separation and priority assignment scheme. However, potential conflict scenarios between UAM and large aircraft are avoided in any airport configuration by protecting both active and inactive procedures.

4) *Dynamically Integrated*: UAM operations are excluded only from airport procedures that are actively in use for the current airport configuration. This ATC ConOps is the most integrated scenario considered in our analysis. It would require UAM operations to be aware in near real-time of changes to airport configuration in order to vacate airspace inside recently activated procedures [30].

TABLE II: Airspace constructs that may influence UAM operations in four ATC integration ConOps scenarios.

Airspace Constructs	ATC Excluded	Fully Segregated	Statically Integrated	Dynamic. Integrated
OTC	x	x	x	x
SFRA	x	x	x	x
Active APs		x	x	x
Inactive APs		x	x	
SUA	x	x		
MVA		x		
sUAS 107		x		
ACA	x			

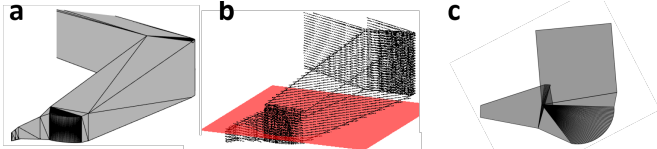


Figure 1: Illustration of pre-processing steps (a) a mesh of the surface of a 3D construct model; (b) sampled boundary points and a horizontal plane at  $h$ ; (c) sliced 2D obstacle

### C. Geometry Processing to Identify Available Airspace

Each 3D airspace construct is represented as a polygon mesh, which is an ordered set of vertices, edges, and faces that define the construct. To obtain the unavailable airspace (i.e. airspace inside the construct) at a given altitude  $h$ , we slice the constructs by a horizontal plane at  $h$ .

The key step in processing large-scale, geometrically complex construct data is boundary point sampling of the unstructured polygon mesh. To slice the unstructured mesh model, we sampled an ordered set of boundary points of each 3D construct at desired altitudes  $h$ , as illustrated in Figure 1. Specifically, we generated a set of regularly spaced boundary points for each face of the construct at multiple altitudes. Then, we constructed a set of 2D obstacle polygons from the boundary points. Using the boundary points, instead of expensive grid or tessellated structures, reduces computational load and is necessary to handle large-scale (city-wide) construct data.

Finally, following the topological approach in [8], [9], we compute the alpha-shape of the points, where alpha represents the safety radius of the design aircraft based upon its navigational accuracy and flight performance. The available airspace is the complement of the alpha-shape, as shown in Figure 2.

### D. Airspace Availability Metrics

After the available airspace over a Region of Interest (ROI) is generated for each ATC ConOps scenario, it is used to provide insight into two basic network design questions:

- 1) How does airspace availability affect the markets that can be served by UAM?
- 2) How does airspace availability influence the efficiency of UAM flights?

We define four metrics to give *quantitative* answers to the above questions. Each metric takes a horizontal, 2D

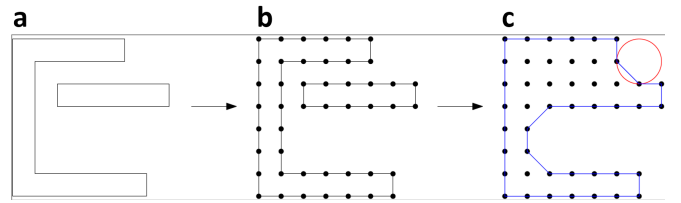


Figure 2: Illustration of alpha shape processing (a) 2D obstacle polygon that is a cross-section of some 3D construct; (b) sampled boundary points; (c) the alpha shape (in blue) connects every pair  $p, q$  of points whenever a radius- $\alpha$  circle (in red) has  $p, q$  on the boundary and no points are inside. (Note that the two obstacles are merged because the channel between them is too narrow for an aircraft to fly through.)

slice of the available airspace (formally: a cross-section of the airspace at a given altitude) as the input, and outputs a number characterizing the airspace availability at the altitude (the "quality" of the airspace for potential UAM use). We focus on cross-sections because envisioned UAM flight profiles operate enroute at a fixed altitude (our approach may be extended to layered airspace or full 3D trajectories in future work). Furthermore, it is informative to observe how the availability metrics change with the altitude. The calculation process and rationale for the metrics are presented below, and an application of the metrics is demonstrated in Section IV.

