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REVIEW PAPER

Super Close Runway Operations (SupeRO): review of paired approach concepts on closely spaced parallel runways

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Abstract

Arrival throughput and runway capacity at an airport are major bottlenecks in air traffic management. Civil aviation organizations like the Federal Aviation Administration and Eurocontrol predict a large growth in demand in aircraft operations in the next 20–30 years. Airports with such a high demand can only serve them nowadays if they conduct visual approaches or paired approach procedures like the Simultaneous Offset Instrument Approach. Under instrument meteorological conditions, those procedures are not available and the runway capacity and especially the arrival throughput drops significantly. The common measure to increase runway capacity is the construction of new runways. To operate them according to current standards, large runway spacing is necessary and thus new large areas have to be acquired by the airport. However, this expansion of the airport area often poses a problem, making it difficult or preventing the construction of a new runway. To address this problem, the German Aerospace Center is developing the Super Close Runway Operations concept. In preparation for the development of paired approaches on super close runways as part of the concept, this paper provides a literature review of similar concepts that have addressed paired approaches. Key technologies required were identified as onboard interval management, adapted displays in the primary flight display and navigation display and the coupling of both aircraft systems. In addition to the key technologies, the merging of both approach courses and the appropriate utilization of wake vortex-free areas were identified as the focus of further investigations.

Keywords Paired approaches · Runway capacity · Arrival throughput · Super close runway operations

Abbreviations

ASAS	Airborne Separation Assurance System
CDTI	Cockpit Display of Traffic Information
CDU	Control and Display Unit
DA	Decision Altitude
DLR	German Aerospace Center
EGNOS	European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FMA	Flight Mode Annunciator
FMS	Flight Management System
GBAS	Ground-based Augmentation System
GLS	GBAS Landing System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IATA	International Air Transport Association
ILS	Instrument Landing System
IM	Interval Management
IMC	Instrument Meteorological Conditions
LDA	Localizer Type Directional Aid
LDACS	L-band Digital Aeronautical Communications System
ND	Navigation Display
NOZ	Normal Operating Zone
NTZ	No Transgression Zone
PAC	Paired Approach Operational Concept
PFD	Primary Flight Display
PRM	Precision Runway Monitor
RNAV	Area Navigation
RNP	Required Navigation Performance
RPAT	RNP Parallel Approach with Transition
SAP	Stabilized Approach Point
SBAS	Satellite-based Augmentation System
SOIA	Simultaneous Offset Instrument Approach
STARS	Standard Terminal Automation Replacement System

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SupeRO	Super Close Runway Operations
TACEC	Terminal Area Capacity Enhancing Concept
VDL	Very High Frequency Data Link
VMC	Visual Meteorological Conditions
WAAS	Wide Area Augmentation System

1 Introduction

The number of aircraft movements and passengers is expected to rise over the next two to three decades. The International Air Transport Association (IATA) forecasts nearly 8 billion passengers worldwide in 2040, about twice as many as in 2019 [1]. While Eurocontrol predicted about 16 million flights for Europe for the year 2040 before the COVID-19 pandemic, a post-pandemic Eurocontrol forecast does not reach this level until 2050 [2, 3]. Forecasts by other agencies are more progressive compared to Eurocontrol. IATA, for example, foresees a full global recovery in passenger numbers by 2025 [1]. The Federal Aviation Administration (FAA) forecasts a return to 2019 levels of aircraft operations in the U.S. by 2024. Further, aircraft movements at large hub airports in the U.S. are projected to grow by an average of 66 percent by 2050 compared to 2019 levels [4]. To meet the rising demand, solutions must be found for airports to increase their capacity. One common method of achieving this is to build additional runways. To be able to use these effectively, a simultaneous use of both runways should be aimed for. The ICAO recommends certain minimum spacings for simultaneous operations on parallel runways [5]. If these spacings are adhered to, the airport area usually has to be extended. To avoid this, the DLR Institute of Flight Guidance is developing the Super Close Runway Operations (SupeRO) concept. The concept idea is designed to enable runway spacings of less than 200 m. To achieve this, paired approaches to the two super close runways are to be carried out.

The aim of this study is to determine which paired approach procedures and concepts have been developed and published to date and what knowledge can be gained from them. The intention is to examine whether key technologies and approaches can be derived from the concepts that could be useful for the development of paired approaches on super close runways and should be investigated further. Therefore, the respective concepts are briefly summarized and then examined with regard to their core elements and technology requirements as well as the distribution of responsibility.

At the beginning of this paper, Sect. 2 presents the core elements of the SupeRO concept idea and deals with the concept of a flight corridor, an elementary component of all subsequent concepts examined in Sect. 3. In this section, all concepts are briefly summarized and examined for their readiness and transferability to paired approaches on super close runways. A discussion of the highlighted findings concludes this paper.

2 SupeRO concept

The Super Close Runway Operations (SupeRO) concept idea is an exploratory research based on two parallel runways with a centerline spacing of less than 200 m. This close spacing is intended to achieve that the additional runway fits into the existing airport area and thus avoid an expansion of the airport area to prevent legal and political difficulties due to the new area to be acquired as well as with the new areas affected by noise. The minimum feasible runway spacing is finally determined by the available accuracy of the navigation and flight performance and also by a consideration of the wingspans, if overtaking both while airborne and when rolling out cannot be ruled out.

To make these closely spaced runways usable, three different modes are intended for SupeRO. One of these is the SupeRO segregated mode. In this mode, one runway is used exclusively for departures and the other exclusively for arrivals. Unlike in segregated mode, as described by ICAO in [5], in which arrivals and departures can be operated simultaneously, in SupeRO segregated mode successive departures and arrivals are directly dependent on each other, as there is a fixed time interval between the touchdown of the arrival and the initiation of the take-off roll of the departure. The operational concept and the benefit mechanism of the SupeRO segregated mode as well as an early-stage pilot support system for departures were published in [6, 7]. In this mode, the capacity gain results from saving most of the runway occupancy time of the arrival. The SupeRO segregated mode represents a near-term solution for the implementation of the concept idea. The remaining two modes are paired departures and paired approaches, while the focus of this study is on paired approaches.

To increase the arrival throughput at an airport, in addition to the construction of additional runways, the reduction of longitudinal separation between the aircraft is a common approach. One example is the recategorization of the aircraft wake turbulence categories ("RECAT-EU" [8]). This is a low-cost and simple approach but has only a small increase in runway throughput (5 to 8 percent [8]). As shown in Fig. 1, due to the hazardous wake vortices of the leading aircraft, there is a physical limit that prevents further reduction in in-trail separation.

But due to the aerodynamical properties of the wake and its spread, a wake vortex-free region is located diagonally behind the leading aircraft. Those wake vortex-free regions were entitled as "flight corridors". The initial idea of a flight corridor was to reduce the in-trail separation onto a single runway [9]. Therefore, wake stations

