Navigating the Uncertain: Integrating Uncrewed Aircraft Systems at Airports in Uncontrolled Airspace

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***Abstract*—The introduction of fixed-wing cargo Uncrewed Aircraft Systems (UAS) has the potential to revitalize traffic at under-utilized regional airports. These regional airports are often non-towered airports in uncontrolled airspaces with increasingly non-cooperative air traffic. This work proposes to adapt current U-space architectures for the terminal airspace of these airports. This will reduce traffic intent uncertainty as all airspace users must be electronically conspicuous to the U-space environment. To further mitigate traffic intent uncertainty in uncontrolled airspaces, this paper analyzes the spatial traffic density of crewed traffic at four German non-towered airports in 2022. The investigated flight routes and traffic patterns of crewed traffic help to understand current flight intents and enable a more seamless airspace integration of UAS together with crewed traffic. In addition, this paper introduces a UAS holding stack concept for non-towered airport approaches within a U-space environment. UAS holding stacks are intended to handle increased traffic intent uncertainty in the context of tactical conflict management provided by U-space services. The results of this paper will enable more efficient airspace integration of UAS in terms of strategic and tactical flight planning and conflict management at non-towered airports.**

Keywords*—*UAS, regional airport, U-space, terminal airspace, traffic pattern, VFR traffic, e-conspicuity

I. INTRODUCTION

Today's Air Traffic Management (ATM) systems are expected to be increasingly impacted by highly automated flight operations that do not have human pilots on board the vehicle. These air transport operations are termed Uncrewed Aircraft Systems (UAS) with fixed-wing cargo UAS to be assigned a high potential to revitalize traffic at under-utilized regional airports. Fixed-wing cargo UAS for regional operations are considered as an ideal proving ground for increasingly autonomous aviation technologies [1], [2]. They face fewer safety regulations compared to highly automated passenger operations while mitigating pilot shortages in the regional realm. In this paper, UAS refer to regional cargo UAS that are likely to have a Maximum Takeoff Weight (MTOW) of less than 25 tonnes with less than 9 tonnes of additional payload [2].

It is anticipated that current regional air cargo fleets will need to be retrofitted over the next decade as they are ageing out [2]. In Europe, regional turboprop aircraft such as ATR 42, ATR 72, and Embraer EMB 120 are most likely to be converted to UAS, as they currently account for 89% of domestic regional air cargo operations in the range of less than 1,000 kilometers in 2022 [3].

Regional air transport operations at smaller, under-utilized airports, often referred to as regional airports, are likely to be one of the initial use cases for fixed-wing cargo UAS [1], [4]. For simplicity, the term airport will be used for both, airport and airfield in this paper. In Europe, 50% of all air transport operations are handled at less than 2% of airports, although there are over 2,500 smaller, regional airports across Europe [5], [6]. In the US, there are more than 5,400 airports, with 70% of air traffic being handled at less than 1% of airports [7], [8]. However, most of the less busy regional airports are not equipped with an operational control tower and are located in uncontrolled airspace where aircraft are not actively separated by Air Traffic Control (ATC). These airports are referred to as non-towered airports in this paper. Compared to towered airports, they are increasingly serving air traffic flying under Visual Flight Rules (VFR) with crewed aircraft visually separating themselves. In addition, the intent of VFR traffic is often non-cooperative, i.e., aircraft location and flight plan are not broadcast (e.g., via ADS-B, Automatic Dependent Surveillance - Broadcast) around many regional airports. This makes VFR traffic intent predictions unreliable.

Thus, compared to Instrument Flight Rules (IFR) traffic operating under ATC supervision, non-cooperative VFR traffic will not actively cooperate to resolve a potential conflict. Therefore, it is critical to analyze the airspace environment in which cargo UAS are likely to be introduced for initial operations. Operational procedures and novel concepts for the integration of UAS need to be derived, especially around non-towered airports in uncontrolled airspace with increasingly non-cooperative VFR traffic. To enable an efficient and safe integration of UAS in uncontrolled airspace, data and analyses on VFR traffic's intent at non-towered airports need to be provided. To date, few such data and analyses are available.

First, this paper investigates current crewed traffic intent and air traffic volumes at less busy regional airports. These non-towered airports have a high potential for the initial introduction of cargo UAS in uncontrolled airspace in Germany (i.e., class G). In Germany, VFR is generally the only operating mode that is permitted for flights in uncontrolled airspace. IFR flights can only be performed in uncontrolled airspace if a Radio Mandatory Zone (RMZ) is designated. In Germany, RMZs are generally established to enable IFR operations at non-towered airports.

Aircraft pilots operating under VFR usually follow given traffic patterns at non-towered airports for standardized landing and takeoff approaches while visually separating themselves without the help of ATC separation services. However, every airport's airspace environment has unique characteristics due to the airport's layout and its geographical environment that affect the approach of the traffic pattern. Therefore, this paper analyses and traces traffic patterns at different German non-towered airports to assess common patterns of the current crewed traffic's intent.

Second, based on the analyzed traffic patterns and crewed traffic's intent, this paper investigates areas in the airspace of non-towered airports with relatively low traffic density to derive operational procedures for seamless integration of UAS applicable at scale. An operational concept based on UAS approach procedures is introduced to enable safe and efficient separation from current crewed traffic with minimal impact on today's air transport operations.

II. BACKGROUND ON NON-TOWERED AIRPORT OPERATIONS

Today, non-towered airport approaches are typically performed by airspace users flying under VFR. VFR flights can only take place under appropriate weather conditions, known as Visual Meteorological Conditions (VMC), but provide higher operational flexibility than IFR flights. On the other hand, IFR flights can operate under more adverse weather conditions, called Instrument Meteorological Conditions (IMC), but are subject to onboard instrument navigational aids and ATC services. According to ICAO standards [9], airspace users must maintain horizontal and vertical separation minima when flying in uncontrolled airspaces under VMC.

A. Traffic patterns approaches at non-towered airports

At non-towered airports in uncontrolled airspace without ATC services, pilots under VFR must separate themselves visually and ensure minimum separation distances. IFR approaches, on the other hand, are not permitted at non-towered airports in all countries. If pilots are allowed to approach a non-towered airport under IFR, they must follow published procedures and generally communicate their positions and intents at specific points in the airport's terminal airspace.

Visual Operating Charts (VOC) are usually published for VFR approaches, which show a standardized traffic pattern with corresponding information. For example, the VFR pilot can obtain information on the recommended side for the airport approach and traffic pattern entry together with required flight altitudes and geographical information.

