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A Concept for Procedural Terminal Area Airspace Integration of Large Uncrewed Aircraft Systems at Non-Towered Airports

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***Abstract*—Uncrewed aircraft systems are expected to revitalize traffic at under-utilized airports. These airports are often located in uncontrolled airspace and do not have an operating control tower to provide separation services for approaching aircraft. The lack of operating control tower presents a unique challenge for the integration of uncrewed aircraft at these non-towered airports. This paper offers a methodology to systematically assess traffic activities and quantify flight behaviors of crewed aircraft using historical flight data. To integrate uncrewed traffic, especially in off-nominal flight situations such as during a lost command and control link, this paper proposes a concept of a holding stack above the traffic pattern airspace to handle increased traffic uncertainty and to provide safe integration procedures. Twelve non-towered airports, relevant for initial cargo uncrewed aircraft operations across Germany, California, and Texas, and their airspace environments are investigated. Results are presented on the viability of a holding stack in the analyzed terminal area airspace and the influence of crewed aircraft's historic flight behavior on different integration procedures.**

***Keywords*—UAS, non-towered airport, traffic pattern, holding stack, LC2L**

I. Introduction

Large uncrewed aircraft systems (UAS) offer many benefits, such as better asset utilization, the ability for a remote pilot (RP) to operate the aircraft from anywhere, and improved economics [1]. Among the many use cases enabled by this technology (e.g., firefighting, inspection work, and public safety), previous work has shown that the regional air cargo use case is one of the most likely initial use cases for remotely piloted aircraft [2]–[4]. A significant portion of current regional air cargo flights use airports without an operational control tower (Note: in this work, the more colloquial "non-towered" descriptor will be used to describe airports without an operational control tower) [5]. These non-towered airports are commonly located in uncontrolled airspace and aircraft pilots following Visual Flight Rules (VFR) do not receive Air Traffic Control (ATC) separation services when approaching these airports. Non-towered airports are expected to play an increasingly important role in future air mobility concepts [6]. Larger, fixed-wing regional cargo UAS (with a maximum takeoff weight of up to 25 tonnes) are expected to take advantage of the less busy non-towered airports throughout the world [1].

In both Europe and the United States (US), thousands of non-towered airports are currently under-utilized [2], [3], [7], [8]. They are expected to be leveraged as part of new and emerging air traffic concepts. However, it remains to be determined how UAS can be integrated at non-towered airports, given that crewed traffic behavior is more uncertain and less predictable compared to operations at towered airports [9]–[11]. Pilots under VFR individually decide how to integrate into the terminal area of non-towered airports based on ongoing traffic activities, wind conditions, and personal preferences. This variability makes prediction of VFR traffic intent around non-towered airports more uncertain compared to operations under Instrument Flight Rules (IFR), which have to file a flight plan prior their flight. Additionally, there are limited data on operating schemes, traffic behaviors, and VFR intent prediction at non-towered airports. Therefore, a

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common operating environment for large UAS flying under IFR or new flight rules will be needed in and around non-towered airports. This research aims to answer the following questions: First, how could UAS be procedurally integrated into the terminal area of non-towered airports, which rely heavily on visual observations, especially with crewed aircraft in the airport vicinity? Second, how might crewed aircraft track history and UAS procedural integration options affect UAS flight planning at non-towered airports?

This work proposes a concept for procedural terminal area integration of large UAS at non-towered airports whereby, where appropriate, a holding stack over the airport with different holding layers is implemented, providing the UAS space in which to loiter when the traffic uncertainty in the terminal area exceeds a pre-determined threshold. In the holding stack, UAS could safely monitor ongoing terminal area activities of crewed aircraft before integrating into the standard traffic pattern (TP) of the airport. The exact means of this monitoring are outside the scope of this paper.

This paper maintains a similar scope to the authors' previous works [2]–[5]. Other UAS vehicle types, such as electric vertical takeoff and landing (eVTOL) aircraft, are not explicitly out of scope in this concept, though the focus is primarily on larger fixed-wing aircraft (e.g., Cessna 208). These types of UAS will likely fall into the "certified" category, which is defined by the European Union Aviation Safety Agency (EASA) as operations with the highest safety risk and requires certification of the UAS operator, the UAS and the RP [12]. Note that there are no currently "certified" civilian UAS operations. It is assumed (see previous work) that initial larger UAS operations are likely to replace current regional air cargo operations and that such operations will be "certified". Further, it is assumed that the UAS can solely operate under IFR.

The paper will provide an overview about current crewed integration procedures and integration hurdles of UAS at non-towered airports in Section II. Section III will propose the foundational concept of this paper, a holding stack concept for UAS in terminal area airspaces to safely integrate UAS at non-towered airports. Accordingly, a methodology is introduced for systematically analyzing the terminal area airspace of non-towered airports. Using that methodology, Section IV will derive metrics and quantitatively assess historic crewed aircraft activities at twelve airports and discuss implications for potential UAS integration procedures. The final Section V presents concluding remarks and future work.

II. Background: Current Integration at Non-Towered Airports

A. Integration Procedures of Crewed Aircraft

The current integration procedures of crewed aircraft at non-towered airports depend on a few important factors, namely the flight rules under which the aircraft is flying, the meteorological conditions, and the presence of an appropriate Instrument Approach Procedure (IAP) for the active runway end(s) [13]. Note that, although there may be slight differences between operations in the US and Germany, the general rules described herein apply to flights in both countries.

1) Flight Rules and Meteorological Conditions: The flight rules under which an aircraft is operating govern the flight. There are two main flight rules: IFR and VFR. Under IFR, it is incumbent upon ATC to separate IFR aircraft from other IFR aircraft. In general, in the US, this separation is achieved at non-towered airports via the procedural paradigm of "one in, one out", whereby ATC will only clear one IFR aircraft into a terminal area at a time. In Germany, however, flights under IFR are not common in uncontrolled airspace and will not receive ATC services. To accommodate IFR flights at non-towered airports, Germany has established Radio Mandatory Zones (RMZ) around 27 non-towered airports [14]. Within an RMZ, all aircraft are required to establish a very high frequency (VHF) radio link to the ground and to listen to any communication on a designated RMZ radio frequency. Note that it is incumbent upon the pilot on board the aircraft flying under IFR to "see and avoid" and remain "well clear" of other traffic [15], especially aircraft operating under VFR. Under VFR, communication with ATC is generally not required, and the pilot on board must still "see and avoid".

The two meteorological conditions, visual meteorological conditions (VMC) and instrument meteorological conditions (IMC), will also dictate which flight rules can be utilized. Under IMC, only flights operating under IFR are allowed. Under VMC, flights can operate under VFR or IFR, the latter assuming that the pilot is rated for IFR operations and the aircraft has necessary equipage for IFR operations.