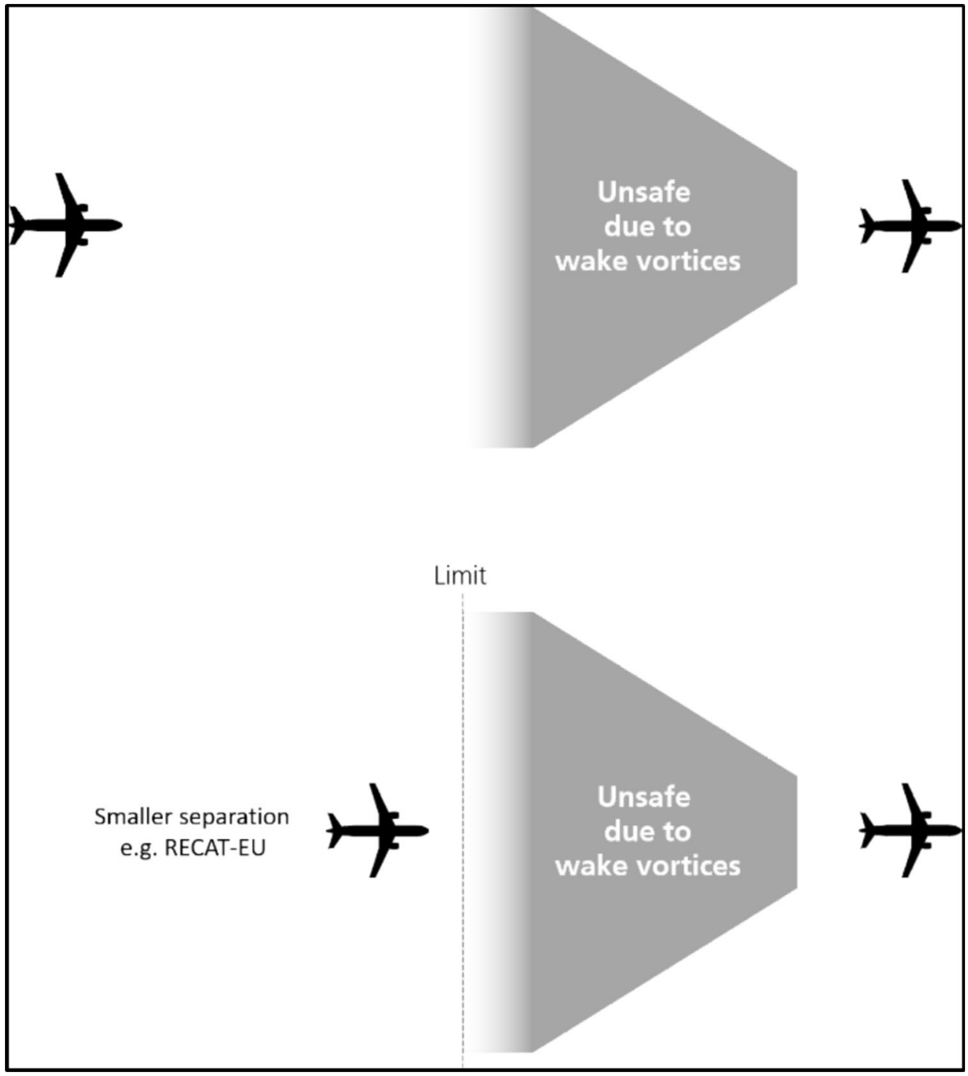

Fig. 1 Illustration of the physical limit of reducing in-trail separation due to wake vortices

are determined along the glide path that are assumed to contain all possible wake vortices. This means, that all the airspace outside of those wake stations are guaranteed wake vortex-free [10].

The authors of [11] deliver a more detailed investigation of the usage of flight corridors on closely spaced parallel runways. Therein, the safe region right behind a leading aircraft is identified (see Fig. 2). This region is considered to be wake vortex-free if the rolling moment induced by an encountered wake vortex is less than one-sixth of the roll control authority available through the use of the ailerons. The paper provides a computational tool to calculate the wake vortex propagation. It calculates the initial size of the wake hazardous area, which is dependent on the wing span ratio of both aircraft. Aerodynamic phenomena then cause the area to grow to a certain maximum before it subsequently continues to grow proportional to the square-root of time. In addition, the computational tool takes the effect of cross winds into account [11].

The tool can then be used to calculate the location and time of the intrusion of the wake at the adjacent runway. With these calculation results, the size of the safe area can be determined for given lateral runway spacings. This enables requirements to be placed on aircraft performances (e.g. required minimum approach speed). On the other hand, it will be possible to determine a minimum required lateral runway spacing for given aircraft performances.

Figure 3 shows a calculation example that was made with the computation tool provided by [11] for two runways with a centerline spacing of 150 m. For both aircraft, an Airbus A320 and an approach speed of 140 knots were selected. The lead aircrafts position is located at the point of origin of the diagram. The ordinate shows the lateral and the abscissa shows the longitudinal distance from the leading aircraft. Each pair of graphs illustrates the boundaries of the wake hazardous area behind the leading aircraft for different cross wind speeds. As can be seen, if there is no cross wind, the wake from the leading aircraft approaching the left

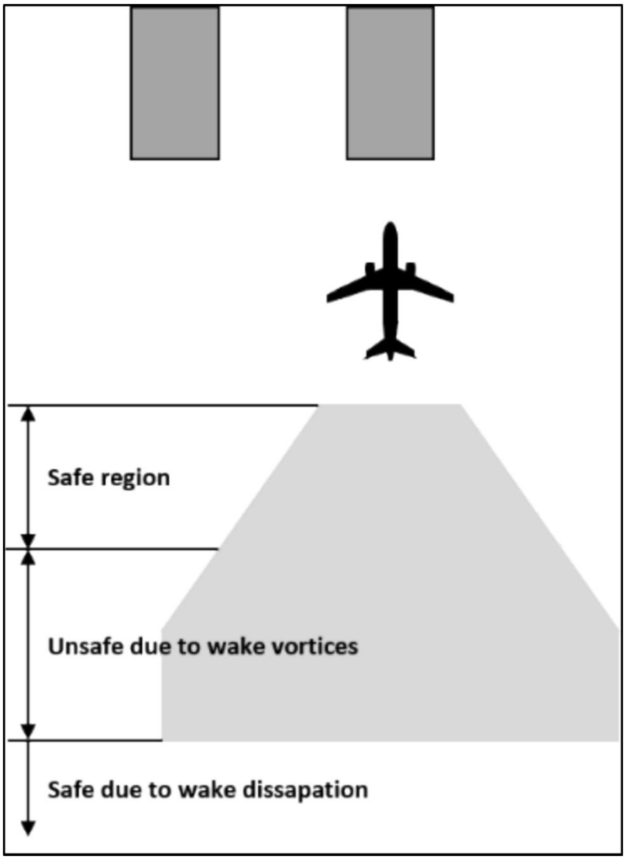

Fig. 2 Safe region behind a leading aircraft based on [11]

runway intrudes the adjacent runway approximately 1100 m and 15 s respectively behind the leading aircraft itself. At cross wind speeds of 5 knots the intrusion time shifts to 25 s after the leading aircraft, providing an additional safe range of about 700 m. Stronger cross winds, e.g. 10 knots, would result in the wake vortex not affecting the adjacent runway at all. The results demonstrate the benefit of the trailing aircraft approaching the upwind runway. Accordingly, as cross wind speeds increase, the safe area would decrease if the leading aircraft were flying downwind of the cross wind. Furthermore, the diagram also demonstrates that the smaller the lateral spacing between the runways and thus also between the approaching aircraft, the smaller the longitudinal size of the safe area. For this specific calculation example the head or tail wind was neglected, since for wind speeds lower than about six knots it has no greater influence on the intrusion time than one second [11].

This example shows how the calculation tool can be used to explore the spacing limits and aircraft performance requirements for paired approaches to super close runways resulting from wake vortices. In addition to the rear boundary defined by the hazardous wake vortex area, the following aircraft should not overtake the leading aircraft in order to avoid a risk of collision due to blundering and to avoid reversing the wake vortex problem between the aircraft.

To ensure that paired approaches on super close runways can develop their maximum usability, they should also be feasible under Instrument Meteorological Conditions (IMC), so that these can also be carried out if there is no visual contact between aircraft. Due to this condition combined with the small lateral spacings, active coupling of both aircraft systems is envisaged, meaning a direct connection of the flight management and flight guidance systems, so that the flight guidance of the leader directly influences the flight guidance of the follower. For example, the flight management system of the follower should be automatically informed about a new selected or managed speed of the leader without the follower having to detect it first. This is intended to ensure that the pair separate themselves from each other and no longer require external monitoring.

In summary, the following core characteristics are envisioned for paired approaches in the SupeRO context:

- Lateral spacing of less than 200 m
- Entering and maintaining an exact relative position to each other (safe area)
- Coupling of both aircraft systems
- Feasibility under IMC

To this end, the paired approach part of the SupeRO concept aims for single-runway airports, which could be extended by a super closely spaced parallel runway next to the existing one while staying inside the existing airport surface area. Since simultaneous approaches on two parallel runways are only possible down to 915 m (3000 feet) runway spacing without specific examination according to [5], already existing airports with two very closely spaced parallel runways below 915 m runway spacing will also be of interest if paired approaches prove to be feasible. This limit was chosen because it represents the minimum runway spacing for dependent simultaneous approaches according to ICAO Doc 9643. These airports could offer the potential to use an adapted SupeRO concept on their existing runways. The potential of existing airports to apply the SupeRO concept was investigated by [12]. The following map (Fig. 4) shows the locations of large single-runway airports (182 airports) as well as airports with two parallel runways (dual runway airports) with runway spacings below 915 m (45 airports).

Beside the designated use of SupeRO as a capacity-increasing concept, it may also be beneficial in reducing the noise impact. If demand does not require paired approaches at all times of the day, they could still be used to extend noise breaks between two operations by pulling apart the approaching aircraft. Figure 5 illustrates this consideration.