1) *Percentage of Available Airspace*: The most basic metric is the percentage of the total airspace in the study's ROI that is available to support UAM. It is the ratio of the area of the available airspace at the given altitude  $h$ ,  $AA(h)$ , to the total area of the ROI, or  $100 \cdot \text{area}(AA(h)) / \text{area}(\text{ROI})$ . In particular, at the surface-level ( $h = 0$ ) this metric provides an impression of how much of the metropolitan area UAM could possibly access.

Furthermore, since access to open water or rural regions is not as valuable to a UAM network as access to city centers, we also define a modification of the metric: *Percentage of Accessible Population*, that UAM could potentially reach, or  $100 \cdot \text{pop}(AA(h)) / \text{pop}(\text{ROI})$ . Population accessibility was estimated by re-gridding 2010 U.S. Census block-level data into 0.1 NM squares and determining if the centroid of each square resided beneath  $AA(h)$ . As an example, 44% of the airspace is available and 48% of the population is accessible in the ROI displayed in Figure 3. For airspace above approximately 152m (500ft) AGL, this metric has limited utility as it no longer serves as a proxy for surface population access.

2) *Connectivity of Available Airspace*: While the percentage of available airspace gives a first impression of accessibility to UAM flights, a more detailed look may be needed to distinguish between two cases:

- the airspace forms a single connected region vs.
- the airspace comes in many small chunks.

To consider this, sub-volumes of fragmented available

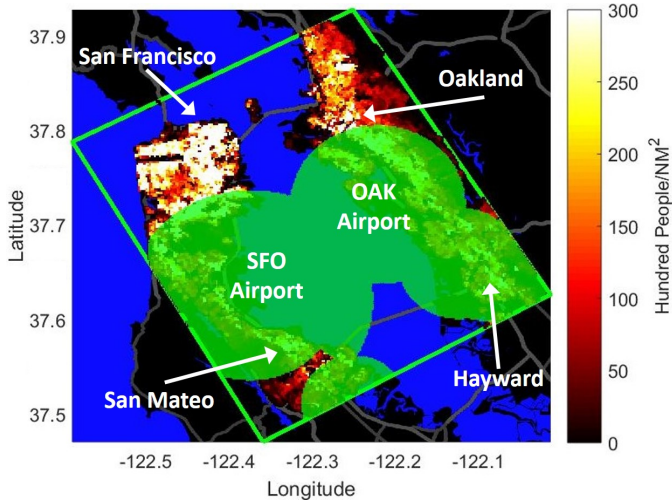


Figure 3: 44% of the airspace and 48% of the population is accessible outside surface-level, airport controlled airspace (green) in the San Francisco ROI (the rotated rectangle)

airspace (i.e. connected components) are identified. These sub-regions reveal areas of the ROI that may require circuitous routing (potentially beyond the study boundary) or vertical maneuvering to connect. For example, the available airspace (44% of total ROI) in Figure 3 has three fragmented components: the top one accounts for 79% of the available airspace, while remaining two account for 21% of the airspace. Perhaps more informative, 97% of the accessible population resides in the largest sub-region.

3) *Convexity of Available Airspace*: We also consider a measure of the convexity of each connected component  $CC$  of the airspace. To do this, we lay down a dense grid and define the *straight path support*, or *convexity* metric as the percentage,  $100 * |\{p, q : pq \subset CC\}| / |all\_gridpoint\_pairs|$ , of pairs  $p, q$  of gridpoints for which the segment  $pq$  lies within the connected component. For a convex region (where any two points can be connected by the straight path), the metric will give a score of 1, while increasingly irregular airspace shapes with offshoots, lobes, or holes would have a score progressing towards zero. A measure of convexity is a useful indicator for the efficiency of potential routes in the airspace and the dispersion, rather than concentration, of flights in the airspace. For example, the convexities of the three sub-regions in Figure 3 moving clockwise from top to bottom are 95%, 98%, and 96%.