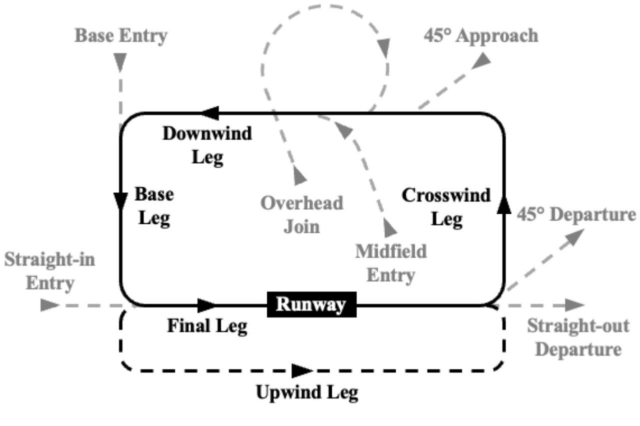

Fig. 1. VFR traffic pattern at non-towered airports

Before a VFR pilot enters a traffic pattern, the pilot must be able to assess the traffic in the traffic pattern and in the vicinity as well as the wind conditions. Ideally, the pilot should fly at an altitude above that of the non-towered airports traffic pattern, so that the pilot does not interfere with airspace users entering the traffic pattern.

Traffic patterns are usually flown at a minimum of 500 feet Above Ground Level (AGL) counterclockwise at a distance of at least one and a half kilometers from the runway so that the left-seated pilot can keep the runway in view throughout the airport approach. Typically, VFR pilots enter the traffic pattern at the beginning of the downwind leg (e.g., via a 45° approach, see Fig. 1) at the required traffic pattern altitude with appropriate aircraft speed and flight heading. This involves maintaining a constant traffic pattern altitude throughout the downwind leg of the circuit before entering the base leg with a steady descent throughout the final leg before landing the aircraft on the runway. If the pilot is unable to approach the runway during the base and final leg, the pilot usually flies upwind parallel to the runway and joins the downwind leg via the crosswind leg. As a rule of thumb, the flight maneuver from the end of the downwind leg over the base leg to the final leg should take about one minute.

In addition to the downwind entry of the traffic pattern, VFR pilots can also fly directly into the base leg as part of a base entry or enter the final leg of the traffic pattern as part of a straight-in approach. Alternatively, midfield entries or overhead joins are also a possibility for pilots to integrate into the traffic pattern. In this case, if the pilot approaches from the upwind side, the pilot flies above the traffic pattern orthogonally to the runway (approx. 500-1,000 feet above the traffic patterns altitude) and joins the downwind leg directly or in the course of a loop. Similarly, if approaching from the downwind side, the pilot passes the runway orthogonally above traffic pattern altitude and enters the crosswind leg towards the downwind leg.

The dimensions of the traffic pattern are usually not strictly defined and allow VFR pilots to make flexible adjustments depending on the conditions of the terminal airspace environment. It can be stated that non-towered airport traffic patterns offer a relatively high degree of flexibility for VFR pilots, creating a dynamic airspace environment that is dependent on current air traffic, pilot skills and aircraft capabilities, wind conditions, and VOC requirements. It can be concluded that the higher the VFR traffic volume in the airspace around the non-towered airport, the more unpredictable the pilot behavior and traffic pattern integration procedures and the greater the overall uncertainty in the terminal airspace.

B. High traffic volume operational concepts

From 2001 to 2006, NASA conducted the Small Aircraft Transportation System (SATS) program to enable efficient self-sequencing of crewed air traffic at non-towered airports with high traffic volumes under IMC. The goal of the program was to solve the so-called one-in/one-out paradigm, which states that under IMC only one IFR aircraft at a time can be on approach or departure or on a runway of the non-towered airport. The SATS core concept was based on a Self-Controlled Area (SCA), which enabled pilots to take over the separation in the terminal airspace under their own responsibility. An Airport Management Module (AMM) was designed to automatically coordinate sequencing and provide the necessary information for approaches and departures under IMC, without conventional ground-based surveillance or sequencing instructions by ATC. Additionally, pilots were required to have completed special training and carry aircraft equipment such as an ADS-B transponder, a cockpit display for traffic information, and special software for conflict detection to be allowed to operate in a SCA. The operational procedure required pilots to request clearance to enter the SCA via the AMM over a data link communication. The AMM then automatically calculated separation and sequencing information based on aircraft performances and the vehicles position. If compliant with the SCA requirements, the AMM then issued clearance to the pilot by providing associated approach or departure information and airport meteorology for the operation in the SCA [7], [10].

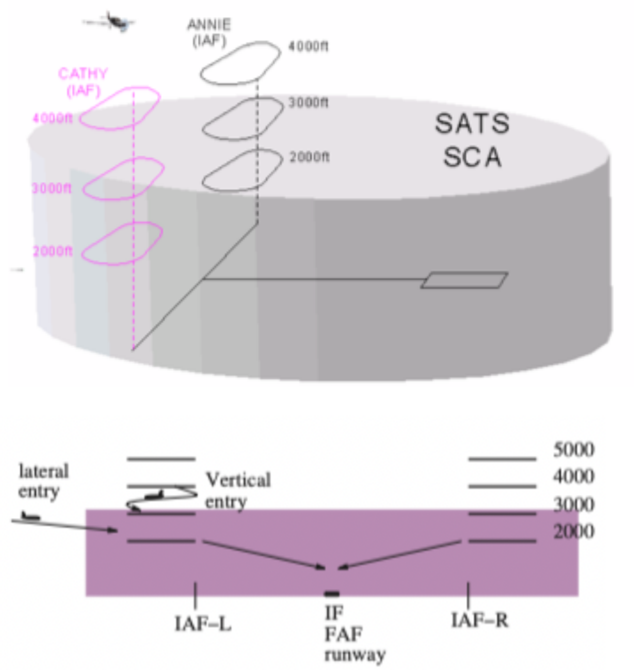

Fig. 2. SCA at a non-towered airport [10], [11]

The operational concept of the SCA at SATS airports intended that aircraft approach fixed points arranged in the shape of a T, called Initial Approach Fixes (IAF) (see Fig. 2). IAF served as entry points into the SCA on both sides of the T, IAF-L and IAF-R. If the aircraft was outside the SCA under ATC control, it had to wait at 4,000 feet. The holding areas within the SCA were located at 2,000 feet and 3,000 feet and served as an IAF. Based on the decisions of the AMM, aircraft entered the IAF either vertically or laterally. If the aircraft approached the IAF vertically, it remained at 3,000 feet until it descended to 2,000 feet. If the AMM decided on a lateral entry, the aircraft approached the IAF directly at 2,000 feet. If the AMM would give the signal for a landing approach, the pilot continued to the Intermediate Fix (IF) and from there via the Final Approach Fix (FAF) to the runway. As a result, the SATS operational concept allowed for four simultaneous and self-organized aircraft approaches under IMC at non-towered airports [11], [12].

Despite the proven operational efficiency, the SATS program was not realized because the technological hurdles and requirements were too high for aircraft at the time. There were also doubts if SATS would really be competitive with road transportation [13].

C. *Initial UAS operational integration concepts*

The integration of UAS into the airspace has been the subject of ongoing discussion and research for several years now. With the progressing development of UAS with different operational requirements and capabilities, concepts must be developed on how to integrate UAS cooperatively with existing air traffic in different terminal airspace environments around airports. This is recognized to be one of the greatest UAS airspace integration challenges [1], [14], [15].

There are different concepts and approaches that address the integration of UAS into controlled terminal airspaces. In 2013, Geister & Geister introduced an initial concept to handle multiple fixed-wing UAS in the terminal airspace of a towered hub airport [14]. An airport-based ground control station was intended to navigate UAS and enable dual threshold operations on a single runway. This concept was intended to be applicable to any towered airport with a parallel runway layout.

