# Curved flight procedure construction with site-specific statistical meteorological data: A Swedish example



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# Curved flight procedure construction with site-specific statistical meteorological data: A Swedish example

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a study of using site-specific statistical meteorological data in the construction of curved flight procedures to explore its potential in reducing the environmental impact of air traffic near the airports. In the study, the statistical meteorological data which covers a 10-year period of time, from 2009 to 2018, have been collected for the air space centred two major Swedish airports, Arlanda at Stockholm (ESSA) and Landvetter at Göteborg (ESGG). Two procedure design practices, one is an area navigation (RNAV) standard instrument departure (SID) procedure from runway 08 of Arlanda airport and another is a required navigation performance authorization required (RNP AR) approach procedure heading to the runway 03 at Landvetter airport, have been performed and analyzed. Applying the 95th percentile wind speed from statistical meteorological data, instead of the ICAO standardized tailwind component (TWC), offers varying benefits depending on the specific case. For the RNAV SID procedure from ESSA, the part of the designed departure path which is outside of the regulated noise dispersion area is significantly reduced. Whilst for the RNP AR approach procedure to ESGG, the smaller turning radius resulted from the lower TWC which is calculated from the local meteorological data makes it possible to avoid flying over an inhabited area. Besides the notable potential of noise impact reduction, flight distance shortening of 3.7 NM (RNAV SID ESSA case) and 1 NM (RNP AR ESGG case) compared to the same procedures designed on ICAO standard TWC have been observed. In general, the presented results are positive in supporting the use of local meteorological data in planning curved flight procedures during departures and approaches. A validation performed using an A320 full flight simulator has confirmed the operability of the ESGG RNP AR procedure from the design practice. In the full flight simulator, even with the 100th percentile wind condition from the collected statistical meteorological data, the designed RNP AR approach procedure can be operable considering RNP 0.3 corridor while a 30° bank angle is required for approximately 20 s during the turn.

## 1. Introduction

More efficient aircraft operation is one of the keys to achieve a sustainable aviation in the future. Optimizing flight procedures with Performance-Based Navigation (PBN) capabilities in terminal manoeuvring area (TMA) can be effective in reducing the impact of aircraft generated noise and emissions near the airports (ICAO, 2009; López-Lago et al., 2020; Timar et al., 2013). State-of-the-art near-airport PBN flight procedures, such as Required Navigation Performance (RNP) procedures, are designed following the regulations set by International Civil Aviation Organization (ICAO) Doc 8168 – Aircraft Operations and Doc 9905 – Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual (ICAO 2018; ICAO 2020; ICAO 2021). As described in these design regulations documents, standardized meteorological assumptions regarding wind vector and temperature are normally adopted in the design process. Since the standardized

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assumptions are made with ultraconservative safe margins for all, this would frequently result in unnecessary speed restrictions that the aircraft must comply with in different regions. Due to the speed restrictions, high lift devices may be deployed earlier and last for longer periods. A study conducted earlier within the framework of the program Non-Straight Approaches Sweden (Icke Raka Inflygningar Sverige-IRIS) (Näs and Ekstrand 2018) has shown that, allowing an early acceleration to a speed that the wing flaps can be retracted would save up to 3% fuel consumption for climb phase during departure. For arriving flights, a similar benefit could be obtained for postponing speed restrictions to enable flying in with minimum high lift devices deployment for a longer period. A lower noise exposure is also expected with a lower degree of high lift devices deployment. The possibility of relieving the unfavourable speed constraints is offered in ICAO Doc 9905 (ICAO 2021), from which using historical statistical meteorological data instead of standardized wind assumptions for the calculation of various turn parameters during curved flight procedure is possible. This is of particular interest when turning with a constant radius, named Radius to Fix (RF) turn, which is a turn strategy that provides the highest predictability of where in the airspace the aircraft will be during the turn. The RF turn is typically associated with RNP operations which are a type of procedure offering significant operational and safety advantages over other area navigation (RNAV) procedures through incorporating on-board navigation performance monitoring and alerting. However, the source and values of the historical statistical meteorological data on site should be documented, as clearly stated in section 3.2.6 of Doc 9905 that, "Other *tailwind gradients, or specific values, may be used after a site-specific determination of wind has been carried out based on that location's meteorological history (using available information from other sources). The source and values used should be documented*".