4) *Route Deviation within Available Airspace*: Our final metric provides greater insight into the efficiency of potential UAM operations. For two points  $p, q$  in a connected component of the airspace, let  $SP(p, q)$  denote the length of the actual possible shortest  $p$ - $q$  path within the airspace. The *stretch*  $s(p, q) = SP(p, q) / |pq|$  of the pair signifies the deviation of the path from the straight line  $pq$ . Our *deviation* metric  $\sum_{p, q} s(p, q) / |gridpoints\_pairs| * 100$  is simply the average stretch for all pairs. Since the stretch between arbitrary gridpoints is, perhaps, not that interesting, we calculated the stretch only between 18

Points of Interest (PoIs) in the San Francisco Bay Area; the PoIs were selected to capture a spread of major population, financial, recreational, and tourist locations.

For an example, Figure 4 displays the shortest paths between the 18 PoIs at 366m (1200ft) Mean Sea Level (MSL). The greatest path stretch is 901%, and the average path stretch is 47% (shortest paths are only calculated for unobstructed PoIs). The path stretch provides insight into the efficiency of flight on a specific route, and the deviation metric gives an estimate of the potential efficiency of the whole network. We believe that images like Fig. 4 may be useful when identifying areas or corridors where flight density may increase due to obstructed airspace.

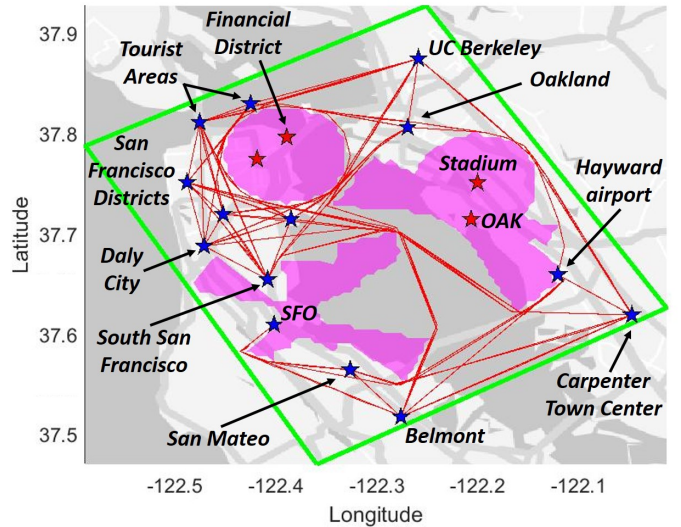


Figure 4: Shortest path connections between PoI at 366m (1200ft) MSL in the fully segregated ATC scenario

#### IV. CASE STUDY

The approach introduced above to identify potentially available airspace for UAM operations is demonstrated in this section through a case study. The approach is readily applicable to other locations as well.

##### A. Selection of Case Study Area

The influence of the various airspace constructs on UAM airspace availability is dependent upon city topology, weather, and security, among other factors. Especially impactful is the proximity of airports to the downtown area due to their controlled airspace, procedures, and comparatively low minimum vectoring altitudes. Other relevant factors include airport runway configuration, geography, and complex metroplex interactions.

Considering these factors, the San Francisco Bay Area was selected as an exemplar as it has two major airports moderately close to one another and the region's city centers. This creates complex metroplex interactions and airspace availability patterns that may not have been intuitive. Furthermore, San Francisco was a previous case study for numerous UAM works [1]–[3], [5], [7], [19].

## B. Application to the San Francisco Bay Area

A rectangular ROI was defined to encompass a majority of the densely populated regions of San Francisco, Oakland, Hayward, and San Mateo. The following airspace constructs were modeled within the ROI: 13 controlled airspace volumes, 332 sUAS facility map volumes, 184 airport procedures at SFO and OAK, 17 minimum vectoring altitudes, and 2 frequent TFRs. Procedures for San Jose Intl. Airport (SJO) were also modeled, but they did not interact with the ROI at the altitudes of interest. The ROI contains no SFRA and does not have prohibited airspace.