2) Integration of Crewed Aircraft Under IMC: At non-towered airports under IMC, the integration problem for an IFR aircraft is trivial, assuming the presence of an appropriate IAP. In the US, ATC will procedurally allow only one IFR aircraft at a time into the terminal environment, and VFR aircraft are not a concern, given that they may not operate under IMC. In this scenario, the crewed aircraft will fly the IAP down to the appropriate altitude, at which point the pilot on board visually identifies the runway and continues to land.

3) Integration of Crewed Aircraft Under VMC: At non-towered airports under VMC, however, the integration problem for an aircraft operating under IFR becomes significantly more complex, given the presence of VFR aircraft. The pilot on board an IFR aircraft must still "see and avoid" VFR aircraft in the vicinity. Normally, the IFR pilot would broadcast their intentions via air-to-air communication using VHF radio transmissions. However, IFR traffic usually has no priority over VFR traffic in the TP. As soon as the IFR aircraft has entered the TP, it is subject to the same right-of-way rules as VFR traffic. Generally, the pilot of the IFR aircraft has three options: to continue under IFR using the IAP, to continue under IFR using a visual approach, or to cancel IFR and continue under VFR. According to discussions with current regional air cargo pilots, the second and third options are quite commonplace in their operations. For the second and third options, the pilot then will integrate into the non-towered terminal environment using the standard TP for the airport. The airport TP is located at an altitude above the airport (typically 1,000 ft (~300 m) above ground level (AGL) [16]) that allows for pilots to visually assess ongoing traffic activities before safely descending towards the runway.

The altitude of the TP and the TP integration procedures can vary for different airspace environments, depending on the airport layout, the surrounding topography of the airport, and the individual skills and preferences of the pilot [16]. As seen in Fig. 1, there are several methods of entry into a standard TP. The Federal Aviation Administration (FAA) suggests using the 45° approach or the overhead join approach at non-towered airports, depending on the direction from which the aircraft is approaching [16]. In the US, a generic TP —per appropriate regulations and guidance —applies at most non-towered airports. In contrast, in Germany, a Visual Operation Chart (VOC) prescribes more directly the integration of crewed aircraft, see Fig. 2. In general, however, the two TP integration layouts follow the same procedures as described above. The UAS integration concept presented in this paper will assume VMC, in which traffic largely relies on TP integration procedures and represents the most complex integration environment at non-towered airports.

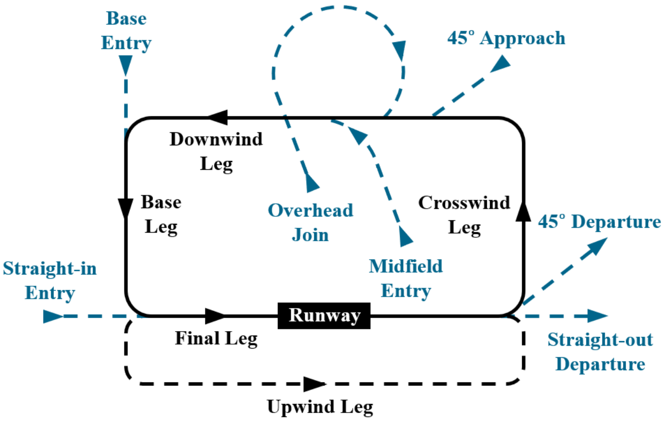

Figure 1: Standard airport TP scheme [17]

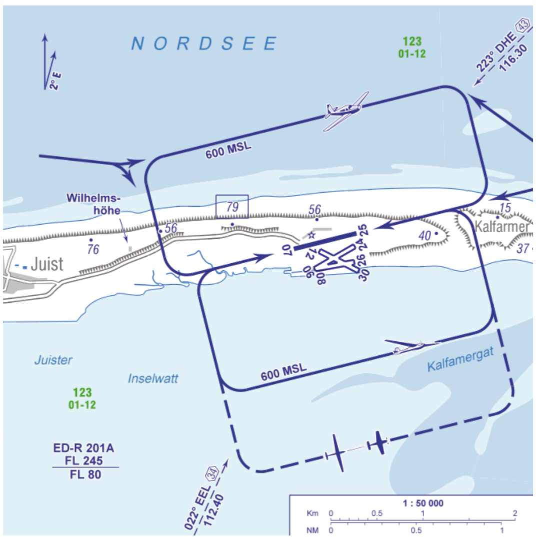

Figure 2: VOC of Juist (EDWJ) [18]

B. Integration Hurdles for UAS

1) Landing: At present, there are very limited options for large, fixed-wing UAS to integrate at non-towered airports and none of these options are currently approved for widespread, nominal usage. Military UAS, such as the MQ-9 Reaper, typically will execute a long, straight-in approach, the type of approach that the FAA, in Advisory Circular 90-66C, explicitly recommends against when traffic is present in the pattern [19]. Additionally, currently certified civilian autoland systems found on some airliners generally necessitate an appropriate landing guidance system (e.g., Instrument Landing System) and associated IAP, which often has a straight-in component. For smaller aircraft, such as those used for regional air cargo, the only currently-certified autoland system is for use in emergency only (e.g., the Garmin autoland system [20]). Although not currently certified, there have been advances made in autopilot and autoland systems that do not require an expensive landing guidance system [21]. For the purpose of this concept, it is assumed that such a system will be certified in the future and that such a system can fly a conventional TP with no other traffic in the pattern, confirm runway occupancy, and perform an automated landing. This assumption does not, however, imply that the UAS can merge and space with other traffic in a TP, only that it can fly a TP in an automated fashion and execute a landing.

2) See and Avoid: As discussed above, the pilot on board a crewed aircraft needs to "see and avoid" other traffic, especially traffic operating under VFR. A UAS, by nature, does not have a pilot on board. Therefore, it may only fly under IFR and systems such as Airborne Collision Avoidance System X (ACAS X), provide Detect and Avoid (DAA) and Collision Avoidance (CA) capabilities to the RP such that the RP can keep the UAS "DAA well clear" of other traffic [22], [23]. For the purpose of this concept, it is assumed that the UAS contains a certified onboard system, such as an ACAS X variant, and that such a system functions correctly in the more demanding terminal environment. Note that the development of such a system is still an area of active research, especially at lower altitudes. Additionally, a Ground-Based Surveillance System (GBSS) could be used as a local low-altitude radar to provide information about aircraft, especially non-cooperative aircraft without a transponder.