As the impact of weather condition on aircraft operation is substantially strong, the importance of meteorological data in air traffic management (ATM) has been widely realized (Troxel and Reynolds 2015; Gultepe et al. 2019; Mondoloni and Rozen 2020). There have been plenty of research in aviation sector which uses meteorological data, focusing on predicting flight delays to improve the predictability and safety of ATM (Maxson 2018, Josefsson et al. 2020; Garani et al. 2022), and evaluating the climate impact of air traffic (Maxson 2018, Garani et al. 2022; Simorgh et al. 2024). When optimizing flight trajectories with historical meteorological data against climate and economic impacts, studies have been mainly concentrated on the trajectory part of cruise altitude at large scales (Irvine et al. 2013; Cheung et al. 2015; Ramée et al. 2020; Dancila and Botez 2021; Chen et al. 2022; Simorgh et al. 2024). With regards of optimal aircraft operations close to the airports, Dönmez et al. investigated the impact of wind uncertainties on parallel-point merge systems for optimizing aircraft sequences within TMA (Dönmez et al., 2022). Most frequently, certain groups of historical meteorological data which are of interest were used in these studies, while the potential of using weather forecasting data and especially the nowcasting data which involves very short-term prediction from the present to a few hours ahead have been investigated and discussed (Gultepe et al., 2019; Ramée et al. 2020). As it is common that aircraft are used as a meteorological observation system for supplementing the data, through Aircraft Meteorological Data Relay for example, sharing meteorological data between aircraft and air traffic towers (ATCs) could benefit improving weather data resolution and accuracy, hence ATM efficiency (Rosenow et al., 2021)

Compared to the research areas mentioned above, public information regarding the use of historical statistical meteorological data in supporting flight procedure design is less available. A previous project named Validation and Improvement of Next Generation Airspace (VINGA) under Single European Sky ATM Research (SESAR) Joint Undertaking conducted by the authors is one of the sources for relevant information. As reported in the final report of the VINGA project (Wiklander et al., 2011), it has concluded that a fuel saving of 50–75 kg per approach can be obtained if statistical wind data is used in the procedure design to prevent unnecessary speed constraints from being applied. The benefit has been achieved with the consideration of safety margins for RNP AR 0.3 procedure design. Considering the average flight distance of 1067 km in 2022 within the European Civil Aviation Conference (ECAC) region, the fuel saving equals about 1.5%–2.2% per flight for the reported aircraft. In the same period, a more detailed study investigating the meteorological influences on the design of advanced aircraft approach procedures for reduced environmental impacts (Ren et al. 2011) can be found. Ren et al. in the study revealed the importance of the wind profiles and local pressure variations in the development of advanced approach procedures. Through comparing the same procedure design focusing on area navigation (RNAV) and continuous descent approach (CDA) in different wind profile cases, Ren et al. have showed that, when using the standardized meteorological assumptions (please note, a very different assumption was regulated by UK Civil Aviation Authority and used in their study), the aircraft would need to deploy high lift devices earlier than using statistical wind profile. In addition to that, as the aircraft were required to follow the prescribed airspeed profiles in the study, when flying the same procedure, using the conservative standardized wind profiles could have a considerably negative impact on flight duration and hence fuel burn. The results of the developed flight trials in their study with statistical wind profile demonstrated reductions of flight segment below 9000 ft up to 6 nmi per flight, peak noise reductions of 3–6 dBA and approximately 10% reduction in fuel burn over ICAO standard design cases for both narrow and wide body aircraft.