The topological approach from III-C was used to identify airspace outside any of the constructs present in each ATC scenario displayed in Table II. As this study was initially focused on identifying all potentially available airspace, both the "keep in" aircraft geofence and "keep out" airspace construct geofence of the alpha shape method were set to zero (i.e. the airspace directly up to the edge of each airspace construct was considered as available).

After applying the topological approach, the four metrics introduced in subsection III-D were calculated and images displaying the airspace, population, and routing availability were produced for the case study.

## C. Results

Figure 5 shows variation in available airspace by ATC scenario and flight altitude. Detailed plots of airspace availability at six altitudes are presented in Figure 6. Unavailable airspace contained within each of the constructs has been color coded to display its influence. A number of insights concerning airspace assessment for UAM integration may be gained through inspection of Figure 6. These insights display the utility of the geometric approach for airspace assessment developed in this paper.

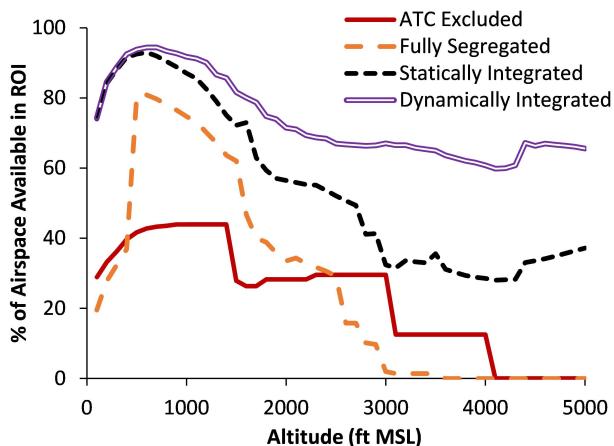


Figure 5: Total airspace availability by scenario and altitude

At 30m (100ft) MSL terrain and obstacles (indicated in black in Figure 6) penetrate the airspace on both sides of the bay and within the San Francisco metropolitan area. These obstructions prevent flight in about 25% of

airspace containing about 50% of the population for all four ATC scenarios. In scenarios 3 & 4 the airspace required for airport arrival and departure procedures is nearly negligible at 30m, and since UAM can access controlled and part 107 airspace freely, it leaves substantial un-obstructed airspace. Exclusion from controlled airspace and part 107 airspace in scenarios 1 & 2, respectively, reduces airspace availability to below 30% and population accessibility to below 15% as shown in Table III.

Ascending to 152m (500ft) MSL, airspace is unaffected by a majority of the terrain and obstacle obstructions. The inability to access controlled airspace remains a significant limiter for scenario 1. Interestingly, while the two TFRs for the baseball stadiums in Oakland and San Francisco remove only a small percentage of the airspace (12%) in scenario 2, they are located in densely populated regions and prohibit accessibility to 25% of the population. These TFRs are active during afternoon and evening hours up to 400 hours per year.

Furthermore, available airspace is maximized in the San Francisco Bay Area from 183-305m (600-1000ft) in scenarios 2, 3, & 4 as apparent in Figure 5. This altitude band maximizes airspace availability because the influence of low altitude airspace constructs (terrain, surface obstacles, and part 107 airspace) diminishes and the influence of higher altitude constructs (minimum vectoring altitudes and airport procedures) has yet to set in.

Returning to Figure 6, airport arrival and departure procedures encompass a great deal of airspace by 457m (1500ft) MSL. At this altitude the interaction between procedures from OAK and SFO segments the airspace of scenarios 2 & 3 such that the north bay and south bay do not have a feasible flight route connection within the ROI. While these regions may be connected through flight just outside the ROI (or at lower altitudes), the low convexity of the airspace and extensive route diversions makes it potentially less useful to support efficient UAM flights.