In 2022, the European SESAR Joint Undertaking research project “INVIRCAT” proposed a concept of operations for the integration of UAS in controlled terminal airspaces of towered airports under IFR [16]. Different technical and operational aspects for a seamless integration of UAS into controlled terminal airspaces were investigated, followed by simulations to validate the concept. The concept of operations included aspects like system latency regarding command and control (C2) link and voice communication link, automatic take-off and landing, handover of UAS control between different remote pilots and impact on ATC, and contingency procedures such as C2 link failure [17].

However, most of the research in this area has been focusing on integrating UAS at major towered airports under ATC supervision with the help of defined IFR approach procedures. It can be assumed that the integration of UAS at towered airports with published IFR procedures is likely to occur relatively seamlessly with UAS following the already standardized procedures for crewed aviation. Today, standard arrival routes (STAR) guide IFR aircraft from the en-route airspace to initial approach fix points to separate approaching traffic based on checkpoints that restrict flight levels and speeds. However, UAS integration at airports becomes significantly more complex when only VFR aircraft are permitted in that airspace. Accordingly, airspace environments of non-towered airports represent an increased uncertainty as see-and-avoid principles and schematic traffic patterns are the common separation procedures for today’s airspace users.

As emerging fixed-wing UAS operations will increasingly occur at smaller regional airports, the uncertainty of VFR traffic intent must be given greater consideration. To date, there have been very few studies analyzing VFR data in the context of UAS airspace integration. Bulusu et al. is the only published recent research that investigates VFR traffic intent uncertainty and its potential impact on UAS operational capacities at one regional US airport, Fort Worth Alliance KAFW [18]. Bulusu et al. analyze one month of traffic data in the terminal airspace of Fort Worth Alliance KAFW to generate spatial-temporal occupancy maps to analyze the interaction probability of UAS with VFR traffic. Bulusu et al. emphasize that the characterization of VFR traffic intent uncertainty is an important step towards strategic and tactical air traffic flow management for an efficient UAS integration.

In addition to limited research on VFR traffic intent uncertainty, few concepts investigate integration procedures of UAS at non-towered airports. In [15] and [19], a concept was derived that proposes a UAS holding pattern above the traffic pattern of the non-towered airport. In this concept, UAS had to resolve potential conflicts with VFR traffic at a safety altitude. It was proposed that UAS had to wait in a holding pattern above the traffic pattern before the remote pilot could decide to descend and enter the traffic circuit of the non-towered airport.

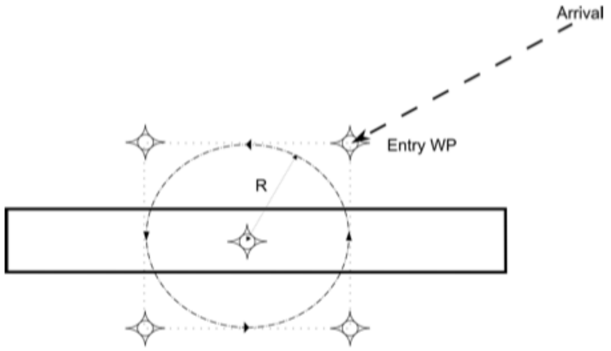

Fig. 3. UAS holding pattern above airport traffic pattern [15]

The UAS holding pattern is defined above the highest point of the traffic pattern to allow the UAS remote pilot to decide when and how to enter the traffic circuit and, if necessary, to establish radio contact with other airspace users. The holding pattern consists of five waypoints (WP) which, depending on wind direction and traffic, can enable the remote pilot to approve an omnidirectional landing. The four outer WP represent the entry into the holding pattern and allow the UAS to enter the holding pattern (via the entry WP) in a clockwise or counterclockwise direction (see Fig. 3). The outer WP also serve as exit WP, from which the UAS descends into the beginning of the downwind leg at traffic pattern height.

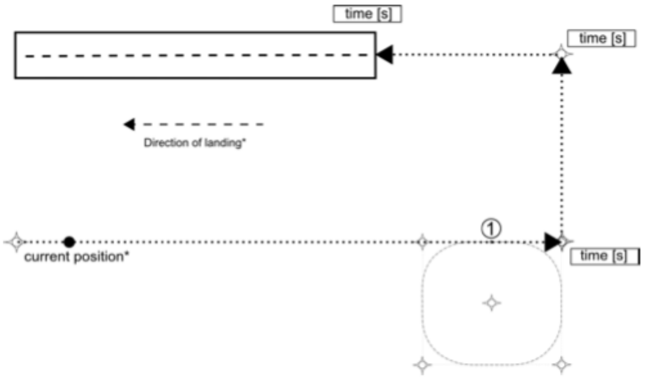

Fig. 4. UAS holding pattern at the end of downwind leg [15]

In addition to a UAS holding pattern above the traffic pattern of the non-towered airport, [15] and [19] also propose to place UAS holding patterns next to the downwind leg before UAS enter the base leg (see Fig. 4). These holding patterns next to the downwind leg are intended to enable UAS to maintain sufficient separation from the aircraft ahead. These downwind leg holding patterns could also give way to other aircraft that choose the base entry or straight-in entry of the traffic pattern, for example, or to aircraft that fly a traffic pattern in the opposite direction [19].

However, this concept is largely confronted with non-cooperative VFR traffic, which leads to increased traffic intent uncertainty in the traffic pattern and in the terminal airspace around the non-towered airport. It remains to be clarified how the UAS or the remote pilot will predict and detect intent of VFR traffic in-flight and resolve potential conflicts. Future UAS are likely to have highly automated onboard detect-and-avoid (DAA) capabilities that are going to act as an additional safety net to flight rules that provide air traffic separation in the first place. Nevertheless, operational frameworks and respective flight rules need to be developed to reduce traffic intent uncertainty and to enable cooperative air traffic procedures for all airspace users in terminal airspace environments [20].

III. U-SPACE AIRSPACE CONCEPTS

Future UAS operations are expected to be conducted in dedicated airspace environments. “U-space” is Europe’s uncrewed traffic management system that defines technical and operational requirements within a regulatory framework for future UAS operations [21]. UAS operations within U-spaces must utilize U-space services (e.g., UAS flight authorization service, traffic information service, network identification service, and geo-awareness service) that are provided by different U-space service providers (USSP).

U-space airspaces will be based on four different U-space levels (U1 to U4) with different U-space services offered in each level. The higher the U-space level, the more advanced the U-space services, enabling increasing automation of UAS operations and enhanced connectivity between airspace users. Additionally, all airspace users in U-space airspaces are obliged to be electronically visible (e-conspicuity obligation) to the ground and to other U-space users (e.g., broadcasting their flight intent via certified ADS-B out to a USSP) [22].