The two most relevant studies, however, were reported around 2010 with meteorological data back to the period of 2000–2009, whilst the climate has been gradually changed and regulations for procedure design have been revised during the past 14 years. For example, in section 3.2.4 of the third edition ICAO Doc. 9905 from year 2021, the turn radius applied is based on a standard bank angle of 25°, which has been increased from 18° as regulated in previous editions. This change has a great positive impact on the maximum allowed speed in RF turns as the previous applied bank angle of 18° very often resulted in penalising speed constraints. On the other hand, the increase of the bank angle in the calculation may pose a negative effect on the benefit of adopting statistical wind data other than standardized wind table, since the use of statistical wind in the procedure design could in many cases be used to increase the maximum allowed speed. With the new regulation of applying 25° bank angle, penalising speed constraints more seldom pose a problem for RF turns in RNP AR approach. But, as can be seen later in the paper, there are still situations where the use of statistical wind is beneficial in procedure design. Nevertheless, each procedure will have to be examined separately with the use of statistical wind data for the possible benefits. Moreover, in both VINGA project study and (Ren et al. 2011) the average/mean wind calculated from the meteorological data was used and this is considered optimistic; while in the latter study, the wind data from a mesosphere-stratosphere-troposphere (MST) radar located 200 km away from the airport was adopted in the study, which is not considered as site-specific determination of wind in practice and may not be valid considering the large difference in terrain and local climate in other countries. Therefore, an updated site-specific historical meteorological database with higher resolution covering the near airport air space is required to analyse the benefits of site-specific procedures with the revised regulations.

In 2012, Usanmaz and Turgut developed a Turkish wind model which can be used for procedure design in Turkish airspace (Usanmaz and Turgut 2012), where no practical cases were reported but a turn area construction example was demonstrated. The statistical data used in the study covered an extra wide range of data from year 1971–2010 and were obtained from the Turkish rawinsonde station network which includes 8 stations across Turkey. A methodology of retain the highest observations from three of eight stations was used to complete the model, this was done to ensure the model to be fitted anywhere in Turkey for the safest estimation. However, it is still a database from observations of widely spaced stations, and using the highest observations for all airports can still be conservative for some locations. In addition, it is not a necessary statistical advantage to use as much data as possible in this case to determine the suitable wind data for today's aircraft operations. A too long period may be negative since changes to the climate may affect winds and temperatures over time and the values in old times may significantly be different from today. Hence, to determine which sub-set of the historical meteorological database is appropriate for being adopted in the procedure design is another key question to answer. In the procedure design manuals, there are some occasions mentioning the use of 95 percentile value from statistical data, but no details on how to calculate/select the statistical wind data for RNP procedure design are clearly available. One study from Pérez Sanz et al. (Pérez Sanz et al., 2023) has been found in exploring how to select the suitable statistical data for PBN based approach procedure design where vertical guidance is barometric. With the consideration of 95 and 99 percentile and minimal values from the statistical temperature database, not statistical wind database, it investigated the impact of different selections on the calculation of final approach segment and obstacle clearance height and proposed the methodology for selecting the suitable temperature.

The presented work aims to illustrate a way of implementing the proper statistical meteorological data in curved flight procedure design and demonstrate its potential benefit in practical cases. The authors believe well established case studies can be valuable for both the scientific and industrial communities by promoting further development and research in the adoption of statistical meteorological data. The possibility of using statistical wind has been documented since the first edition of RNP AR procedure design manual from 2009 but has yet to be clearly described how to do it and has not been in practical use (limiting to our knowledge). The obstacle to making this happen is the lack of practical cases, especially good practical cases with meteorological institute, airport procedure designer, ATM controller and airliners/pilots involved. Some studies have realized the potential but have not done practical detailed cases because it is not easy to find representative cases from artificial/general procedures to show the real potential. It is a case-dependent scenario, and one must investigate each existing procedure in detail to find out which ones could benefit from applying the statistical wind and what the benefit could be. In particular, the work focuses on contributing to the following aspects.

- Providing RNP AR procedure design study with recent updated in-site statistical meteorological data and the most recent released procedure design manuals.
- Providing guidelines in how to select and apply the suitable statistical data into procedure design
- Providing practical procedure design cases with in-site statistical meteorological data which are designed by airport operator and validated by airliner pilot using full flight simulator.
- Encouraging research and development in using statistical meteorological data in curved flight procedure design through demonstrating the potential of individual cases.