At higher altitudes airspace availability generally continues to reduce, and does so dramatically in scenarios 1 & 2. It is noteworthy that there is a slight increase in airspace availability in scenario 1 as aircraft can fly above controlled airspace top altitudes in some cases, but this diminishes too as other controlled airspace shelves appear. The appearance of the minimum vectoring altitudes in scenario 2 rapidly reduces availability to zero, and the presence of more and larger procedure containment volumes in scenarios 3 & 4 fragment the airspace and reduce availability. Table III lists a sample of the computed metrics for the four ATC scenarios at six altitudes.

## D. Discussion

The structure of available airspace varies widely between the four ATC scenarios, depending on which airspace constructs UAM operations are excluded from. While the general trends seen in San Francisco may hold true in other

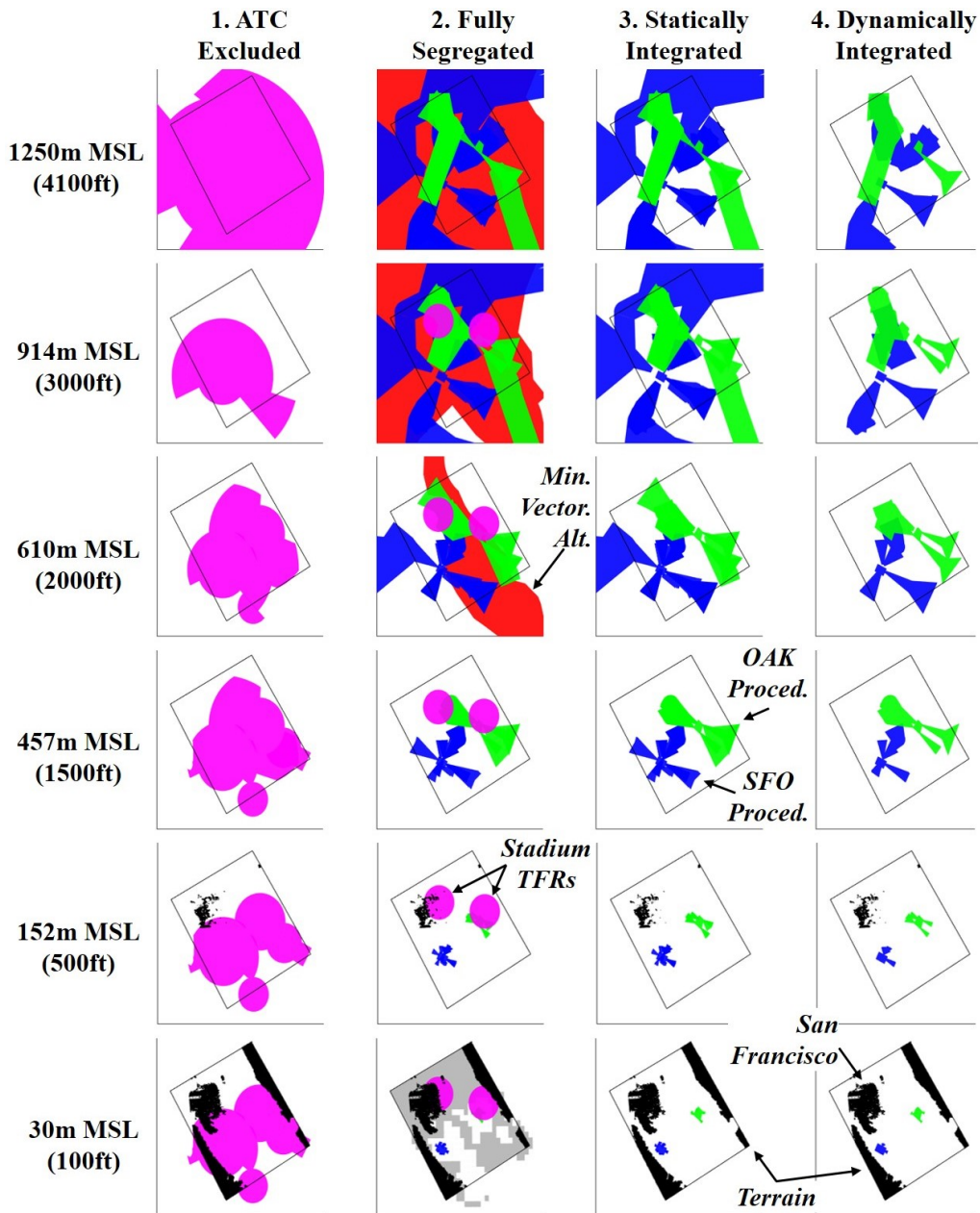


Figure 6: Available airspace (white) in San Francisco for four ATC scenarios. *black: structures/terrain, pink: airport airspace/SUA, blue: SFO procedures, green: OAK procedures, red: min. vectoring altitudes, grey: part 107 sUAS airspace*