Accordingly, U-space airspaces around non-towered airports in uncontrolled airspace will allow for cooperative air traffic only, as all airspace users must broadcast their flight intent by means of being e-conspicuous. Thus, UAS obligated to receive U-space services will be informed about the flight intent and position of crewed and uncrewed traffic. However, crewed traffic will not necessarily be aware of the flight intent of UAS. Crewed traffic will only be required to broadcast their flight intent out. Therefore, it can be anticipated that VFR traffic will continue to largely rely on existing SAA principles in lower-level U-space airspaces (e.g., U1 and U2). These lower automated U-spaces will provide initial U-space services primarily intended for UAS operations [20]. Additionally, it can be assumed that UAS receiving U-space traffic information services will give right-of-way to VFR traffic. Moreover, it can be expected that UAS will adapt their flight procedures according to the intent of VFR traffic. To allow for a seamless terminal airspace integration of initial UAS operations, UAS should interfere with current traffic patterns of crewed airspace users as little as possible while still maintaining operational efficiency and safety.

A first regulatory sandbox for a U-space airspace around a German airport was set up at Magdeburg-Cochstedt EDBC, which also serves as the National Experimental Test Center for Uncrewed Aircraft Systems and is operated by the German Aerospace Center (DLR) [23].

IV. METHODOLOGY

This work proposes to adapt current U-space architectures for the terminal airspaces around non-towered airports to enable a seamless integration of UAS together with crewed traffic. Current U-space architectures are based on the regulatory framework of the latest SESAR Joint Undertaking U-space Concept of Operations (ConOps) Edition 4 that was published in July 2023 [24]. According to EASA's Easy Access Rules for Standardised European Rules of the Air (SERA) 6005(c) "Requirements for communications, SSR transponder and electronic conspicuity in U-space airspace", all airspace users in U-space airspaces are obliged to be e-conspicuous to the U-space environment. Moreover, UAS are required to receive traffic information services from USSP [22].

If non-towered airports used for future UAS operations are allocated a U-space airspace, the flight intent of all airspace users can be tracked during the flight by means of e-conspicuity obligations. This paper analyzes historical flight data to understand how today's crewed traffic navigates at non-towered airports and approaches traffic patterns. The spatial traffic density of crewed traffic is analyzed over the time period of one year. This will help to derive trends of flight intents of crewed traffic and to reduce operational traffic intent uncertainty. Mitigating traffic intent uncertainty in uncontrolled terminal airspaces will enable more efficient integration of UAS in terms of strategic and tactical flight planning and conflict management.

A. *Data sources*

Flight tracking information from Flightradar24 covering one year of data are analyzed at four non-towered airports in Germany [25]. These non-towered airports have a comparatively high potential for the initial introduction of fixed-wing cargo UAS. Flightradar24 uses a large number of ground-based ADS-B receivers that collect data every second from aircraft in their vicinity that are equipped with an ADS-B transponder. Furthermore, these are complemented by data from multi-lateration (MLAT), and data collected from the Open Glider Network utilizing commercial FLARM transponders. The data from 2022, the latest year available, are distinguished by origin and destination, speed, heading, and four-dimensional waypoints indicating the longitude, latitude, altitude, and time of every aircraft in the airspace.

A three-dimensional box with a size of approximately 10 by 20 kilometers or the airport's RMZ and a height of 1,200 meters (approx. 4,000 feet) was placed around each selected airport to represent a notional U-space airspace. All flights in this notional U-space airspace were analyzed and distinguished by different altitude bands. The spatial density of air traffic was evaluated for each airport in the entire area and at three different altitude bands: 300-450 meters (approx. 1,000-1,500 feet), 450-600 meters (approx. 1,500-2,000 feet), and 600-750 meters (approx. 2,000-2,500 feet). Accordingly, corresponding traffic patterns were traced to identify areas with relatively low volumes of crewed traffic for a potential utilization by UAS.

To assess the density of air traffic the average number of simultaneous flights per square kilometer (ASFK) was used [26]. This was calculated for each cell in a regular rectangular grid with cell size 100 meters by 100 meters. The ASFK is defined as follows: For each cell all time intervals of aircraft passing through it were recorded. The overall sum of these intervals divided by the overall recording time (one year) gives the average density for a single cell. By normalizing this number by the area of the cell (0.01 square kilometers) the ASFK is obtained.

B. *Selection of potential UAS airports*

In a previous analysis [4], less busy public airports with potential for initial cargo UAS operations were identified as "potential UAS airports" (P2 airports). The analysis distinguished between the availability of current certified landing systems that are likely to be needed for initial UAS airport approaches (i.e., ILS CAT III and GLS) and airports without these landing systems that enable automatic landing. The results showed that Germany has 151 relatively less busy non-towered P2 airports in uncontrolled airspace class G, none of which have relevant certified landing systems. Only nine towered airports in controlled airspace class D have relevant landing systems that are likely to enable automatic landing for initial UAS operations.

Focusing on operations at the non-towered airports, which make up the majority of P2 airports, there are 13 non-towered P2 airports in Germany that were used for commercial air cargo operations in 2022. It can be assumed that airports with commercial air cargo operations are likely to be used for initial cargo UAS operations. Seven of these 13 airports are located within an RMZ that allows IFR approaches at non-towered airports in Germany. To analyze current crewed traffic intent and spatial traffic densities at non-towered airports, this paper investigates four different German P2 airports that have comparatively unique geographical characteristics.

- Emden EDWE is a mainland airport located at the German North Sea and has the highest air cargo volume of any airport in airspace class G with an RMZ.
- Juist EDWJ is located on an island in the German North Sea and has the highest air cargo volume compared to any other island airport in airspace class G. None of the German island airports have an RMZ.
- Strausberg EDAY is located east of Berlin, the capital of Germany, about 30 kilometers straight-line distance from Berlin-Brandenburg EDDB, one of the four German hub airports. Strausberg EDAY is a non-towered airport with an RMZ.
- Frankfurt-Egelsbach EDFE operates the highest number of flights of all P2 airports with commercial air cargo operations in Germany in 2022. Frankfurt-Egelsbach EDFE is a non-towered airport with an RMZ. Additionally, Frankfurt-Egelsbach EDFE is located in the immediate vicinity of Frankfurt EDDF, the largest hub airport in Germany, which is around 10 kilometers on a straight-line distance northwest.

V. RESULTS

The following section investigates terminal airspace flights and traffic patterns at the four P2 airports. Juist EDWJ (14,764 flights, median of 30 daily flights) and Strausberg EDAY (13,022 flights, median of 34 daily flights) can be regarded as relatively similar airspace environments in terms of flights (see Table I.). Emden EDWE has about twice as many flights as Juist EDWJ and Strausberg EDAY. Frankfurt-Egelsbach EDFE is the busiest of the P2 airports with over 100,000 flights in 2022 and a median of 273 daily flights.

TABLE I. AIR TRAFFIC IN NOTIONAL U-SPACES AT P2 AIRPORTS

P2 airport	**Number of flights in 2022**				**Airspace Bounding Box [km²]**
	Total	***Most busy day***	***Least busy day***	***Median***	
EDWE	27,883	214	15	70	363.65
EDWJ	14,764	194	1	30	183.97
EDAY	13,022	76	5	34	92.08
EDFE	100,867	462	115	273	162.70

A. Air traffic analysis at potential UAS airports

In its VOC, Emden EDWE has its traffic pattern located north of the airport. The circuit shape of the traffic pattern can be anticipated in Fig. 5d. Within each of the three investigated altitude bands in Fig. 5a-c, there are over 7,000 airspace users annually approaching the airport.