The two biggest airports in Sweden, Arlanda (ESSA) and Landvetter (ESGG) which served about 22 million and 5 million passengers in 2023 respectively, were selected for the study with meteorological data provided by the Swedish Meteorological and Hydrological Institute (SMHI). The procedure design practices were conducted by professional procedure designers from the owner and operator of the two airports – Swedavia. Full flight simulator of A320 was used to validate the operability of the designed procedures by pilots from Novair Airline. Eventually, the paper is organized as follows. In the methodology part, the tailwind component (TWC) as well as the basics for turn calculations from ICAO regulations are briefly introduced first. Then the site-specific meteorological data collected for the two airports are described, followed by the methods used for meteorological data processing and subsetting. In the end of the methodology part, information and process of the procedure design practices are given. In the result and discussion part, a comparison between the TWCs which are calculated from the statistical meteorological data and from the ICAO regulation is made first. Then the outcomes from the two procedure design practices, area navigation (RNAV) standard instrument departure (SID) and RNP AR approach, are presented, followed by the full flight simulator validation made for the RNP AR procedure. Conclusions are listed in the end of the paper to summarize the key findings and recommendations from the study.

Nomenclature

| | |
|---|---|
| APCH | Approach |
| ATM | Air traffic management |
| CONF | Flap configuration |
| DER | Departure end of runway |
| ESGG | Göteborg Landvetter ICAO airport code |
| ESSA | Stockholm Arlanda ICAO airport code |
| FAP | Final approach point |
| FMS | Flight management system |
| GS | Ground speed |
| IAS | Indicated airspeed |
| ICAO | International civil aviation organization |
| IRIS | Non-straight approaches Sweden program |
| METAR | Meteorological aerodrome report |
| MSL | Mean sea level |
| TAS | True air speed |
| TMA | Terminal manoeuvring area |
| TWC | Tailwind component |
| RF | Radius to fix |
| RNAV | Area Navigation |
| RNP | Required navigation performance |
| RNP AR | Required navigation performance authorisation required |
| RWY | Runway |
| SESAR | Single European Sky ATM Research |
| SID | Standard instrument departure |
| SYNOP | Synoptic Observation |
| VINGA | Validation and Improvement of Next Generation Airspace |
| h | Altitude in 1000 ft above sea level |
| kt | Knot |
| NM | Nautical miles |
| r | Turn radius in nautical miles |
| R | Rate of turn in degree per second |
| V | Speed in knot |
| $\alpha$ | Aircraft bank angle in degree |

## 2. Methodology

### 2.1. Curved flight procedure design - regulations

As stated in section 3.2 "Calculating Turn Radius And Bank Angle" of the latest released third edition of ICAO Doc. 9905 (ICAO 2021), for RNP AR procedures, the turn radius of RF turns is calculated using as a speed *V* which is the sum of true air speed (TAS) and the designated tailwind. The TWC, according to ICAO standard wind, is given by an equation in the same document, as outlined below.

$$\mathrm{TWC} = 2\mathrm{h} + 47\ \mathrm{Kt} \quad (1)$$

where h is in 1000 ft above sea level and the TWC in knot (kt) for the highest altitude within the turn should be used. The rate of the turn *R*, which is limited to a maximum value of 3°/s, and the radius of the turn *r* are then determined by:

$$R = (3431\tan\alpha)/(\pi V) \quad (2)$$

$$r = V/(20\pi R) \quad (3)$$

where $\alpha$ is the bank angle of the aircraft and here a standard bank angle of 25° is applied. In reality, modern aircraft with RNP AR capability have the ability to (automatically) bank at an angle of up to 30° when needed.