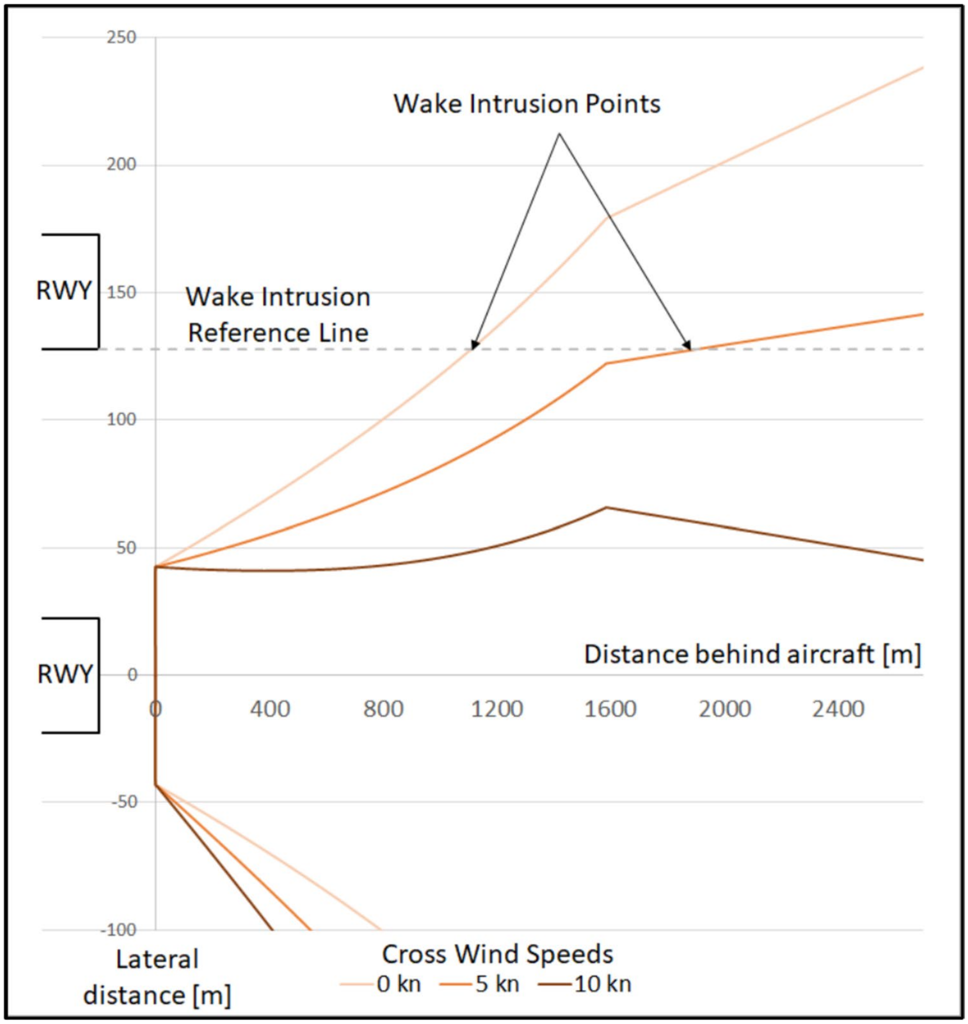

Fig. 3 Calculation of the wake vortex propagation for different wind speeds using the tool provided by [11] (A320, 140 kn approach speed)

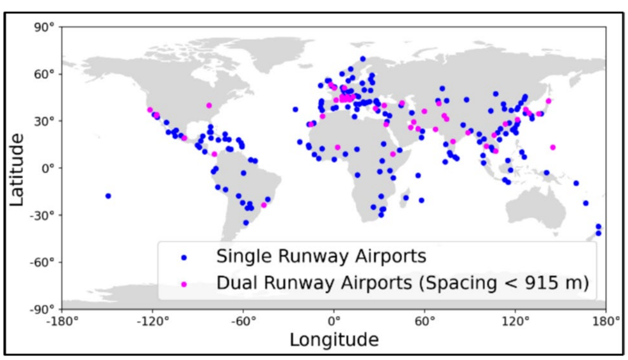

Fig. 4 Locations of large single-runway airports und dual-runway airports with less than 915 m runway spacing

2.1 Climate impact considerations

SupeRO's target of increasing runway capacity seems to be in conflict with the climate crisis, as it will allow more

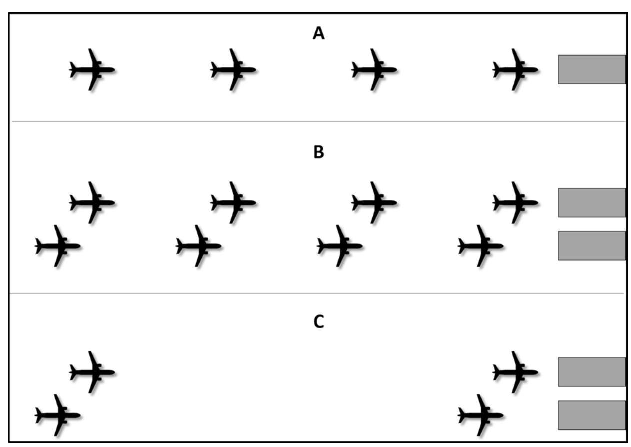

Fig. 5 Modifying an original approach stream (**A**) by doubling the number of aircraft to increase arrival throughput (**B**) or by pulling apart the aircraft to increase the duration of noise breaks (**C**) using paired approaches

flights than currently possible. Therefore, the following considerations and hypotheses were made:

1. SupeRO is being developed due to expected increase in demand for aircraft operations. Should this demand arise and the airspace accommodate this increase, runway capacity will be a limiting factor. This could lead to more holding queues or avoidable detours on approach and thus to more fuel consumption and emissions than if these flights could land directly.
2. If major progress were made in researching sustainable aviation fuels or other environmentally friendly options, such as electric or hydrogen-powered engines, emissions could be reduced to net zero. Assuming that SupeRO will be operational by 2050 and that these climate-friendly measures will have been applied by then, the amount of flights may no longer have a significant impact on climate change.
3. Electrical or hydrogen-powered aircraft tend to have less passenger capacity as current aircraft types. Therefore, even if passenger demand remained the same, the number of flights would increase and exacerbate the runway capacity problem.

3 Review of concepts

In this section, various concepts are presented whose operating mechanism is also based on the utilization of the wake vortex-free area right behind the lead aircraft. For this purpose, each concept is first briefly summarized. Second, the readiness level is investigated and finally, similarities and transferability to the SupeRO concept idea are discussed.

3.1 Simultaneous Offset Instrument Approach

3.1.1 Summary

The Simultaneous Offset Instrument Approach (SOIA) is an approach procedure, which utilizes the wake vortex-free region behind a leading aircraft by flying a visual swing-over maneuver with the trailing aircraft on the final approach segment. It is applicable for closely spaced parallel runways with a centerline distance from 3000 feet down to 750 feet. The approach consists of a straight-in final approach course like an instrument landing system (ILS) approach with a precision runway monitor (PRM) onto one runway and an offset Localizer Type Directional Aid (LDA) PRM approach to the other runway. The offset final approach course has an offset angle from 2.5 to 3.0 degrees. Between the offset and the straight-in final approach course a 2000 feet wide No Transgression Zone (NTZ) is located. The LDA aircraft follows the offset course until it reaches the LDA Decision Altitude (LDA DA) at a distance between both courses of 3000 feet. From this point, the LDA aircraft has to continue the approach under visual conditions. If the LDA aircraft cannot establish visual contact with the leading ILS aircraft at this point, the LDA aircraft has to perform a missed approach. If visual contact is established the LDA aircraft will fly visually to the stabilized approach point (SAP), which is a designed point on the extended centerline of the targeted runway. It is located approximately 8500 feet from the runway threshold. After the SAP both aircraft continue their approach on a straight-in course, while the LDA aircraft always stays behind the leading ILS aircraft to ensure that the LDA aircraft cannot be affected by the wake vortex of the leading ILS aircraft [13].

A scheme of the SOIA procedure is shown in Fig. 6.