The traffic pattern of Emden EDWE is increasingly being approached from the east. Consequently, future UAS that approach Emden EDWE are confronted with crewed traffic flying the traffic pattern in a clockwise direction. In addition, it can also be observed that most of the crewed traffic does not fly the downwind leg, but flies directly into the base leg or the final leg (see in Fig. 5a-c).

For the operational integration of UAS at Emden EDWE, it can be suggested that UAS might approach the airport from the southwest or southeast. This enables UAS to avoid interfering with crewed traffic that increasingly flies northern base entries at Emden EDWE.

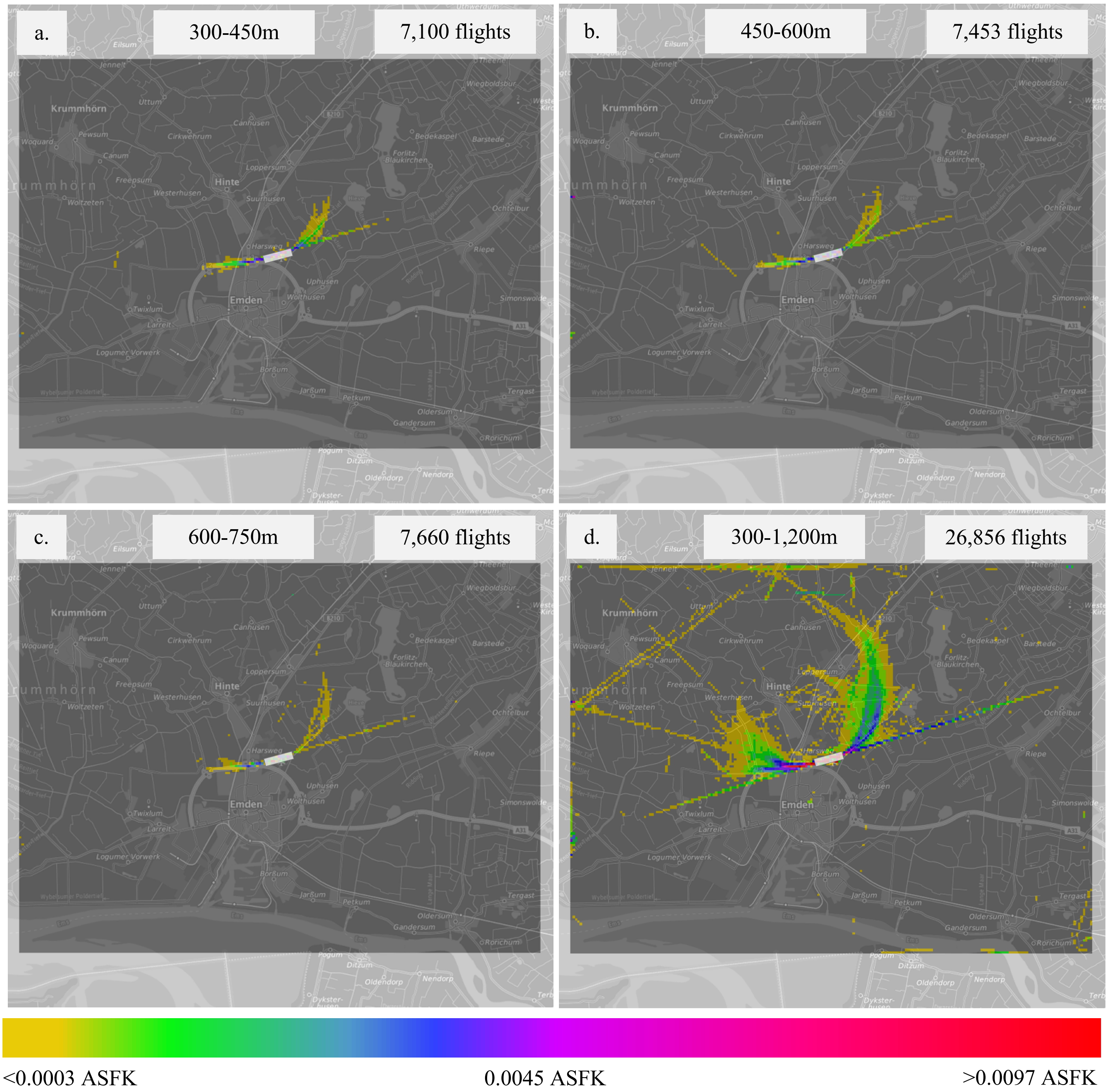

Fig. 5. Visualization of flights and traffic patterns at Emden EDWE

Juist EDWJ has two traffic patterns displayed in its VOC, one in the north and in the south of the runway. Fig. 6a-d clearly show that the southern traffic pattern is more intensively utilized by crewed traffic than the northern circuit. East of the airport, a flight path can be observed leading aircraft towards another airport, Norden-Norddeich EDWS.

At Juist EDWJ, incoming air traffic increasingly enters the southern traffic pattern at the end of the downwind leg (see Fig. 6b). The proportion of air traffic flying either clockwise or counterclockwise on the southern traffic pattern is about equally distributed. There are also relatively few straight-in entries into Juist EDWJ. Straight-in approaches can only be observed from the east. The VOC also recommends flying straight-in approaches from the east, likely to avoid flying over more densely populated areas to the west of the airport.

Interestingly, it can be noted that relatively few air traffic approaches the airport via the northern traffic pattern. This could be due to the fact that most of the air traffic comes from the south from the mainland and therefore chooses the shorter route to the airport runway via the southern traffic pattern. While there is relatively dense traffic in the southern traffic pattern at altitudes of 600-750 meters (see Fig. 6c), there are comparatively few airspace users in the downwind leg in the northern traffic circuit. Traffic in the northern traffic pattern increases at lower altitude bands, with crewed aircraft tending to fly the traffic circuit counterclockwise (see Fig. 6a-b).