In summary, it is imperative that the RP has sufficient knowledge of the traffic at the airport. Nonetheless, absent a robust merging and spacing integration capability, it is feasible that there will be levels of traffic at a non-towered airport at which a UAS cannot be safely integrated, even if the RP has sufficient knowledge of said traffic. To further support UAS airspace integration in complex airspace environments, it can be expected that safe and efficient separation of UAS from VFR traffic (i.e., merging and spacing) in non-towered airport environments will be achieved through the provision of a digitalized airspace ecosystem. "U-space" is Europe's traffic management system for UAS operations that defines technical and operational requirements by providing a regulatory framework [24]. Initial U-space services such as UAS flight authorization, traffic information, network identification, and geo-awareness, which are generally provided by third-party service providers, will be required to enable UAS integration in airspaces with increased traffic densities. Additional U-space services such as conflict detection and resolution can be expected to provide safe and efficient separation procedures for UAS as well as traffic management strategies to integrate UAS together with crewed traffic in uncontrolled airspace such as at non-towered airports.

3) Lost Command and Control Link: The RP operates the UAS via the command and control (C2) link, through which the RP can upload commands and receive telemetry. However, in the event of a lost C2 link (LC2L) (i.e., the C2 link is severed), the RP is no longer able to operate the UAS, and the UAS will execute a LC2L procedure. In a LC2L procedure, the UAS is expected to follow the procedure automatically, only deviating if there is a DAA alert, which is assumed to be resolved automatically. The development of such procedures, especially for non-towered airport environments, is ongoing and procedures are not yet certified. To that end, RTCA, Inc. has published DO-400, "Guidance Material: Standardized Lost C2 Link Procedures for Uncrewed Aircraft Systems" [25]. Two recommendations from DO-400, Recommendations #13 and #14, discuss the need to define arrival, approach, and landing LC2L procedure guidelines and to "investigate the potential need to separate UA holding patterns from traditionally piloted aircraft holding patterns". This work aims to address these two recommendations for the non-towered airport environment.

C. Theoretical Integration Procedures of UAS

A UAS flying IFR is, as discussed in Section II-A3, generally assumed to fly an IAP. However, many IAP are straight-in approaches for landing and, if there is traffic in the pattern, a straight-in approach for landing is not recommended [16]. Further, a visual or VFR approach is often preferred for operational efficiency. It is assumed that, if a UAS is not able to land or integrate into the TP, the UAS will need to hold someplace until it is safe to land. Recalling the assumption that, for certain low levels of traffic, the RP can successfully integrate the UAS into the TP (here called a "visual-like" approach), these assumptions lead to five theoretical cases for UAS integration in VMC, see Table I. It is assumed that a UAS in a LC2L state is incapable of executing a "visual-like" approach. Although novel flight rules have been proposed in literature (see [26], [27]), no novel flight rules are assumed in this work.

TABLE I. Theoretical cases for UAS integration in terminal area airspaces at non-towered airports

Case	C2 Link	Traffic in TP	Anticipated UAS Behavior
1	Nominal	None	Execute IAP or "visual-like" approach
2	Nominal	Minimal	Execute "visual-like" approach
3	Nominal	Sufficient	Execute holding maneuver
4	Lost	None	Execute IAP
5	Lost	Any	Execute holding maneuver

These five theoretical cases indicate the need to measure the complexity of the traffic within the TP airspace volume, as well as the need for some sort of holding maneuver. This work proposes a holding maneuver to be applied in Case 3. A holding maneuver may also apply in Case 5, though further distinction based on the phase of flight is an area of future research. Inherent in the five cases is the assumption that traffic in the pattern can be detected and the complexity assessed and that there exist certain safety thresholds at which the UAS moves from one case to the next. Especially important is the determination of when the UAS should execute the proposed holding maneuver. In this work, however, these five cases are purely conceptual and a step towards a robust, real-world implementation. Although historic data is used to give a glimpse at what traffic might look like at a non-towered airport, it is crucial that, for a real-life application of this concept, some type of real-time traffic monitoring (e.g., a GBSS or U-space) is implemented. Further, without a rigorous safety analysis of that real-time data, these safety thresholds are very difficult to ascertain. However, metrics of complexity in the TP airspace volume can nonetheless be applied to assist in stepping towards future safety analyses and testing integration concepts in simulation. This work will discuss seven metrics and the implications that they might have for integration of UAS into non-towered environments.

III. Proposed UAS Holding Stack Concept and Methodology

Increased uncertainty and complexity in an airport environment can be caused by temporary factors such as poor weather conditions, runway unavailability, or traffic congestion. In these cases, at major hub airports, ATC might set up holding patterns in a multi-layer holding stack to queue arriving IFR aircraft over time until congestion has been cleared, for example. A prominent example is London Heathrow (EGLL), one of the busiest airports in the world, where four different holding stack locations are deployed to systematically separate arriving IFR aircraft [28].

This research proposes a holding stack concept for UAS to safely and systematically integrate into a non-towered airport in case of increased traffic uncertainties and complexities. The holding stack concept is intended to provide a space for UAS to loiter in a safe manner, for example due to traffic in the pattern, runway blockage, a loss of C2 link, or a combination thereof. Traffic management of the holding stack such as UAS integrating into the holding stack or from the holding stack into the airport TP and highly automated merging and spacing with other UAS and crewed aircraft could be managed by establishing a U-space ecosystem and providing digital services (see Section II-B2). The location of the holding stack should be sufficiently separated from traffic, while nonetheless being close enough to the TP that integration is feasible given the inherent uncertainty and complexity of the non-towered environment. Additionally, the holding stack should be close to the airport of interest so that the UAS can divert to the holding stack in the event of a safety threshold discussed in the previous section being exceeded without adding excessive distance and time to the flight. To meet these requirements, the proposed location of the holding stack is directly above the TP airspace of a non-towered airport, as depicted in Fig. 3.

Although unlikely that there will be a "one size fits all" approach to placing a holding stack at a non-towered airport, there are some general limitations: 1) The bottom of the holding stack will need to be vertically separated from historic traffic at the airport. 2) The top of the holding stack is limited by overhead traffic streams and relevant UAS performance characteristics, such climbing and descending capabilities. 3) If multiple UAS are allowed in the holding stack simultaneously, some means of holding stack management (i.e., entry, exit, direction) will need to be developed. Limitation 1 will be addressed in this paper, to assess the feasibility of the concept. Limitation 2 is partially addressed, though no consideration for UAS performance is taken. Limitation 3 will be explored in future work, following the assessment of feasibility, and establishing of metrics for quantitative description of the airspace around a non-towered airport.