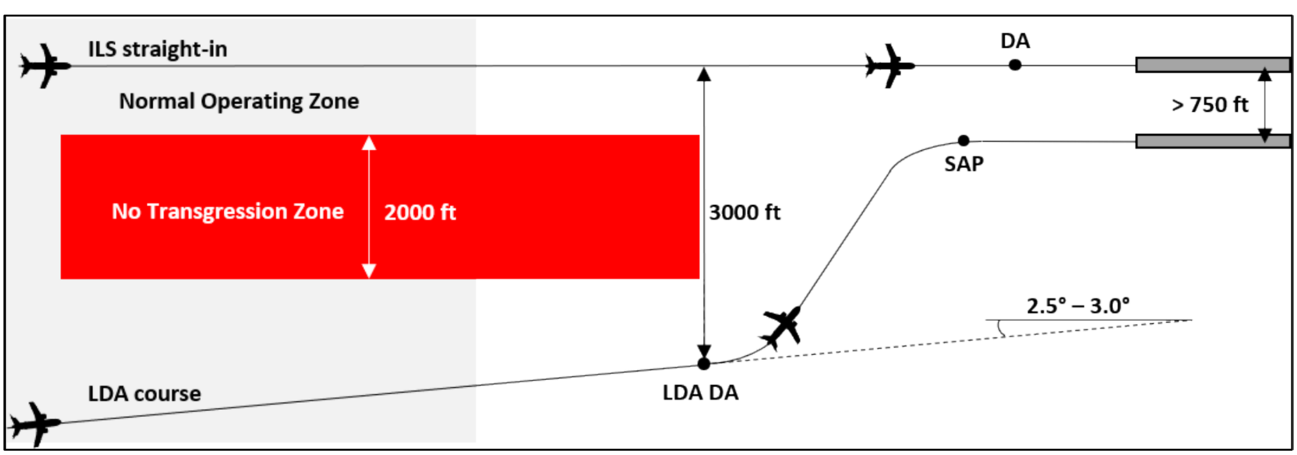

Fig. 6 Scheme of the SOIA procedure based on [13]

3.1.2 Readiness

The SOIA procedure is already usable at San Francisco International Airport (KSFO) and at Cleveland Hopkins International Airport (KCLE) [14]. Both airports have closely spaced parallel runways (750 feet (230 m) [15] at KSFO and 1241 feet (380 m) [16] at KCLE).

By using the SOIA procedure under Visual Meteorological Conditions (VMC), which are mandatory due to the visual segment in the SOIA procedure, San Francisco International Airport achieves an overall capacity of up to 104 operations per hour. Of these, 54 operations are arrivals and 50 are departures while using runways 01L/R mainly for departures and runways 28L/R for arrivals. At lower departure rates, up to more than 60 landings per hour were achieved [17]. In the Airport Capacity Profile Report for KSFO published by the FAA in 2019 a theoretical rate of 80 arrivals per hour under VMC was estimated, if there would be no departures and only arrival operations on runways 28L/R today [17].

If the direction of the wind does not allow operations on runways 01L/R anymore, the SOIA procedure is not further used. Instead, the aircraft arriving on parallel runways will be staggered by 2.5 nautical miles. This results in a reduced reported capacity of 85 operations per hour. Under IMC the capacity drops down to 74–78 operations per hour including an hourly arrival rate of 34–35 [17].

3.1.3 Transferability to SupeRO

As seen in the previous section the SOIA procedure presents a suitable possibility to increase runway capacity at airports with closely spaced parallel runways for centerline distances down to 750 feet. For the example of KSFO the SOIA procedure increases the arrival throughput under VMC up to 59 percent compared to the IMC operations, where the separation between arrivals is given by FAA J.O. 7110.308 (54 instead of 34 arrivals [17]). This reduction in capacity resulting from the downgrading of weather conditions from VMC to IMC illustrates the need for the SupeRO concept to be able to operate under IMC as well. Nevertheless, the SOIA procedure shows by the fact that it is already being performed, that paired approaches are already technically feasible today.

In the following, the SOIA procedure is compared with the intended core elements of paired approaches in the SupeRO context.

The SOIA procedure is applicable from 3000 to 750 feet (915–230 m). In the context of SupeRO, even smaller spacings are to be realized. However, the possible range of the SOIA procedure indicates that this procedure is also aimed at the target group of airports with a runway spacing of less than 915 m mentioned in Sect. 2.

A relative position is only vaguely defined in the SOIA procedure. It is limited by the continuation of visual contact and not overtaking. This procedure is not transferable to paired approaches in the SupeRO context. As explained in Sect. 2, an exact relative position must be maintained for these approaches so that the following aircraft cannot be affected by the wake vortex of the preceding aircraft. In relation to a forward boundary, however, both concepts share the approach that the leading aircraft should not be overtaken. Aircraft are only paired in the SOIA procedure to the degree that the aircraft are positioned on the approach courses in such a way that the following aircraft has the opportunity to ensure visual contact approximately 30 s before reaching the LDA DA [13]. There is no active coupling of the flight systems between the aircraft. Although special training is required for this procedure, no assistance systems are used to help establish the required relative position. The relative positioning on the extended centerline is done exclusively manually by visual contact. This means that after leaving the LDA course, on which a lateral deviation was still monitored by the PRM controller, the responsibility lies entirely with the pilots of the following aircraft. As paired approaches on super close runways are also intended to be operated under IMC, this procedure cannot be used due to the lack of visual contact. This makes it clear that an active coupling between the two aircraft is necessary to maintain the required relative position even without visual contact. How the distribution of responsibility changes through the use of such a coupling depends on the actual implementation of the coupling and the degree of automation achieved.

3.2 RNP Parallel Approach with Transition

3.2.1 Summary

Another simultaneous approach type to closely spaced parallel runways is the required navigation performance (RNP) Parallel Approach with Transition (RPAT). It is applicable to runway centerline distances down to 750 feet. The procedure consists of an ILS straight-in course onto one runway and a parallel offset RNP approach course including a transition segment onto the other runway. The ILS aircraft operates in at least 2300 feet wide normal operating zone (NOZ). A 2000 feet wide NTZ is located between the ILS and the RPAT aircraft, from which the RPAT course is separated by two times the RNP value (see Fig. 7). For example, this leads to a distance between both courses of about 6800 feet for RNP 0.3 and to 4370 feet for RNP 0.1. The NTZ ends at the final approach fix. From this point, the pilots of the RPAT aircraft have to maintain separation visually, since the pilots of the trailing aircraft are responsible to stay behind the leading aircraft. To perform the RPAT procedure, there

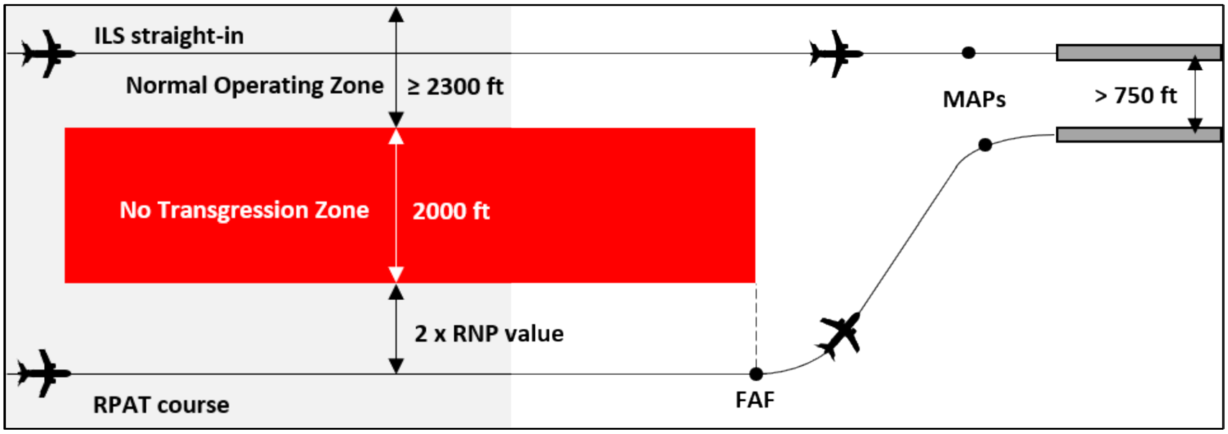

Fig. 7 Scheme of the RPAT procedure based on [19]

must be a minimum visibility of 2000 feet vertically and 4 nautical miles horizontally [18].