cities, the actual airspace and population accessibility for cities with distinct layouts and aviation activity may be quite different. For example, New York will likely have much less available airspace due to more prevalent surface obstructions, controlled airspace, and airport procedures while Atlanta may have very few limitations as its major airport is located well away from its city center. These differences point to the value of a geometric airspace assessment approach to rapidly identify integration opportunities and challenges for new aviation operators in a specific city.

3D airspace availability and population accessibility data, such as that introduced in Figure 6, may be useful for the design of UAM networks and routing. More specifically,

population accessibility at the surface (approximately up to 152m (500ft) AGL) outlines where vertiports may potentially be placed and UAM services provided, as discussed in Section V below. Airspace availability above 152m AGL, on the other hand, is valuable to assess how aircraft routing and network flows may be designed.

As an example, Figure 7 displays the shortest path routing between 18 PoIs in the San Francisco Area for each ATC integration ConOps scenario at 457m (1500ft) MSL. PoIs that reside beneath available airspace are indicated with blue stars while those beneath an inaccessible airspace construct are colored red. Table III also presents the number of accessible PoIs for each image.

TABLE III: Available airspace metric values for altitudes and scenarios presented in Figure 5.

Altitude (MSL)	ATC Scenario	Available Airspace	Accessible Population	Accessible PoIs
30m (100ft)	1	29%	14%	4
	2	20%	10%	3
	3	74%	54%	14
	4	74%	54%	14
152m (500ft)	1	42%	37%	5
	2	81%	61%	12
	3	93%	86%	14
	4	94%	86%	15
457m (1500ft)	1	28%	32%	5
	2	62%	54%	12
	3	72%	84%	16
	4	82%	92%	18
610m (2000ft)	1	28%	34%	6
	2	34%	44%	8
	3	56%	73%	13
	4	71%	87%	16
914m (3000ft)	1	30%	34%	9
	2	2.0%	0.6%	0
	3	32%	45%	8
	4	67%	85%	15
1250m (4100ft)	1	0%	0%	0
	2	0%	0%	0
	3	28%	42%	5
	4	60%	74%	11

Several insights into route structure and UAM service to the representative PoIs may be gained from Figure 7. First, regions of readily connected airspace may be identified. For example, exclusion from controlled airspace in the first scenario prohibits flight to a majority of the PoIs, but does enable west San Francisco to Berkeley connections in the north bay. The dynamically integrated scenario, on the other hand, is the only one to support a viable route within the ROI between the north and south bay areas.

Second, the shortest path routings display the relative value of accessing different airspace constructs. For example, while the fully segregated scenario opens up a large proportion of airspace compared to the ATC excluded scenario (62% compared to 28%), its benefit for flight routing is actually quite small as the north and south bay areas remain fully separated and a TFR in San Francisco forces significant flight diversions.

Finally, images like Figure 7 are useful to identify bottleneck areas. For example, all flights must pass just west of SFO in the dynamically integrated scenario to connect the north and south bay. There is a similar density of flight routes skirting north of the inaccessible airspace between San Francisco and Oakland. Both areas represent potential congestion points in this UAM flight network.

## V. APPLICATION TO ATC DESIGN

The geometric approach to assess airspace availability presented in this paper may be used to evaluate a variety of design tradeoffs for UAM networks and low altitude ATC. More specifically, the 2D and 3D modeling artifacts of the approach may support various analyses.