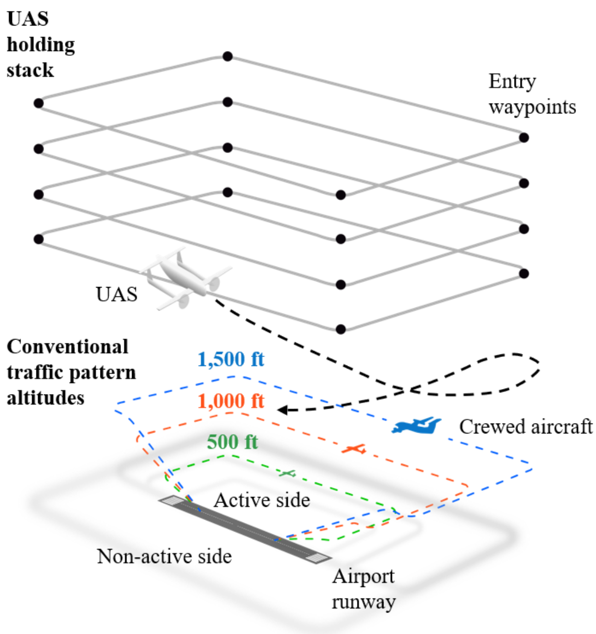

Figure 3: Conceptual scheme of the UAS holding stack above conventional TP altitudes

A holding stack location above the TP is expected to be safer than placing it next to the TP as lower traffic densities can be expected above conventional TP integration altitudes and UAS are able to enter the holding stack from any direction without crossing conventional TP integration altitudes. Conventional TP integration altitudes are standard altitudes where a crewed aircraft is recommended to integrate into the TP. Even though some non-towered airports have specific assigned TP integration altitudes, crewed aircraft are commonly expected to integrate into the TP at 1,000 ft (~300 m) AGL [16]. Depending on the performance characteristics of different aircraft, higher performance aircraft (e.g., jet aircraft) are expected to integrate into the TP at an altitude of 1,500 ft (~450 m) AGL, whereas lower performance aircraft (e.g., piston aircraft) may be expected to integrate into the TP at a lower altitude, as low as 500 ft (~150 m) AGL. The concept expects UAS to integrate from the holding stack into the TP at a conventional TP integration altitude based on the performance characteristics of the UAS (higher UAS performance, higher TP integration altitude) using recommended TP entry procedures.

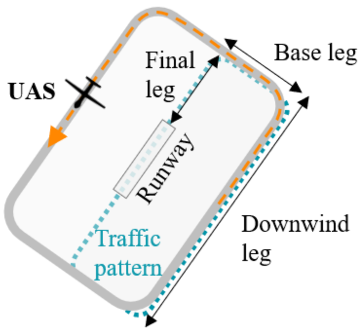

Figure 4: UAS holding stack design (top view)

The size of the UAS holding stack is proposed to be based on the size of the historically flown TP and will vary by airport. The size of the historically flown TP can be determined by assessing the airspace segments with the highest historic traffic densities. Based on the airspace segments with the highest historic traffic densities, the length of the TP legs such as downwind leg and base leg can be determined. The legs of the UAS holding stack will be determined by the legs of the TP and extended towards the non-active side of the airport by doubling their size, see Fig. 4 (if only one TP is active at that airport), subject to applicable terrain and airspace restrictions. Extending the holding stack towards the non-active side of the airport is considered important to allow UAS sufficient time and space to integrate from the holding stack with crewed aircraft coming from the non-active side of the airport. In short, it is expected that the holding stack will be twice the size of the historically flown TP.

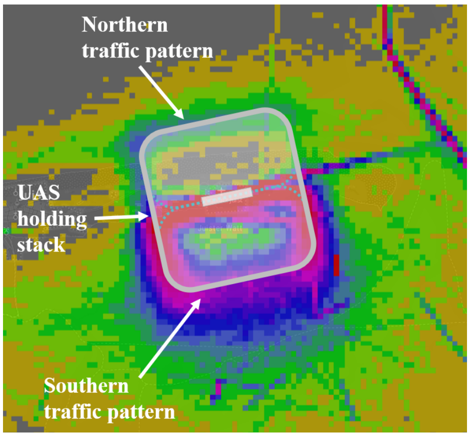

Figure 5: Juist (EDWJ) with two active TP (north and south of runway) and UAS holding stack

Airports with TPs on both sides of the runway are treated slightly differently. For example, Juist (EDWJ) is a non-towered airport located on one of the islands in the German North Sea. Juist has two active TPs, north and south of the runway respectively, which can be seen in its VOC in Fig. 2.

The traffic density heatmap of Juist shows that the southern TP has a higher traffic density than the northern TP over an exemplary altitude band of 1 to 3,000 ft AGL (~900 m) (see Fig. 5). In the case of two active TPs, the length of the UAS holding stack legs are determined by the TP on the same side of the runway, which in turn is determined according to the highest historic traffic density, as explained earlier in this paper. In other words, the holding stack is not simply double the size of the busier historically flown TP, but is an overlap of both TPs.

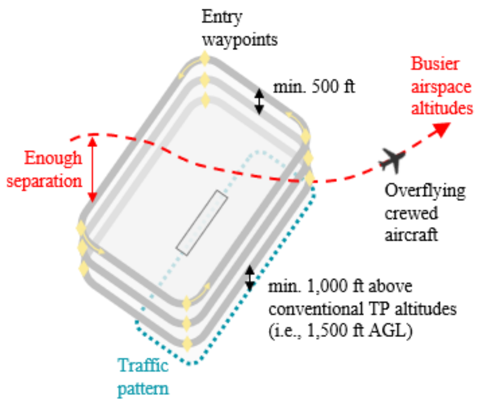

Figure 6: UAS holding stack design with layers

A holding stack for UAS is proposed to consist of different vertical layers, similar to ATC stacking arriving IFR aircraft in holding stacks at major hub airports, see Fig. 6. The lowest altitude at which the holding stack can begin will vary by airport, but generally will start at 2,500 ft (~760 m) AGL. The highest conventional TP altitude, that of jet aircraft (see Fig. 3), is at 1,500 ft (~450 m) AGL. The recommended overhead join approach is 500 ft (~150 m) above that, or at 2,000 ft (~610 m) AGL. Another 500 ft (~150 m) above that altitude is needed to comply with separation minimums [17]. Note that, for airports with TPs at other altitudes (e.g., at 600 ft Mean Sea Level (MSL) at Juist (EDWJ), see Fig. 2), the holding stack altitude will need to be adjusted accordingly. The number of levels in the holding stack, as well as the upper altitude limit of the holding stack, will be dependent on traffic and UAS demand at the airport of interest. For example, a holding stack upper altitude might be limited by the presence of a low-altitude airway (e.g., Victor airway in the US) above the airport. Finally, each holding stack level will be separated by 500 ft (~150 m), in accordance with separation minimums. Entry into the holding stack is notionally designated at the corners of each level. A UAS exiting from the holding stack should join with a standard 45° entry into the TP, see Fig. 3.

A. Defining the TP Airspace Volume

This paper proposes a two-step methodology to identify and assess the TP at an airport. The two-step methodology consists of first identifying the bounds of where crewed traffic has historically flown the TP. Historic traffic in this volume of airspace, referred to as "TP airspace volume", is then assessed using various metrics in the second step, which will be covered in the following section.