The RPAT procedure therefore resembles the SOIA procedure in its structural design. Both have an instrument part of the approach with an NTZ and a transition segment where separation is maintained visually. The key difference between both procedures is the dependency of ground-based navigational aids. While in the SOIA procedure, the second aircraft is dependent on the ground-based LDA, in the RPAT procedure the second aircraft relies on satellite-based navigation. But for the same reason as with SOIA, the RPAT procedure is also not usable under IMC [20].

3.2.2 Readiness

As mentioned the RPAT procedure as well as the SOIA procedure is not available under IMC. Thus, the DLR investigated a possibility to conduct the RPAT procedure under IMC by using an airborne separation assurance system (ASAS) to maintain separation. Therefore, the RPAT aircraft predicts the ILS aircrafts 4D trajectory by using for example ADS-B out of the ILS aircraft. This shifts separation responsibility to the pilots and reduces the workload of controllers. Using 4D trajectory and ASAS would allow the RPAT aircraft to get to a merge point inside the wake vortex-free zone behind the leading ILS aircraft even under IMC [21].

Flight trials consisting of one research aircraft as RPAT aircraft and two other research aircraft of different types as leading ILS aircraft were conducted. The trial results show that timing for the aircraft to be paired is crucial. While the RPAT aircraft was able to reach the merge point with high precision in the trials with one of the leading aircraft, there were issues with the ADS-B reception in the trials with the other leading aircraft and thus with the prediction of its 4D trajectory. This shows that a lack of data can lead to necessary breakout maneuvers and therefore to more missed approaches. Nevertheless, the results show that the procedure would be technically feasible under IMC with the necessary technical adjustments, such as the use of ASAS and a 4D FMS, and if data transmission can be ensured [21].

3.2.3 Transferability to SupeRO

Like the SOIA procedure, the RPAT procedure provides a simultaneous landing capability for closely spaced parallel runways down to a minimum of 750 feet (230 meters) runway spacing. Compared to the SOIA procedure, the approach course of the RPAT procedure is not dependent on ground-based navigation aids. Considering the even smaller intended separation, this would be an advantage for paired approaches in the SupeRO context. This is because the results from Sect. 2 already indicated that there is a strong cross wind dependency affecting the size of the safe area. This means that for paired approaches on super close runways, the cross wind could be decisive for which runway is approached by the leading aircraft and which by the trailing aircraft. Compared with the SOIA procedure, in which each runway in each operating direction would have to be equipped with an LDA, only one runway would have to be equipped with an ordinary ILS for the RPAT procedure.

With regard to the other intended core elements for paired approaches on super close runways, there are no new findings from the RPAT procedure due to its high similarity of it to the SOIA procedure. There is also no active coupling of the aircraft systems, an exact relative position is not defined and the visual separation on the last segment rules out execution under IMC.

This is different from DLR's version of the RPAT procedure. In this case, a merge point is used to specify an exact relative position, which the following aircraft attempts to meet using the prediction of the 4D trajectory from the ADS-B out data of the leading aircraft. In addition, ASAS is intended to ensure separation even under poor visibility conditions. However, both aircraft systems remain independent of each other and there is no active coupling. In addition, the results of the flight tests also show how crucial a secure and stable data connection between both aircraft is. If the aircraft lose their connection to each other, they can no longer ensure that they are in the required relative position to each other. Furthermore, without a link between the two aircraft systems, the leading aircraft has no knowledge of the position and situation of the aircraft immediately behind it.

3.3 Paired Approach Operational Concept

3.3.1 Summary

The initial idea of a paired approach concept originates from [22]. Continued efforts to develop paired approach procedures to increase airport landing rates subsequently occurred in the late 1990s and early 2000s [23–26]. The first paired approach operational concept (PAC) was then presented in 2001 [27, 28].

When two aircraft have been paired, there are two hazardous areas for the trail aircraft; named “blunder danger zone” and the “wake danger zone”. The blunder danger zone concerns the area in front of the trail aircraft and is based on the possibility of the lead aircraft deviating from its approach course in the direction of the adjacent course ("blunder"). Accordingly, a collision of the two aircraft may occur in this area should the lead aircraft blunder. This hazardous area, ahead of the trail aircraft, represents the forward limit of the safe area in which the trail aircraft may be located. The wake danger zone is originated by the wake vortices of the lead aircraft. The extension of this hazardous area is caused by the spreading of the wake vortices and their shifting due to cross winds. Since wake vortices, as described in Sect. 2, grow over time and shift with the wind, they do not immediately impact the approach course of the trail aircraft. Instead, the wake vortices encountering the adjacent approach course further back results in a rear limit of the safe area. As long as the trail aircraft remains between these two boundaries, a paired approach can be performed safely. The researchers additionally provide this area with safety buffers and call it the "protection zone" (see Fig. 8) [28]. For two aircraft to be pairable each aircraft has to be sufficiently equipped. For the lead aircraft, there are certain requirements for its speed capabilities. It must be capable to maintain a speed given by the controller before the final approach fix (FAF) and perform a certain speed profile after the FAF. Furthermore, at least ADS-B and a Cockpit Display of Traffic Information (CDTI) are required for the trail aircraft. The developed CDTI features consist of an additional initialization page on the Control and Display Unit (CDU) to select the targeted leading aircraft and to arm the paired approach functions.

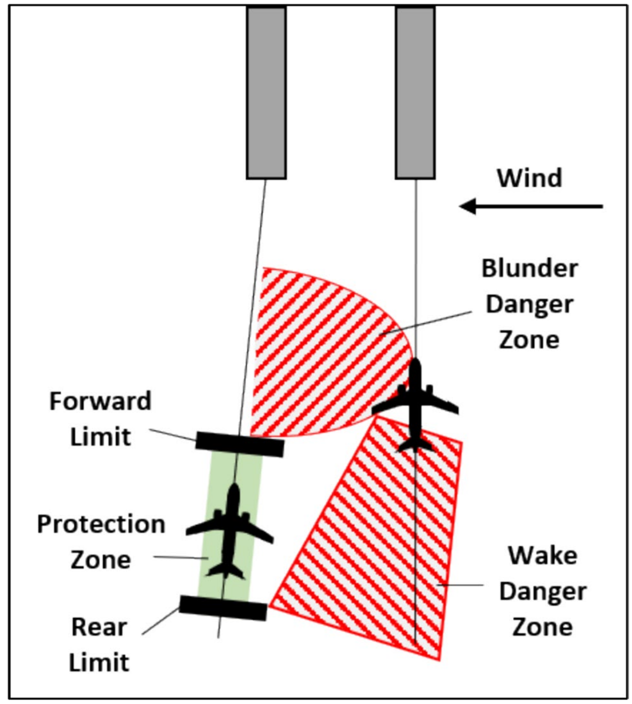

Fig. 8 Scheme of the safe "protection zone" based on [28]

Moreover, it provides additional information on the primary flight display (PFD) and the navigation display (ND) about the targeted aircraft as well as the relative position to be achieved and maintained [27].

The basic scheme of the approach is presented in Fig. 9. In this concept the leading aircraft is performing an ILS straight-in approach. Depending on the airport, the trail aircraft flies a straight-in or a 3-degree offset ILS or differential GPS landing system approach ([27]) or RNAV approach ([29]). The offset course ends 0.5 nautical miles from the runway threshold and transitions to a straight-in to the extended centerline of the targeted runway. Moreover, Fig. 9 shows the separation between the involved aircraft. There is a special separation between paired aircraft, which is presented below. Between two pairs as well as between a pair and a not sufficiently equipped aircraft standard separation is applied [27, 29].