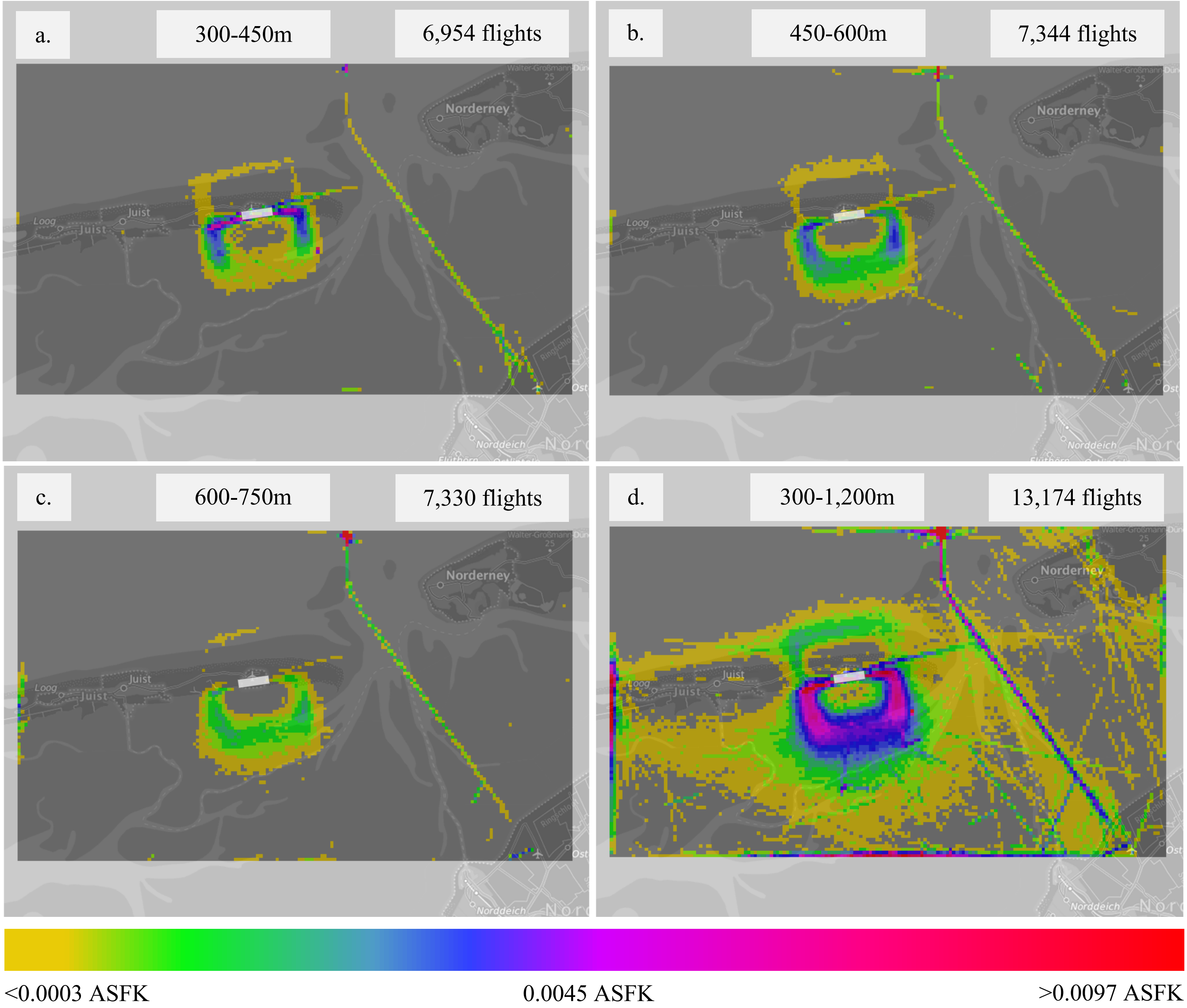

Fig. 6. Visualization of flights and traffic patterns at Juist EDWJ

Based on the analyzed airport approaches of crewed airspace users at Juist EDWJ, UAS are likely to approach the airport via the less busy northern traffic circuit. It could be ideal for UAS to approach the airport via a base leg entry from the northwest or northeast to avoid crewed traffic from the southern traffic pattern. In addition, a straight-in entry from the east is likely to face relatively few crewed airspace users. However, the eastern flight path towards Norden-Norddeich EDWS must be considered.

The official traffic pattern of Strausberg EDAY is oriented southeast of the runway. Compared to the other P2 airports, Strausberg EDAY has significantly fewer flights in lower altitude bands. The comparatively lower ASFK is particularly noticeable in the lower altitude bands in Fig. 7a-c. Most of the air traffic around Strausberg EDAY takes place south of the airport around the official traffic pattern. Almost no approaches pass over the town of Strausberg north of the airport.

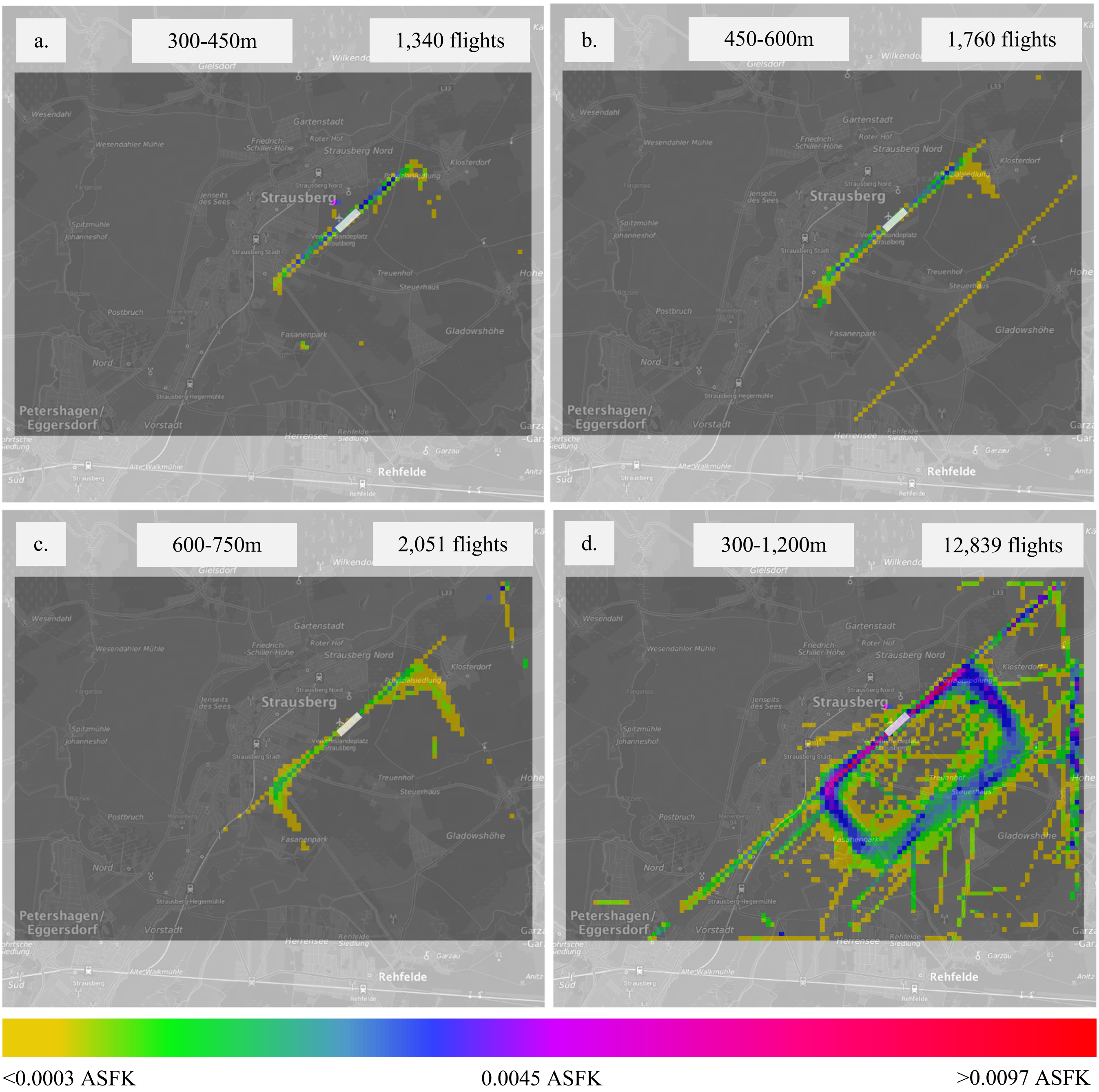

Fig. 7. Visualization of flights and traffic patterns at Strausberg EDAY

At Strausberg EDAY, approaches at lower altitude bands are concentrated following the counterclockwise direction towards the northern runway approach (see Fig. 7b-c). In higher altitude bands, airport approaches are increasingly performed via the downwind leg (approx. 0,0017-0,0038 ASFK), with flight paths coming in a straight line from the south (see Fig. 7d). In addition, Fig. 7d shows that increasing numbers of flights approach the airport runway directly via a straight-in approach from the north (up to 0,0045 ASFK).