Despite best practices and, in the case of German airports, VOCs that suggest the "ideal" TP in terms of integration altitude and distance of the downwind leg from the runway, the historic traffic at non-towered airports is nonetheless distributed, both vertically and horizontally, beyond the "ideal" pattern. Therefore, it is vital to identify the bounds of this spread to properly define the TP airspace volume as the volume around the non-towered airport where historic traffic has flown.

1) Data Selection: Historic air traffic is obtained from two sources. For the German airports, flight data from Flightradar24 covering one year of data (2022) are used to analyze speed, heading, and four-dimensional waypoints indicating the longitude, latitude, altitude, and time of every aircraft in the airspace [29]. Similar data are examined for US airports, using Sherlock Data Warehouse from the NASA Technical Reports Server to access one year of flight track data (2023) from terminal airspaces in California and Texas [30]. Using this historic data, the TP airspace volume can then be defined.

2) Vertical Bounding of the TP Airspace Volume: At each airport, the average number of simultaneous flights per square kilometer (ASFK) is calculated [31]. The ASFK is a measure of the density of historic operations. For each 0.01 km^2 spatial cell, the time spent in that cell by historic aircraft during a given time period (i.e., one year) is recorded in flight seconds. This sum is then divided by the area of the airspace cell (i.e., 0.01 km^2) and the overall recording time (i.e., one year) to provide the average density for a single airspace cell. Fig. 7 shows the ASFK across three different altitude bands for Juist (EDWJ).

As discussed previously, it is anticipated that most traffic would integrate into the TP at conventional TP altitudes between 500 to 1,500 ft (~150 to 450 m) AGL. This can also be seen by looking at Fig. 7 with most traffic integrating in Fig. 7a and almost no TP activities occurring in Fig. 7b. Since traffic can still integrate into conventional TP altitudes from above 1,500 ft (~450 m) AGL, 3,000 ft (~900 m) AGL was chosen as an upper bound to the TP airspace volume. Assessment of several non-towered airports indicated that the density of historic operations above 1,500 ft (~450 m) AGL was minimal, however, traffic used the airspace above conventional TP altitudes before integrating into the TP. These traffic activities above conventional TP altitudes are likely to have an impact on the decision of the viability of the holding stack location and the amount of holding stack layers. A discussion of the differences in traffic densities in different altitude bands of the TP airspace volume at airports of interest and the implications of these differences will follow in Section IV-B.

3) Horizontal Bounding of the TP Airspace Volume: As shown in Fig. 7c, the horizontal bounds of the TP airspace volume can then be drawn around all airspace cells that represent an airspace density of at least $8 * 10^{-4}$ ASFK (light green on the given scale). This threshold implies that, over the course of the year, there was a total of ~2,500 flight seconds ($7 * 10^{-1}$ flight hours) spent within the 0.01 km^2 spatial cell. This threshold was based on visual assessment of the historic traffic at the airports of interest. However, future work

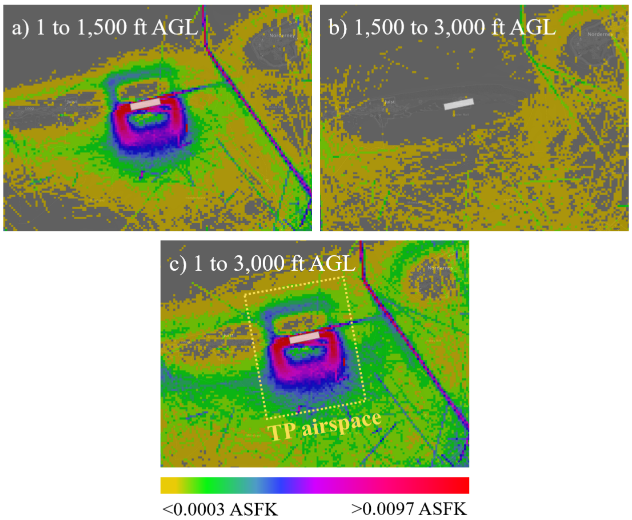

Figure 7: Juist (EDWJ) with identified TP airspace volume

will apply further mathematical rigor to refine this bounding threshold. In summary, every TP airspace volume is vertically bound at 3,000 ft (~900 m) AGL but has individual horizontal bounds based on the density of the TP at each non-towered airport.

IV. Metrics and Data Analysis

Operations can vary significantly from one non-towered airport to the next. To gain a better quantitative understanding of operations at non-towered airports, this paper proposes several metrics to describe operations. These metrics will be applied across twelve example airports. It is intended that these metrics can be utilized to design scenarios and simulations that will help to define the undefined safety thresholds discussed in Section II-C. As mentioned previously, the actual definition of these safety thresholds is beyond the scope of the current work. A discussion of how these metrics may impact the integration of UAS into non-towered airports will follow.

A. Example Non-towered Airport Selection

Twelve different airports, four each from Germany, California, and Texas were chosen as airports of interest. Different regions were chosen to provide a varied and international view of non-towered airports. These three regions were previously identified as regions where UAS are likely to be introduced for use in the regional air cargo use case [2]–[4]. The historic traffic density at each airport of interest, as well as the identified TP airspace volume for each non-towered airport, is shown in Fig. 8. Flight data are extracted from the identified TP airspace volumes, which are aligned with the runway center-line of the respective airport and are shown in Fig. 8 as the yellow box. For airports with multiple runways, the TP airspace volume was aligned with the busier runway.

The twelve airports were selected due to their strategic location for initial regional cargo UAS operations. Locations considered relevant for the initial deployment of highly automated regional cargo operations are suburban areas (e.g., Watsonville (KWVI), Marina (KOAR), Visalia (KVIS), and Hillsboro (KINJ)), hard to reach areas such as rural regions or islands (e.g., Juist (EDWJ) and Norderney (EDWY)), and areas close to main airports or cargo hub airports (e.g., Egelsbach (EDFE), Schönhagen (EDAZ), Selma (0Q4), Houston SW (KAXH), Pearland (KLVJ), and Lancaster (KLNC)).

B. Distinction by Altitude Bands

It is relevant to consider the share of aircraft that operates in different altitude bands of the TP airspace volume. Ideally, the holding stack should be placed at an altitude that is de-conflicted from other traffic. This distinction by altitude bands helps to understand crewed aircraft behavior in TP airspace volumes in order to minimize interaction of UAS with crewed aircraft when choosing a suitable location for the UAS holding stack. As discussed in Section III-A2, the vertical bound to the TP airspace volume was placed at 3,000 ft (~900 m) AGL. To provide a more detailed picture of traffic at the airport of interest, the flights found in the TP airspace volume are divided into three sets.