In the initial approach, the following aircraft approaches the leading aircraft using interval management. In doing so, it should reach an assigned spacing goal that is inside of the safe area. This spacing goal is calculated using the final approach speeds of the aircraft involved. At this point, the safe area is only limited to the front by the blunder danger zone. There is no rear limit due to the wake danger zone in this early part of the approach. In this way, the following aircraft continues to approach the leading aircraft. At the FAF, the interval management is terminated and the aircraft complete their respective approach at the specified final

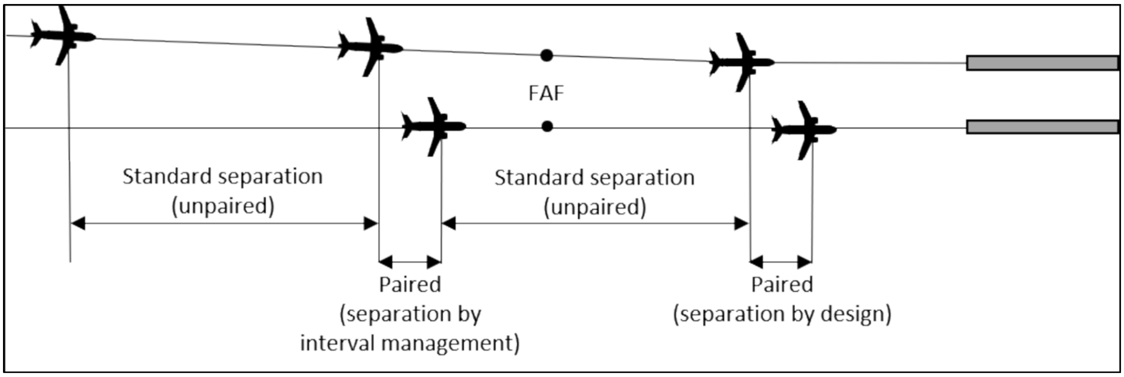

Fig. 9 Scheme of the PAC based on [27, 29]

approach speeds. The assigned spacing goal is calculated in such a way that the aircraft remains in the safe area after the termination of interval management by design, provided that both aircraft continue to fly at the specified final approach speeds. This also considers different approach speeds and the associated reduction or enlargement in the separation [29].

3.3.2 Readiness

Flight trials of paired approaches by the FAA took place at San Francisco International Airport (KSFO) and Tucson International Airport (KTUS) in February 2019. Onboard interval management was used in the trials to achieve and maintain the required relative position. The PAC is designed for use under IMC but the trials were carried out with two different pairs of aircraft under VMC to ensure safety during the trials. One pair consisted of an Airbus A320 family aircraft as lead aircraft and a Boeing 757 as trail aircraft (same wake category). The other pair consisted of a Boeing 777–200 as lead aircraft and a Boeing 757 as trail aircraft (wake categories B and D). The results of the trials showed that a previously defined range of plus or minus seven seconds around the assigned spacing goal at the FAF, at which the interval management is terminated, was achieved in all trial runs.

3.3.3 Transferability to SupeRO

The PAC provides a solid framework for the development of paired approaches on super close runways. It defines an exact relative position range when using the safe area behind a leading aircraft with the boundaries to the blunder and wake danger zone. The assigned spacing goal provides a continuously measurable value that can be used to monitor the relative position of the following aircraft.

The PAC is also designed for a runway spacing of down to 750 feet (230 m), probably based on the San Francisco International Airport. The even smaller spacing of the SupeRO concept could make it difficult to apply the PAC to super close runways. With the PAC, entry into the safe area is achieved via an offset course. However, whether this implementation is also feasible with even smaller runway spacings would have to be investigated by examining the wake vortex area. This is because it is to be expected that even smaller runway spacings could lead to the offset angle having to assume relatively large dimensions if the cross wind is too strong and unfavorable. As a result, the imaginary intersection point of both approach courses would be earlier and therefore less time for reactions in the event that the relative position cannot be maintained. An illustration of this consideration is shown in Fig. 10.

This problem could be avoided by ensuring that the following aircraft always flies upwind of the leading aircraft. This in turn would lead to higher requirements being placed on the merging of two aircraft into a pair. The initial approach would have to be designed in such a way that the aircraft intended as the leading aircraft actually flies ahead. For a side change of leading and following aircraft, it must be assumed that the concept is also possible with the leading aircraft on the offset and the following aircraft on the straight-in course. Otherwise, the approach courses would also have to be swapped with the aircraft changing sides.

Accordingly, for the development of an approach geometry of a paired approach procedure on super close runways a solution to the offset angle problem must be found and the initial approach must be designed in such a way that it is possible to react flexibly to cross wind changes.

Nevertheless, the flight trials carried out showed that with the aid of ADS-B interval management and suitable avionics, a sufficiently high degree of accuracy in maintaining longitudinal separation inside a pair can be achieved. As the onboard interval management between the paired aircraft makes it possible to monitor their relative position even under poor visibility conditions, this could be a key technology in the development of the SupeRO concept.

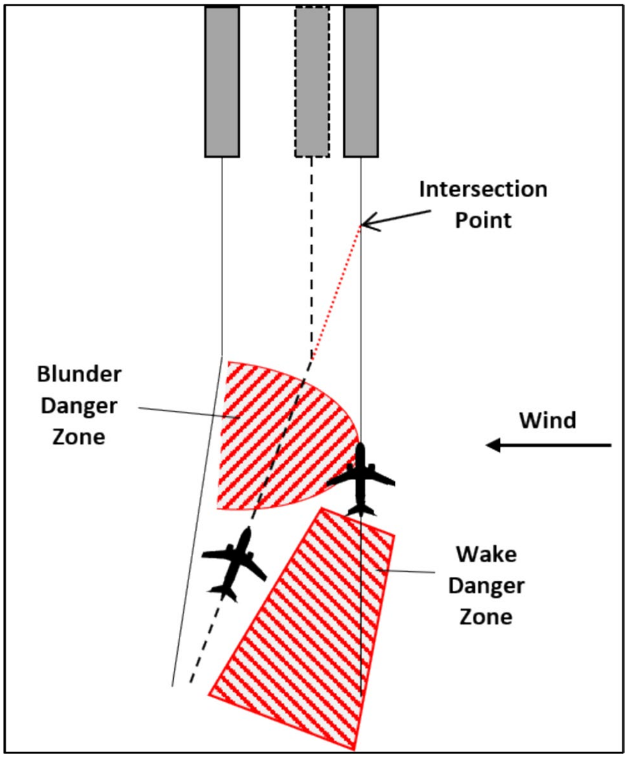

Fig. 10 Illustration of the offset angle problem with super close runways compared to the PAC

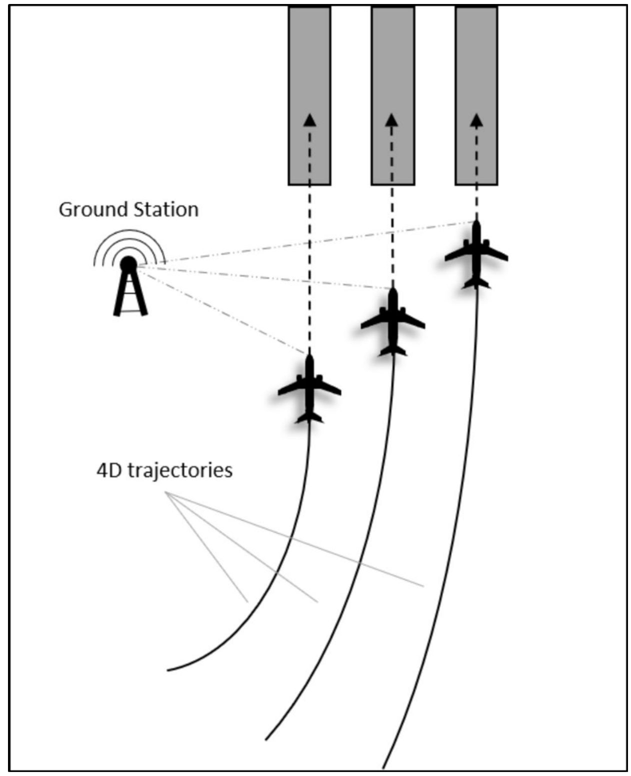

Fig. 11 Basic scheme of TACEC based on [30]

Furthermore, this also underlines the importance of relative navigation for the execution of paired approaches. As long as the relative position to each other is maintained, it can be assumed that the primary approach type, e.g. whether ILS or GLS, is of secondary importance. If this consideration is taken further, an active coupling of the aircraft systems makes it possible to transfer the primary navigation completely to the leading aircraft and to navigate the following aircraft exclusively relative to the leading aircraft. This would have the effect that the accuracy of the primary navigation mode would have no influence on the separation within the pair.

3.4 Terminal Area Capacity Enhancing Concept

3.4.1 Summary

This section presents the Terminal Area Capacity Enhancing Concept (TACEC) developed by [30] in 2003. TACEC exploits the same effect as the PAC. It also uses the idea of a flight corridor according to [9, 11]. However, TACEC extends the idea further than the PAC. While the PAC pairs two aircraft at a time, TACEC provides for the pairing of several approaching aircraft, e.g. three to four aircraft. The researchers assumed that the accuracy required for this concept could be achieved with the use of differential GPS landing systems and 4D trajectories [30].