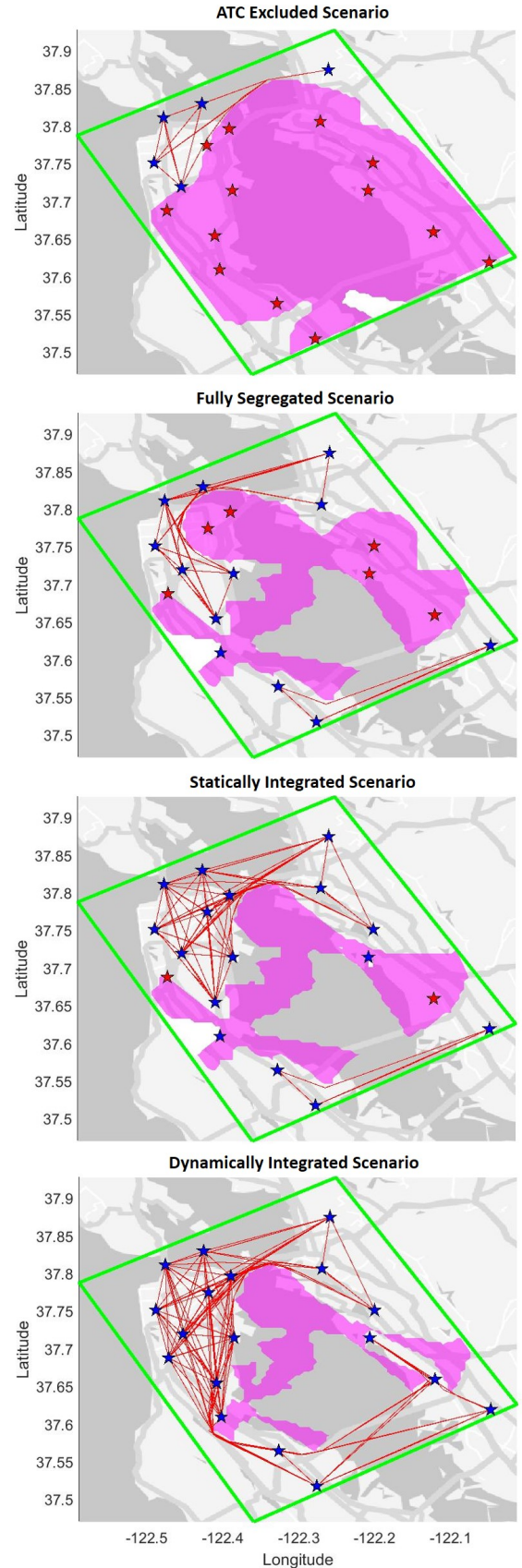


Figure 7: Shortest path routing at 457m (1500ft) MSL between PoIs for four ATC scenarios



1) *Vertiport Siting*: In order for UAM networks to provide competitive services, vertiports must be located near demand centers and support high throughput operations. A key factor influencing feasible vertiport siting is airspace integration of the flight procedures. Viable vertiport locations must not only be capable of supporting the physical footprint of the facility, but must also have unobstructed approach and departure paths (i.e. a "cone of approach") that connect to the en-route network without conflicting with other vertiport, airport, or airspace operations.

The data generated in this study may support vertiport siting from the perspective of feasible airspace integration. Conceptually, the airspace required to support vertiport approach and departure paths in one direction can be modeled as a cylinder with height  $h$  and radius  $r$ . These dimensions are set based upon the performance capabilities of the design UAM aircraft. For perspective, the NASA UAM Grand Challenge recently suggested that the minimum approach and departure gradient for vertiports should be 8:1 up to 305m (1000ft) AGL [23]; this corresponds to  $h=305\text{m}$  and  $r=1219\text{m}$ . Similar to the identification of available airspace, an alpha shape approach may again be used to find areas where such a cylinder may be placed without intersecting obstructed airspace. More advanced modeling may employ stepped cylinders as shown in Figure 8.