$\mathbb{A}$: Set of flights from 1 to 1,500 ft (~1-450 m) AGL
$\mathbb{B}$: Set of flights from 1,500 to 3,000 ft (~450-900 m) AGL
$\mathbb{C}$: Set of flights from 1 to 3,000 ft (~1-900 m) AGL

Here, $\mathbb{A} \subseteq \mathbb{C}$ and $\mathbb{B} \subseteq \mathbb{C}$. $\mathbb{C}$ contains the total number of flights in the defined TP airspace volume. $\mathbb{A}$ is designed to cover the conventional TP integration altitudes (see Fig. 3). $\mathbb{B}$ then covers all flights from the top of the conventional TP to the top of the TP airspace volume. The total number of flights in $\mathbb{A}$ and in $\mathbb{B}$ may exceed the number in $\mathbb{C}$, as flights can transit —and therefore be counted in —both bands. By breaking down the traffic into altitude bands, deviations from convention can be identified. These deviations will be critical in determining the viability of a holding stack at the airport of interest. It is clear from the data that a holding stack could not be placed at lower altitudes (i.e., below 1,500 ft (~450 m) AGL), due to the percentage of traffic operating at these altitudes at all airports investigated. If too much traffic is present at higher altitudes (i.e., $\mathbb{B}$), the holding stack will either need to occur at even higher altitudes (i.e., above 3,000 ft (~900 m) AGL), be located in an area away from the runway (defeating many of the advantages of placing the holding stack above the runway), or be deemed infeasible at the airport of interest.

Data for the twelve airports of interest are presented in Table II. The background color is a gradient based on the assessment of feasibility of a holding stack, with dark green being most feasible and white being least feasible. Each row is scaled only according to the values in that row. In general, a holding stack should be more feasible at an airport with more dark green. Airports with mixed green and white, e.g., Visalia (KVIS), are excellent candidates for future simulation studies to investigate and improve upon this proposed concept, as they are complex environments. Flights found in $\mathbb{A}$, below 1,500 ft (~450 m) AGL, can be assumed to be landing at or departing from the airport of interest, as aircraft overflying an airport rarely do so at these lower altitudes. Next, flights found in $\mathbb{B}$ could be overflying the airport or they could be integrating into the TP at the airport from a higher altitude. To

TABLE II. Number and share of aircraft in different altitude bands in TP airspace volume

Number or Percentage of Aircraft	EDWJ	EDWY	EDFE	EDAZ	KWVI	KOAR	KVIS	0Q4	KAXH	KLVJ	KLNC	KINJ
ℂ 1 to 3,000 ft	7,117	3,495	15,709	6,969	20,231	8,147	24,500	4,193	20,823	17,854	17,914	6,951
𝔸 (% of ℂ) 1 to 1,500 ft	84.3	70.9	99.6	92.0	90.4	66.9	93.8	42.5	51.0	85.6	69.5	80.7
𝔹 (% of ℂ) 1,500 to 3,000 ft	32.0	37.3	3.4	26.0	56.3	59.7	51.3	62.3	58.2	24.8	47.3	43.8
𝔸 ∩ 𝔹 (% of ℂ)	16.5	8.6	3.0	18.1	46.7	26.6	45.2	4.8	9.3	10.4	16.8	24.5
𝔸 \ 𝔹 (% of ℂ)	67.8	62.3	96.5	74.0	43.7	40.3	48.7	37.7	41.8	75.2	52.7	56.2
𝔹 \ 𝔸 (% of ℂ)	15.5	28.8	0.4	7.9	9.6	33.1	6.2	57.5	49.0	14.4	30.5	19.3

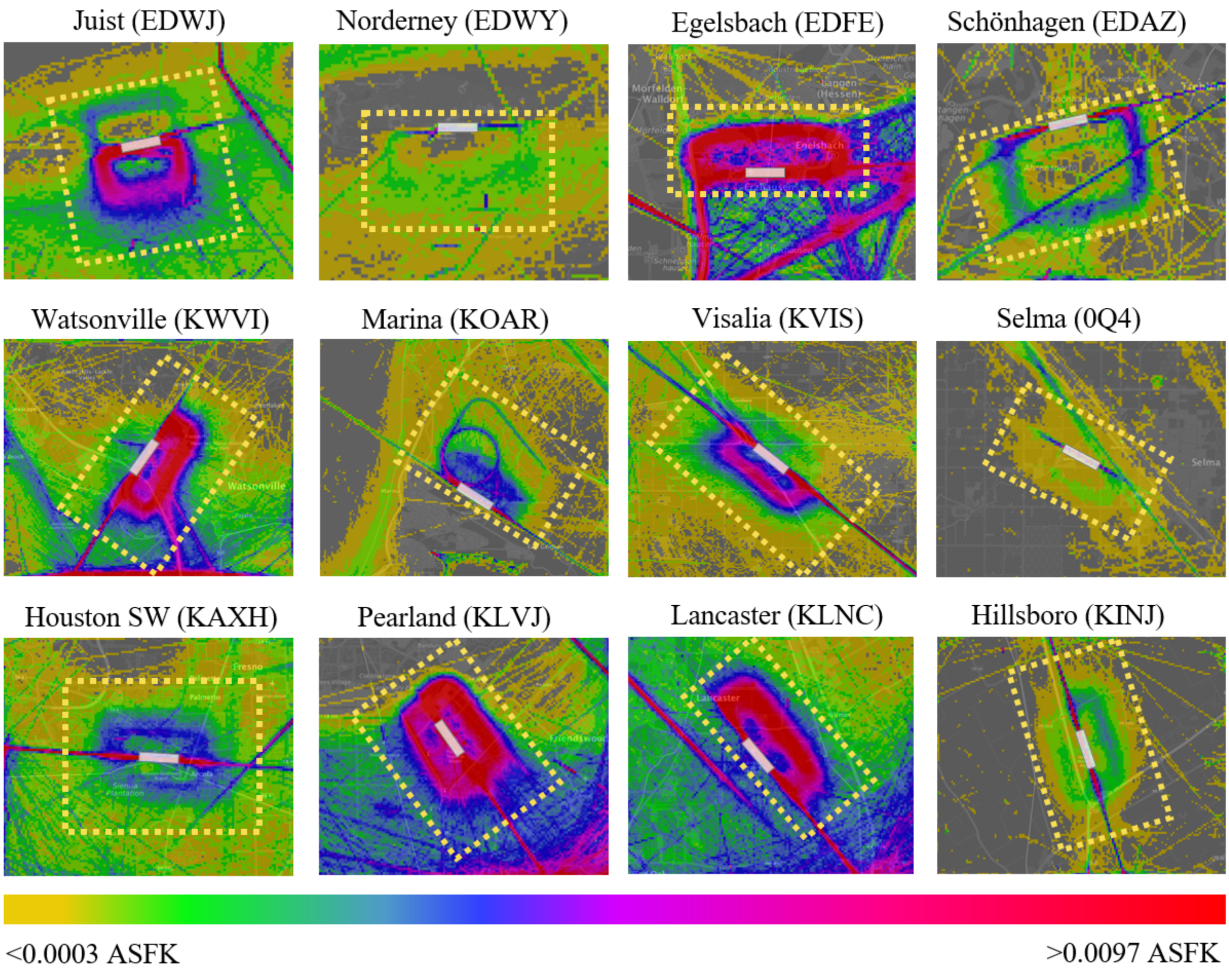

Figure 8: Identification of TP airspace volumes at airports of interest (airports and their TPs are not to scale)