To find suitable aircraft pairs, the aircraft are tracked in the terminal airspace using their ADS-B or TIS-B data. If both aircraft are able to reach the approach meter fix within a two-minute period, their speed capabilities are used to determine whether they are suitable for pairing. If the aircraft could be paired, a 4D trajectory is created, which allows the trail aircraft to enter the safe area behind the lead aircraft, without being affected by the wake vortices. The 4D trajectory is calculated and transmitted from a ground station to the aircraft using a suitable data link. The researchers suggested VDL (Very High Frequency Data Link) Mode 3 as an option. The waypoints contained in the 4D trajectory are updated every minute. The final approach will then be performed by using GLS and auto-land avionics [31]. A basic scheme of TACEC is illustrated in Fig. 11.

3.4.2 Readiness

Since the concept was published in 2003, a series of research papers based on it have been produced. Initially, between 2004 and 2005, research was conducted on the necessary communication, navigation and surveillance requirements, see [31–33]. The results of this work are recommendations of suitable data links for the transmission of 4D trajectories, such as the VDL Mode 3. It must be mentioned that after the publication of these studies, VDL Mode 3 was not further implemented by the FAA. Accordingly, another suitable data link would have to be found. Due to its ability to transmit 4D trajectories via data link, the L-band Digital Aeronautical Communications System (LDACS) would be a suitable option [34]. The assumption that differential GPS systems like GBAS would enable positioning with an accuracy of a few meters is repeatedly mentioned in the studies. The researchers also assumed that all major US airports would have operational GLS by the early 2020s. However, this is not the case, since only three US airports are equipped with GBAS stations [35]. The situation is similar in Europe. There are currently four airports equipped with a GLS CAT I. A further 17 airports in Norway operate a GLS with S-CAT I [36].

In the years that followed, from 2008 to 2016, several studies on adapted procedures for pilots as well as controllers were conducted [37–43]. Aspects such as additional displays, different degrees of automation and off-nominal procedures, e.g. due to blunder or wake vortices, were investigated. Furthermore, approaches to automated pairing algorithms of the involved aircraft were presented. These studies used adapted flight deck displays previously developed by [44]. Briefly summarized, the following results emerged from these studies:

Findings from [37] showed that additional indications in the PFD and ND are useful to pilots. These include, for example, the display of wake vortex information in the PFD and ND or the introduction of a named Longitudinal Situation Indicator in the ND, which describes the point targeted by the autopilot to keep the aircraft within the safe area. Furthermore, the pilots of the following aircraft can see from the Flight Mode Annunciator (FMA) that the speed as well as the lateral and vertical navigation is coupled with the leading aircraft.

The authors of [38, 39] investigated off-nominal situations for the trail aircraft caused by blunder of the lead aircraft or by wake vortices generated by the lead aircraft in simulator trials. In the event of such an occurrence, the test pilots in [38] were to fly a manual breakout trajectory. This was a preset s-shaped trajectory starting with a 10-degree bank angle at altitudes between 250 and 500 feet and a 30-degree bank angle above 500 feet. In all trial runs, pilots were able to fly the breakout maneuver safely and accurately, regardless of what caused the off-nominal situation. However, the location where the off-nominal situation occurred had an impact on the position accuracy and slant range of both aircraft. Further, the pilots advised the researchers that they preferred the 10-degree bank angle because it would be easier to fly. Compared to normal landings, pilots exhibited higher workload and situational demand. However, the workload was always tolerable and there was sufficient situational awareness. The differences between a manually and an automatically flown breakout maneuver were then compared by [39]. During the trial runs with breakout maneuvers flown by the autopilot, the researchers were able to determine a higher accuracy as well as a better separation of both aircraft compared to the manually flown breakout maneuvers. Similarly, a lower workload and higher situational awareness was observed with the breakout maneuvers flown by the autopilot.

Different levels of automation for the pairing of aircraft by the controller were investigated in [40]. Key findings of this research show that mixed automation provides the best results. In this mixed automation, the area controller takes care of pairing the aircraft using an interface on the Standard Terminal Automation Replacement System (STARS). The area controller selects the desired aircraft via the interface and sends a pairing message to the aircraft involved via a data link. After confirmation of both aircraft, the pair is shown on the displays of the area controller and both sector controllers.

While in [40] separation was automatically maintained so that controllers could concentrate on pairing aircraft, in [41] flight deck crews were also involved. Therein, the separation of the involved aircraft as well as the workload and situational awareness of both controllers and pilots were examined. Since in all scenarios the controllers and pilots could perform the paired approach and experience appropriate levels of workload and situational awareness, the concept was deemed feasible by the researchers. While the results from [41] refer to pilots and controllers, an exclusive consideration for controllers can be found in [42]. A detailed description of the problem of scheduling and pairing the aircraft to conduct the paired approach can be found in [43].

3.4.3 Transferability to SupeRO

TACEC bears a similarity to PAC in its basic principles. It is also designed for runway spacings down to 750 feet (230 m). Key differences from the PAC are in navigation and equipment requirements. In PAC, only the trail aircraft must be equipped with additional equipment, such as ADS-B interval management capabilities and a CDTI. The lead aircraft does not require any equipment other than certain speed capabilities. TACEC, on the other hand, requires a 4D trajectory-capable flight management system (FMS) from all participating aircraft. Furthermore, a ground station is required that can track the positions, speeds and headings of the aircraft, calculate waypoints for the individual 4D trajectories and send them to the aircraft via a suitable data link.

Furthermore, the researchers assumed that differential GPS-based landing systems are available nationwide. As already mentioned, GBAS landing systems are currently only in operation at very few airports. Other DGPS systems such as the satellite-based augmentation system (SBAS) achieve the lateral and vertical accuracies in the meter range hoped for by the researchers at the time, but these are not equally available worldwide. SBAS systems are dependent on their respective geostationary satellites. For example, the USA is covered by the Wide Area Augmentation System (WAAS) and Europe by the European Geostationary Navigation Overlay Service (EGNOS). A major disadvantage of GBAS is the need to set up ground stations at every airport. An option to tackle this problem is delivered by [45]. Therein an SBAS to GBAS converter was developed that combines the advantages of both systems. For further descriptions of the operational concept and flight tests see also [46, 47].

One advantage of satellite-based approach procedures, however, is the flexibility in the design of the approach path. This means that curved approaches can also be realized. Secondly, there are no large protection zones on the ground as with an ILS. This is an advantage, as it is assumed that existing protection zones would make taxiing more difficult with super close runways and the associated paired operations.

As with PAC, TACEC defines an exact relative position in the safe area diagonally behind the aircraft ahead. With TACEC, however, the relative position is established by flying the dynamic 4D trajectory.

The studies [37–43] on pilot and controller procedures provided many valuable insights and proved, with the appropriate support tools, that both air traffic controllers and flight crews are able to use the flight corridor identified by [9] for a paired approach and thus increase arrival throughput at airports. The studies showed through the performance achieved by the pilots that a coupling of the two aircraft systems, as was the case in the simulator trials, is a promising approach for carrying out paired approaches under IMC.

4 Discussion

The work on flight corridors forms the basis of all the concepts presented. Identifying the wake vortex-free area right behind an aircraft flying ahead is the crucial finding on which all concepts with paired approaches are based.

To utilize this safe area, two very close runways are required. The SupeRO concept idea envisages the expansion of single-runway airports to include a second super close runway. However, airports with two existing runways with less than 915 m runway spacing could also be of interest for paired approaches. These have the advantage that no additional runway would have to be built. Furthermore, the number of potential airports increases noticeably if this type of airport is included (compare Fig. 4).

Nevertheless, it can be seen that the focus in the development of paired approaches procedures has been on very closely spaced parallel runways, as all concepts are aimed at airports with runway spacings down to 750 feet (230 m). The author of [9] also suggested the possibility of simply enlarging the runway pavement or connect two existing runway pavements. This is, in theory, a promising approach. This would allow the individual runways to be virtually relocated, thereby achieving great flexibility. However, an important safety aspect in the operation of paired approaches on super close runways is the veer-off of one of the two aircraft during roll-out. It is assumed that with a continuous runway pavement, the risk of a collision due to veer-off could increase. In order to be able to assess which super close runway spacings can be achieved and whether a continuous runway pavement could be a suitable option, it is advisable to carry out a detailed investigation of safety with regard to veer-off during super close paired landings. In addition, further analyses of the influence of cross winds, approach speed, the aircraft types involved and runway spacing are planned using the computational program supplied by [11].