Based on the traffic data from Strausberg EDAY, it is likely that UAS will approach the airport from the southwest, below the straight-in approach path from the south or northwest of the city of Strausberg. Generally, UAS will increasingly face crewed airspace users via straight-in approaches, with up to 0,0017 ASFK in the southern and up to 0,0045 ASFK in the northern straight-in entry.

Frankfurt-Egelsbach EDFE is the busiest airport of all investigated P2 airports. It is located in the immediate vicinity to the southeast of the major hub airport Frankfurt EDDF. Frankfurt-Egelsbach EDFE has two traffic patterns indicated in its VOC, north and south of the runway. It can be clearly seen that most of the air traffic approaches the airport via the northern traffic circuit (see Fig. 8b-d). Increasing numbers of crewed airspace users follow the downwind leg of the traffic pattern counterclockwise to the final leg via the base leg (see Fig. 8c). In addition, crewed airspace users tend to approach the final leg at a 90° angle from a direct line from the south (see Fig. 8c-d).

At Frankfurt-Egelsbach EDFE, the controlled terminal airspace (CTR) of Frankfurt EDDF ends directly at the western base leg of the traffic pattern and north of the city of Langen. Therefore, UAS are likely to approach the airport

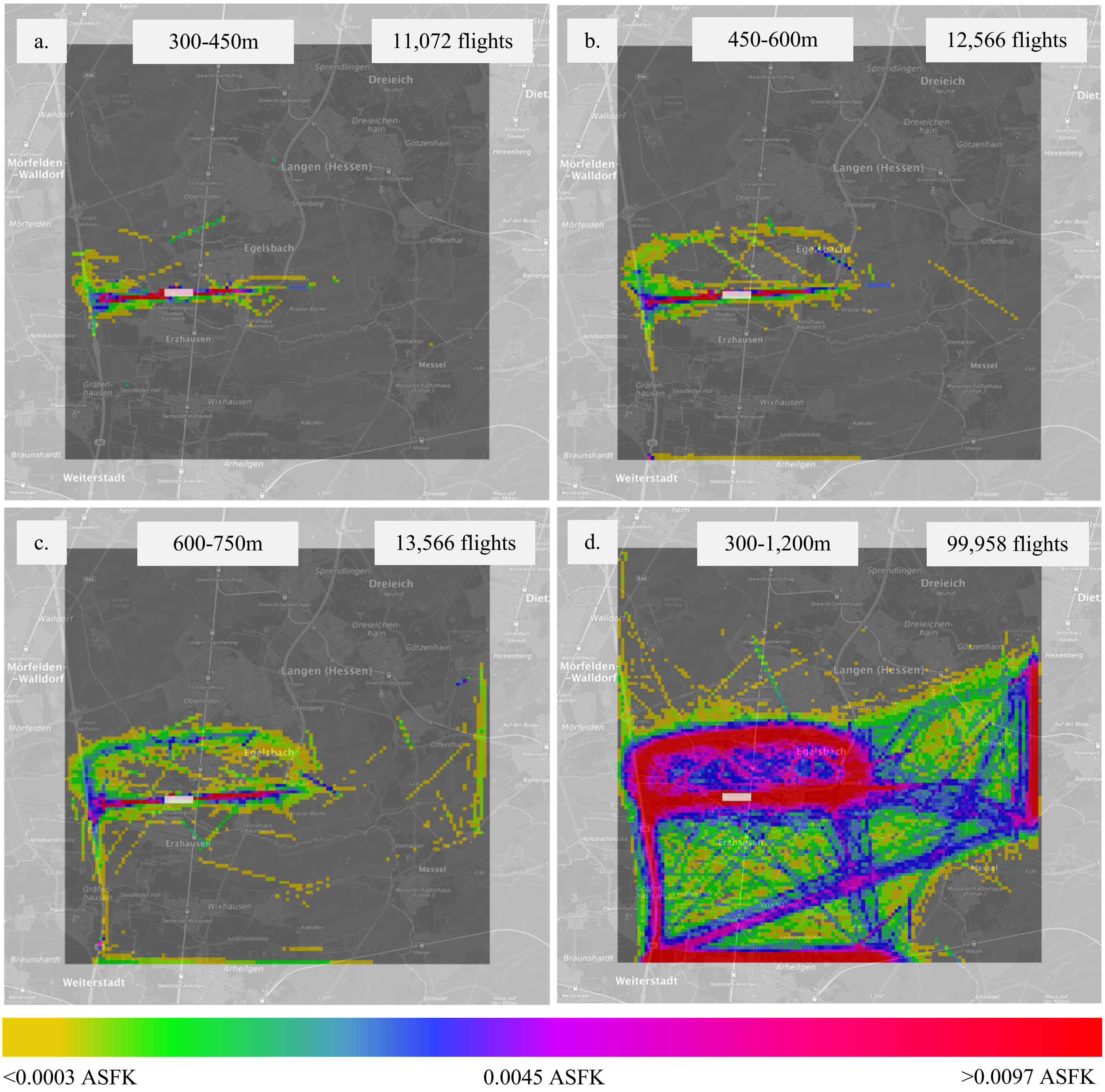

Fig. 8. Visualization of flights and traffic patterns at Frankfurt-Egelsbach EDFE

from the northeast side of the downwind leg of the northern traffic pattern. This is likely to take place via straight-in entry or base entry from the east. This way, UAS will avoid the western and northern boundaries of the CTR and crewed traffic from the south.

B. UAS integration concept in terminal U-space airspaces

Based on the different operational concepts discussed in Section II., this paper introduces a UAS holding stack concept for non-towered airport approaches within a U-space environment. UAS holding stacks are intended to handle increased VFR traffic intent uncertainty in uncontrolled terminal airspaces. The proposed holding stack concept can accommodate multiple UAS to enable high UAS traffic volumes. U-space airspace requirements (e.g., e-conspicuity obligation) will enable UAS to be aware of all airspace users' intent in the vicinity of the U-space.