investigate further, the intersection of the two sets is taken into account, $\mathbb{A}\cap\mathbb{B}$, corresponding to flights that flew through both the upper altitude band ($\mathbb{B}$) and the lower ($\mathbb{A}$), presumably landing at or departing from the airport. Next, the relative complement of $\mathbb{B}$ in $\mathbb{A}$, $\mathbb{A}\setminus\mathbb{B}$, is taken to describe those flights that *only* were present in $\mathbb{A}$. These flights only integrated into the TP airspace volume below 1,500 ft (~450 m) AGL and presumably landed at or departed from the airport. Finally, $\mathbb{B}\setminus\mathbb{A}$ describes those flights that *only* integrated into the TP airspace volume from 1,500 to 3,000 ft (~450 to 900 m) AGL, presumably overflying the airport.

Each individual airport will have its own distribution of traffic. However, these values in Table II can help to better understand how traffic integrates at the airport. Take, for example, Watsonville (KWVI) and Visalia (KVIS). At both airports, approximately 45% of traffic integrates through *both* $\mathbb{A}$ and $\mathbb{B}$, meaning that a UAS aiming to integrate at these airports will likely need to contend with an aircraft transiting altitudes, potentially increasing the difficulty of integration. Another approximately 44% to 49% of flights at these two airports integrated exclusively in $\mathbb{A}$, meaning that a UAS could likely stay clear of this traffic by remaining above 1,500 ft (~450 m) AGL, although the UAS would be flying among traffic in $\mathbb{B}$, unless it was flying above 3,000 ft (~900 m) AGL. However, at these airports, only a small percentage (9.6% and 6.2%, respectively) of traffic solely is found in $\mathbb{B}$, meaning that the traffic is likely overflying the airport and should have minimal impact on a holding stack. Putting these three percentages together, it is reasonable to assume that a holding stack at Watsonville (KWVI) and Visalia (KVIS) would be need to be placed at higher altitudes, even above 3,000 ft (~900 m) AGL, to remain free of historic traffic. Conversely, Pearland (KLVJ), which has a low percentage of overflight traffic (14.4%) and relatively little (10.4%) traffic with large altitude changes may present an easier integration opportunity to the UAS, as the traffic may be more predictable. An airport like Marina (KOAR), on the other hand, with its more evenly-distributed traffic, presents another type of integration hurdle.

It can be clearly seen that the analysis of traffic densities of aircraft in different altitude bands varies by airport and that non-towered airport environments are complex and more susceptible to uncertainty. Further research is needed to investigate traffic densities and the structure of these densities at more granular altitude bands. This density analyses will help to identify locations for UAS holding stacks, Cases 3 and 5 of Tab. I, as well as identify windows wherein Case 1, 2, and 4 operations are viable.

C. *Definition of Metrics*

Seven different metrics are calculated for each airport of interest and are shown in Table III. The size of the TP airspace volume in km^3, V_{tpa}, and the number of flights, N, were previously discussed in Section III-A. Dividing the number of flights, N, by V_{tpa} yields the density of the TP airspace volume, ρ_{tpa}. As in Table II, the green indicates a value that implies a greater feasibility for a holding stack. The next four metrics are normalized by the size of the TP airspace volume, so as to better compare airports. Eq. 1 shows the overall flight time per km^3, $\mathbb{T}$. $\mathbb{T}$ is the flight time in the TP airspace volume for each individual aircraft, t_i, in hours, summed across all N flights that occurred during the period of study (i.e., one year). Eq. 2 shows a similar metric, the overall flight distance per km^3, $\mathbb{D}$. $\mathbb{D}$ describes the flight distance in the TP airspace volume for each individual aircraft, d_i, in km, summed across all N flights.

$$\mathbb{T} = \frac{\sum_{i=1}^{N} t_i}{V_{tpa}} \frac{\mathrm{h}}{\mathrm{km}^3} \tag{1}$$

$$\mathbb{D} = \frac{\sum_{i=1}^{N} d_i}{V_{tpa}} \frac{\mathrm{km}}{\mathrm{km}^3} \tag{2}$$

The next two metrics average the aggregate metrics for each flight to give an average flight time per km^3, $\mathbb{T}_{avg}$, and average flight distance per km^3, $\mathbb{D}_{avg}$, see Eqs. 3 and 4.

$$\mathbb{T}_{avg} = \frac{\frac{\sum_{i=1}^{N} t_i}{V_{tpa}}}{N} \frac{\mathrm{h}}{\mathrm{km}^3\#\mathrm{flights}} \tag{3}$$

$$\mathbb{D}_{avg} = \frac{\frac{\sum_{i=1}^{N} d_i}{V_{tpa}}}{N} \frac{\mathrm{km}}{\mathrm{km}^3\#\mathrm{flights}} \tag{4}$$

TABLE III. Calculated metrics for airports of interest

Metric	EDWJ	EDWY	EDFE	EDAZ	KWVI	KOAR	KVIS	0Q4	KAXH	KLVJ	KLNC	KINJ
Volume of TP airspace V_{tpa}	45.4	18.7	32.2	41.7	70.9	46.9	100.0	22.7	50.4	42.7	29.5	44.3
Number of aircraft N	7,117	3,495	15,709	6,969	20,231	8,147	24,500	4,193	20,823	17,854	17,914	6,951
Density of TP airspace ρ_{tpa}	156.7	187.3	487.1	167.1	285.4	173.8	244.9	184.8	413.3	418.4	606.2	157.0
Overall flight time per km^3 $\mathbb{T}$	42.2	11.1	128.3	15.4	56.4	21.5	28.9	10.3	31.5	129.7	94.9	18.7
Overall flight distance per km^3 $\mathbb{D} * 1e\text{-}2$	19.4	8.4	61.5	13.0	50.4	21.8	26.7	10.2	31.8	65.9	69.7	18.4
Avg. flight time per km^3 $\mathbb{T}_{avg} * 1e4$	59.3	31.8	81.7	22.1	27.9	26.4	11.8	24.5	15.1	72.6	53.0	26.9
Avg. flight distance per km^3 $\mathbb{D}_{avg} * 1e2$	27.2	24.0	39.2	18.6	24.9	26.7	10.9	24.3	15.2	36.9	38.9	26.4