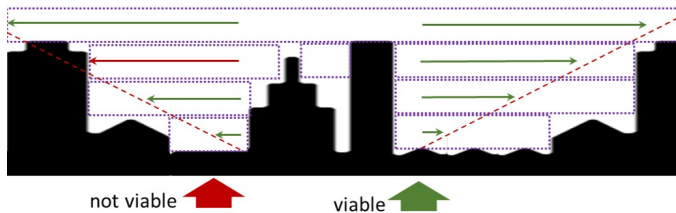


Figure 8: Notional use of obstruction data to assess viable vertiport siting

2) *Risk-Based Airspace Assessment*: EUROCONTROL has proposed that "airspace assessment involves taking a critical look at a certain airspace volume...to identify the types of operation that will be conducted in that airspace, and examining the associated air and ground risks" [12]. The approach in this paper supports such an analysis.

First, this work identifies and models 3D airspace volumes with specific operational and risk characteristics, such as volumes in which sUAS or commercial aircraft are likely to be operating, volumes near terrain or obstructions, or volumes with unique security and population exposure concerns. Future work that considers historical flight trajectory data may enhance the ability of this approach to estimate the risk of airborne conflict in each airspace volume.

Second, the calculation of population beneath each airspace volume, as well as beneath the shortest path flight paths, may be useful to support the evaluation of ground risks for flight in a specific airspace.

3) *System and Technology Tradeoffs*: The ability to identify available airspace readily lends itself to answering a variety of "what if" questions relevant to low altitude ATC or UAM aircraft design. For example, the influence of reducing the required separation minima between UAM aircraft and obstacles or other aircraft on airspace availability may be assessed simply by adjusting the keep-in geofence, or alpha shape radius. Comparing various separation scenarios would provide regulators and operators with a clear understanding of the airspace availability and population accessibility increases that could be achieved.

As another example, the effect of enhancing the accuracy of commercial aircraft navigational performance may also be evaluated through this approach. The flight procedures presented in this analysis assumed a Required Navigational Performance (RNP) of 1, which prescribes a containment boundary of 2NM on either side of the procedure centerline. Future work will re-evaluate airspace availability with RNP values of 0.5 and 0.1.

Finally, the data produced through the proposed geometric approach is also appropriate to support the identification of bottlenecks in the en-route network and estimate maximum route throughput. Reference [17] demonstrated how maximum flow rates at a given flight level may be calculated by applying graph theory and mincut analysis. More specifically, the inaccessible airspace volumes identified at each altitude may be cast as nodes in a directed graph, and the shortest arcs that connect them represent the potential bottleneck points of the flight route. Throughput at these bottleneck points may then be calculated based upon UAM flight profile and separation requirements. Airspace capacity may also be calculated based on peak throughput as demonstrated in [6].

4) *Noise Based Routing*: Noise is a major concern for dense operations and continues to be one of the primary inhibitors to the integration of emerging UAM operations. Even today, runway configurations and arrival departure procedures are designed based on noise footprint and annoyance studies around airports. These studies for future UAM operations will be highly sensitive to actual network routes. Identifying the available airspace will therefore be quite critical to evaluate the impacted population and generating noise maps (similar to [4] which assumed the entire airspace to be available) based on feasible network design and vertiport siting. This in turn will then also dictate the vertiport procedures and operational configurations.

## VI. CONCLUSIONS AND FUTURE RESEARCH

This paper presented a geometric approach for assessing the available airspace for emerging UAM operations. Seven airspace constructs in an urban area were accounted for and four ATC integration ConOps scenarios were identified and studied. Metrics to quantify the quality of available airspace were also defined. A case study of the San Francisco

area was conducted to demonstrate the application of the approach. The evolution of the available airspace for each of the ATC scenarios was also presented based on the appropriate constructs.

The approach developed in this paper is useful as a first step for answering questions pertaining to traffic structure and ATC services for emerging UAM operations. A sample of such applications were discussed in Section V.

Future work will make the approach more comprehensive by including additional airspace constructs and user related data such as special conservation areas (a type of SUA), historical VFR data, actual flight trajectory data, and so on. The authors also seek to conduct more risk-based assessment with population exposure and conflict probability. Another area of research is improvement of computation speed. Parallel processing is a potential candidate. This could enable the approach to be eventually released as a standalone plug and play tool for direct airspace assessment or any further research based on it.

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