It can be assumed that UAS will have minimal impact on crewed traffic by approaching the traffic pattern as late as possible. Approaching the traffic pattern in the last landing segment (e.g., via base entry or straight-in entry) reduces potential conflicts of UAS with crewed traffic within the different legs of the traffic pattern. The analysis of spatial traffic densities of the four P2 airports can be used to identify holding pattern locations for efficient UAS integration. Terminal airspace areas close the final leg of the traffic pattern with relatively low traffic volumes could be assigned as holding stacks with multiple UAS cruising at different altitude bands (see Fig. 9, one holding stack with four vertical holding patterns, each with 300 meters/1,000 feet of vertical separation). If the UAS is aware, based on the traffic information services provided by USSP, that the airspace around the last landing segment is free and traffic intent uncertainty is relatively low, the UAS can approach the non-towered airport at its own discretion.

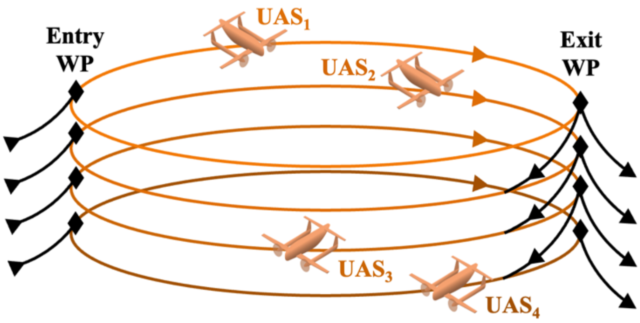

Fig. 9. UAS holding stack concept with four holding patterns

Alternatively, a U-space service could be set up that dynamically assigns UAS holding patterns and stacks based on the traffic intent uncertainty in the terminal U-space airspace. If too many VFR aircraft approach the airport at the same time, traffic intent uncertainty could become too high. The USSP could assign UAS to enter a holding stack until the traffic intent uncertainty decreases so that it is safe for UAS and other traffic to approach the non-towered airport. The USSP would provide the UAS with information regarding the holding stack location, minimum holding altitude, entry and exit procedures with according holding pattern WP, and maximum aircraft speed. The UAS would wait in the holding stack until the airspace in the last landing segment is completely free of traffic, or it could follow the preceding aircraft approaching the airport. The UAS would then enter the last landing segment of the traffic pattern according to the performance of the preceding aircraft.

A holding stack U-space service could be part of tactical conflict management services offered by USSP. Within future U-spaces, tactical conflict detection services will detect in-flight conflicts of UAS based on violations of tactical conflict thresholds [24]. A tactical conflict resolution service will instruct the UAS to resolve the conflict by adjusting in-flight parameters such as speed, flight level, and/or heading [24]. As a result, in-flight conflict resolution could be performed by USSP assigning the UAS to a holding stack to resolve potential conflicts with crewed aviation.

Today, holding stacks are already being utilized by ATC, mainly to resolve congestion at major hubs airports. Holding stacks are intended to handle increasing numbers of IFR aircraft in poor weather conditions or to overcome runway unavailability. London Heathrow EGLL, known to be one of the busiest airports in the world, utilizes four different holding stack locations to queue arriving aircraft over time [27]. ATC assigns pilots specific procedures for separation from other aircraft when entering the holding stacks and when descending from one holding pattern level to another.

At the investigated P2 airports, crewed airspace users generally follow standardized traffic patterns that are officially displayed in the airport's VOC. However, there are significant differences in the ASFK around the airports and in the utilization of the intended traffic pattern as well as their legs. At Juist EDWJ, for example, crewed traffic mostly flies in the southern traffic pattern, which will enable UAS to make increased use of the northern traffic pattern and nearby holding stacks (see Fig. 10).

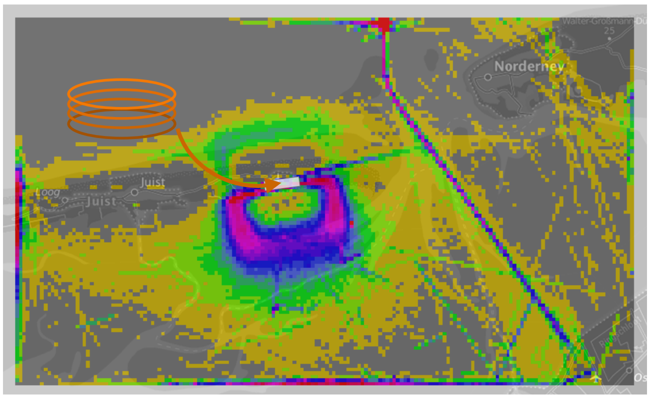

Fig. 10. Exemplary UAS holding stack at Juist EDWJ

In the end, each airport has unique characteristics such as its surrounding geographical environment, the nearby location of cities and other airports, airspace access restrictions and many more. The sum of these factors determines the appearance of unique flight route patterns and the overall behavior of air traffic at individual airports. After all, it is important that the operational integration of UAS occurs as efficient and safe as possible without overly restricting today's airspace operations. Therefore, future U-space airspaces should enable flexible and collaborative air traffic procedures for the comprehensive operational integration of all airspace users, regardless of whether they are crewed or uncrewed.

VI. CONCLUSION

This is the first known research to address the relevance of operational procedures for the integration of UAS within a U-space framework at non-towered airports in uncontrolled airspaces. This paper adapts the latest U-space ConOps architectures which propose all airspace users to be e-conspicuous in U-space airspaces. This will enable UAS to be aware of the flight intent of crewed traffic when approaching a non-towered airport within a U-space airspace. Today, uncontrolled terminal airspaces are characterized by non-cooperative VFR traffic with a relatively uncertain predictability of flight intent, making seamless airspace integration of UAS challenging.

This research investigates different terminal airspace environments of four German non-towered airports. By identifying airspace segments with low volumes of crewed traffic, this paper proposes the utilization of holding stacks for UAS approaches at non-towered airports. If the traffic intent uncertainty in the terminal airspace becomes too high, UAS will cruise in holding stacks before approaching the traffic pattern in the last landing segment. This will enable UAS to interfere with current crewed traffic as late as possible. Additionally, the proposed holding stacks could enable reliable contingency procedures, such as in the event of a lost C2 link (LC2L) between the uncrewed aircraft and the ground control station or remote pilot. In this case, the UAS would be required to remain well clear from other air traffic by remaining in its holding pattern or returning to its holding pattern in the holding stack.

Furthermore, the organization of different vertical holding patterns of the holding stack could be provided by U-space services. USSP could assign holding patterns based on UAS performance characteristics and current crewed traffic in the traffic pattern or prioritize UAS depending on the purpose of their flight missions.

Future work will continue to assess VFR traffic intent uncertainty around non-towered airports with more detailed UAS conflict detection and resolution management concepts. Specific parameters of UAS holding stacks and corresponding traffic pattern approach procedures need to be derived to conduct fast time simulations for concept validation. Furthermore, required terminal U-space airspace capabilities need to be investigated to provide appropriate air traffic services to UAS and crewed traffic. Finally, emerging U-space flight rules (UFR) are likely to pave the way towards highly automated and collaborative flight procedures that enable efficient tactical conflict management services for all airspace users within one airspace environment.

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