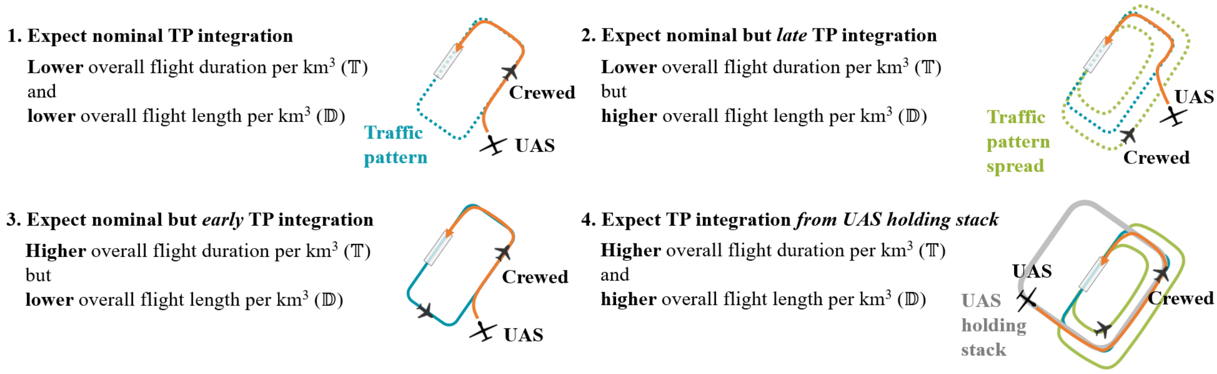

Figure 9: Different integration procedures for UAS based on metrics $\mathbb{T}$ and $\mathbb{D}$

D. Analysis of Metrics and Implications for UAS integration

Looking at Table III, if V_{tpa} is large, that could indicate that larger aircraft (e.g., jets) are flying into that airport and/or that the TP is fairly spread out. A large V_{tpa} would also dictate a larger horizontal footprint for the holding stack. In general, the German airports exhibit more compact TP airspace volumes than their US counterparts. If N is large, it is likely that the airport is consistently busy and thus may present additional integration difficulties to the UAS. Conversely, a small N indicates a less-busy airport, which may not merit a holding stack (e.g., Norderney (EDWY) and Selma (0Q4)). Finally, ρ_{tpa} gives an indication of the structure of the TP itself. A well-structured TP (i.e., the parts of the TP are clearly identified and the majority of traffic follows the pattern), such as that of Egelsbach (EDFE), will have a correspondingly-high ρ_{tpa}. Conversely, a low ρ_{tpa} could indicate that the TP is spread out or that, such as at Marina (KOAR), there are supplementary traffic maneuvers in the TP airspace volume (e.g., at Marina (KOAR), planes for skydiving will follow a circular or rounded quadrilateral pattern at altitudes separate from that of the TP, see Fig. 8).

In Table III, $\mathbb{T}$ and $\mathbb{T}_{avg}$ can also be compared with ρ_{tpa}. These values can have a significant impact on the integration potential at an airport. If, for example, the UAS is in a LC2L state and is headed towards Egelsbach (EDFE), per Section. II-C, the UAS will be able to execute the IAP if there is no traffic (Case 4) or, if there is any traffic, will be forced to execute a holding maneuver (Case 5). An airport with a high value of $\mathbb{T}$ indicates that the TP airspace volume at that airport is more likely to contain at least one aircraft per km^3. A high value of $\mathbb{D}$ indicates that traffic is likely to spatially utilize more of the TP airspace volume. Airports like Pearland (KLVJ) and Lancaster (KLNC) have a high value of $\mathbb{D}$ and show complete, dense TPs. Norderney (EDWY) and Selma (0Q4), on the other hand, exhibit low values of $\mathbb{D}$, presumably because either there is not much traffic and/or the traffic typically can simply utilize a straight-in approach.

Although the exact thresholds between the cases described in Section II-C are an area of future work, the metrics presented herein can be used as input parameters into a simulation study designed to establish those thresholds. Fig. 9 presents four potential integration designs for a UAS integrating into a non-towered airport. It is expected that airports with low values of $\mathbb{T}$ and $\mathbb{D}$ would correspond to Cases 1 and 4 of Table I, and UAS could expect nominal TP integration (top left, procedure 1 of Fig. 9). Airports with high values of $\mathbb{T}$ and $\mathbb{D}$ would likely correspond to Cases 3 and 5 of Table I, UAS could expect to execute a holding maneuver (bottom right, procedure 4 of Fig. 9). Case 2 of Table I presents an additional challenge, given the need to merge and space with traffic already in the pattern. Two ideas, based on the values of $\mathbb{T}$ and $\mathbb{D}$, are presented in the top right (procedure 2) and bottom left (procedure 3) of Fig. 9, though the thresholds between these two are, as mentioned, subject to additional research.

V. Conclusions

The analysis of historic flight activities of crewed aircraft in terminal area airspaces of non-towered airports provides a methodology to UAS operators to quantify and better understand crewed traffic behaviors. This research quantitatively assesses traffic activities in the terminal area airspace and, more importantly, in the TP of non-towered airports —which depend on the individual airport layout, environmental constraints, and the different types of aircraft that operate at these airports. Systematically identifying TP airspace volumes to assess traffic activities in TPs is intended to help determining when a holding stack is feasible for UAS to safely separate from crewed aircraft. A holding stack for UAS, which might be managed by concepts such as U-space, is intended to facilitate safe, procedural TP integration of UAS in addition to onboard conflict resolution capabilities. This approach can also help to inform decision-making processes for UAS contingency procedures. Assuming a UAS needs to divert from its flight plan due to a LC2L and has to approach the closest non-towered airport, assessing historic traffic activity helps to identify the risk of UAS interfering with crewed aircraft for different non-towered airports.

Based on several assumptions such as certified onboard DAA functions for UAS to enable safe separation from VFR aircraft in terminal environments, flight rules to enable UAS operations at scale in uncontrolled airspace, and traffic management concepts such as U-space to enable highly automated and cooperative airspace interaction, this work presents a concept for UAS airspace integration at non-towered airports and a suite of metrics against which that concept can be tested. Further research will investigate integration potentials of UAS into TP airspace volumes by assessing performance-based separation minima between UAS and crewed aircraft. Using performance characteristics of individual UAS (e.g., Cessna 208 UAS), the maximum occupancies of terminal area airspaces of non-towered airports can be algorithmically determined, based on historic traffic densities for an individual time interval (e.g., within the day or hour). This algorithmic approach will help to tailor holding stacks to individual airports to perform simulations across a variety of representative non-towered airport environments.

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