The four concepts presented all exploit the wake vortex-free area right behind an aircraft flying ahead. The first distinction can be made by the type of merging both approach courses. There are approach courses with a final swing-over maneuver and those with a continuous offset approach course. In the case of approach courses with swing-over, a further differentiation can be made between weather conditions and the type of navigation aids. The SOIA procedure can be performed under VMC and uses ground-based navigation aids. This procedure was particularly distinguished by the fact that it is already used in practice. It thereby shows the value of a paired approach procedure due to the increased capacity, but only under VMC. The situation is similar for the ordinary RPAT procedure. Although it uses satellite-based navigation aids and is therefore more flexible in the design of the approach course, it is also not applicable under IMC. If the visual separation is replaced by ASAS and predicted 4D trajectories, as proposed by [21] in the "precision" RPAT procedure, the procedure would also be technically possible under IMC. In all these concepts, the pilots of the trailing aircraft are ultimately responsible for maintaining longitudinal separation. Only the lateral separation is monitored by the PRM controllers, insofar as an NTZ exists.

In the other two concepts, there is no final swing-over maneuver, but a continuous offset approach course. The paired approach operational concept and TACEC differ in their degree of automation and the coupling of the aircraft. While in the paired approach operational concept the aircraft are coupled only up to a defined merging point, in TACEC the aircraft involved remain coupled until landing. Both concepts explicitly exploit the flight corridor and define forward and rear boundaries for the safe area behind the lead aircraft. In the paired approach operational concept, only the trail aircraft must be specially equipped to remain in the safe area by means of interval management.

This lowers the requirements for the aircraft pair since only one of the two must be specially equipped. This has advantages and disadvantages. On the one hand, it allows aircraft that are not adequately equipped to perform a paired approach in the role of the lead aircraft. On the other hand, this also reduces the flexibility in pairing the aircraft, since the equipped aircraft must necessarily be the trail aircraft. Since aircraft type and cross wind play a role in addition to equipment, as many aircraft as possible should be interval management capable for high flexibility in aircraft pairing. In PAC, also the pilots of the trailing aircraft are responsible for longitudinal separation.

TACEC represents the most dependent variant of all presented concepts. In addition to area-wide operational differential GPS landing systems and a suitable data link with which the future waypoints can be received in real time, all aircraft in this concept must be capable of 4D trajectories. A special feature compared to the other concepts is the possible extension of two simultaneous landings to multiple simultaneous landings. Therefore, it can be assumed that the highest arrival throughput can be achieved with this concept, insofar as this concept would be operational. Here, the responsibility for maintaining longitudinal separation within a pair rests with the pilots of each trailing aircraft, while the separation between two pairs is monitored by the controllers. The many human factor studies on this concept and the lessons learned will be useful in developing paired approaches on super close runways. This essentially includes the finding that a high degree of automation is advantageous in paired approaches. Coupling the two aircraft systems and the associated monitoring task of the pilots yielded good results in terms of situational awareness and workload. Even in off-nominal situations and the associated breakout maneuvers, automated execution proved to be the preferred option. Overall, the studies showed that paired approaches under IMC are technically feasible and can be adopted by both pilots and controllers.

An overview of the compared concepts can be seen in Table 1.

For the development of paired approaches, this results in the following findings. Since the development of the SupeRO concept is targeted at an application under IMC and thus visual segments are out of the question, there are two options for aircraft navigation. One option would be for both aircraft to navigate with the help of dynamic 4D trajectories, whereby they automatically remain in the safe area if they adhere to this trajectory. If both aircraft involved are to use a 4D trajectory, this would have to be calculated and transmitted in a coordinated manner from a ground station. A special CDTI would be required from which the pilots could obtain their relative position to each other and information about the other aircraft and initiate appropriate breakout maneuvers in the event of position deviations. If only the following aircraft is equipped with a 4D-capable FMS, the 4D trajectory would have to be predicted by the following aircraft and its own would have to be calculated onboard accordingly. Although this would have the advantage that not all aircraft would have to be equipped correspondingly, it would entail higher requirements and therefore less flexibility in pairing. In this variant, the focus would be on the primary navigation of the individual aircraft. The aircraft would not be actively coupled. The pilots can only monitor the relative position generated by the 4D trajectories via the CDTI. In view of the very close spacing that must be achieved in the course of SupeRO, this is a disadvantage. At these close spacings, it must be assumed that there is very little time to detect a position deviation and for the pilots to react.

The other option is that the required relative position of both aircraft is achieved and maintained with the help of interval management and active coupling of the aircraft systems. If the following aircraft navigates exclusively relative to the leading aircraft after they have been coupled, the primary approach type is of secondary importance. However, this places high equipment demands on the aircraft involved,

Table 1 Comparison of the presented concepts

Concept	Leading Aircraft			Trailing Aircraft			Maintaining Separation
	Navigation	Approach Course	Minimum Equipment	Navigation	Approach Course	Minimum Equipment	
SOIA	ILS	Straight-in	ILS	LDA ILS	Offset + Transition	ILS	Visually
RPAT	ILS	Straight-in	ILS	RNP APCH	Offset + Transition	GPS	Visually
"Precision" RPAT	ILS	Straight-in	ILS	RNP APCH	Offset + Transition	4D-FMS, ASAS	ASAS, 4D Trajectory
PAC	ILS	Straight-in	ILS	ILS/GLS/RNAV	Continuous offset	ILS, IM, CDTI	IM
TACEC	4D Trajectory, GLS	variable	4D-FMS, CDTI, GLS	4D Trajectory, GLS	Continuous offset	4D-FMS, CDTI, GLS	4D Trajectory

as for maximum applicability and flexibility in pairing, all aircraft must have onboard interval management capabilities and the ability for coupling so that each aircraft could be used as the leading or following aircraft.

If functioning relative navigation and a coupling of the aircraft systems can be realized, the paired approaches in the SupeRO context would thus be independent of the primary approach procedure and therefore not limited by the instrument approach procedures available at the respective airports. In this way, the following aircraft would just be attached to the leading aircraft and its chosen approach. Whether the merging of the two approach courses via a swing over or via a continuous offset approach is more suitable depends on the individual airport, on the other influencing factors like the pairing mechanism as well as on the pending findings from the analysis by means of the computational program for the propagation of wake vortices.

5 Conclusion

Paired approaches are a promising way to increase arrival throughput at airports. Such an increase is necessary because aviation authorities are forecasting further growth in demand for aircraft operations over the next 20 to 30 years. Since in many cases, an expansion of the airport area is not possible without difficulties, a more efficient use of the existing airport area and infrastructure is necessary. The SupeRO concept is intended to provide a paired approach option for this purpose, which should allow such efficient use on two super closely spaced parallel runways under IMC.

The aim of this study was to identify key technologies that could enable paired approaches on super close runways under IMC and should therefore be investigated further. For this purpose, existing paired approach concepts were examined for their readiness and transferability to the SupeRO concept idea. Some of the concepts investigated showed how paired approaches can also be technically implemented under IMC. This was mainly shown by flight trials performed, but also by several human factors studies. Although most of the concepts considered were developed in the early 2000s, none of them are in use today, with the exception of the SOIA procedure. One possible reason for this could be the assumption of many researchers that GLS will be necessary for the concepts and will be ready for use across the board in the early 2020s. The lack of this development may have meant that these concepts have not been pursued further to date. Nevertheless, the flight tests from 2019 as part of the paired approach operational concept showed that around 20 years after the original concept idea was published, paired approaches are still being worked on without relying on GLS.

Instead of focusing on the primary approach type, accurately achieving and maintaining the required relative position was identified as the critical element of the paired approaches on super close runways. Onboard interval management and the ability to couple both aircraft systems emerged to be the essential technologies for the realization of paired approaches. These two elements are the basic prerequisites for achieving and maintaining the required relative position at super close runway spacings. For this reason, the main focus of the following investigations should be on onboard interval management and the coupling of the aircraft systems.

Further steps concern the analysis of boundary conditions, which will be carried out using the computational program provided by [11], among others. The analysis should clarify what effects cross winds and the targeted close runway spacing have on the requirements of aircraft characteristics, such as navigation accuracy and speed capabilities, and how the merging of the approach courses is to be designed. The results of this wake vortex analysis combined with the findings of this review will be used to develop a concept of operation for paired approaches on super close parallel runways.

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Conflict of interest The authors declare no competing interests.

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