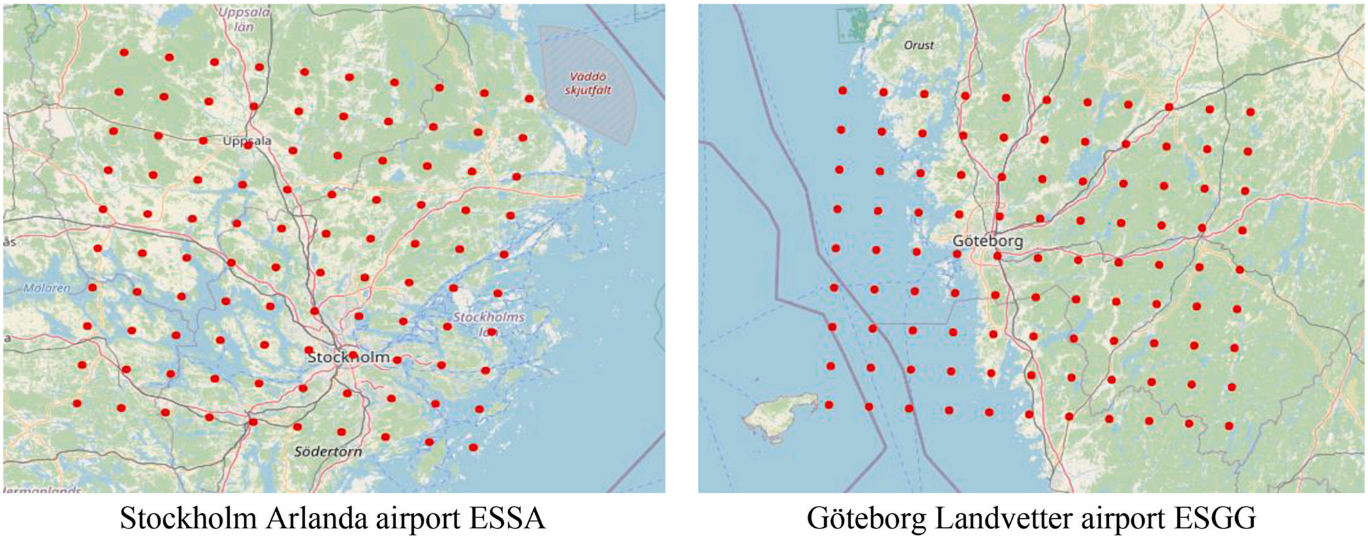


**Fig. 1.** Meteorological data grid points (Red dots) in the air space of the airports. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

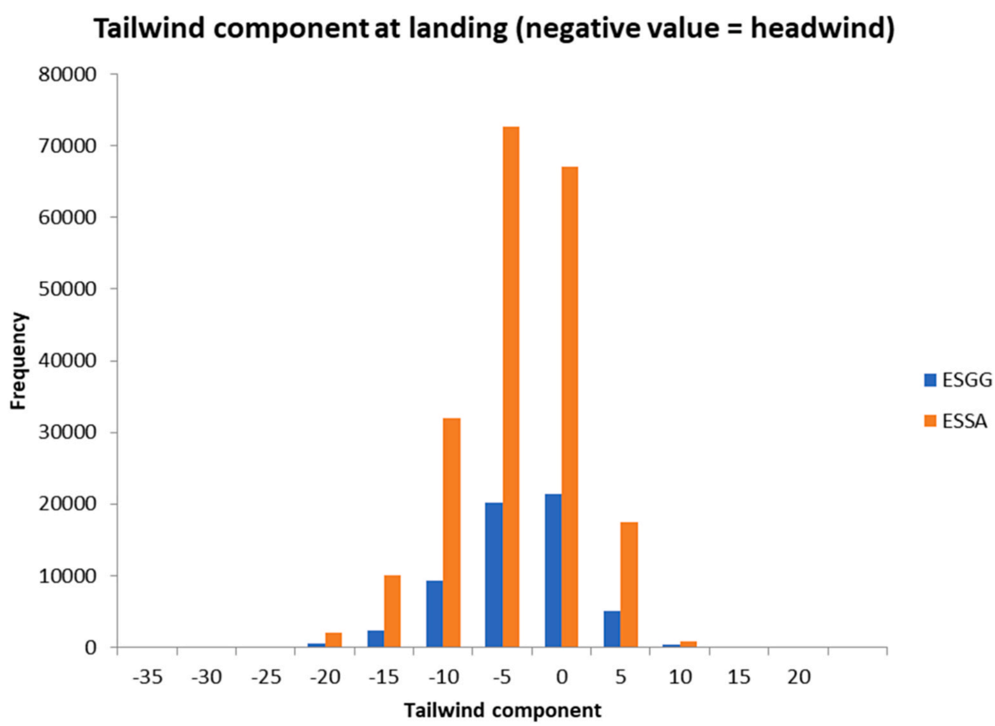


**Fig. 2.** Tailwind component statistics at landings for the two selected airports ESSA and ESGG in 2019–2021.

This applies, for example, the major commercial aircraft manufactured by Airbus and Boeing. While TWC is in kt from equation (1), the speed $V$ and TAS in kt should be used. This gives the radius of the turn $r$ from equation (3) in nautical miles (NM). For the SID procedure, similar calculation process is provided by ICAO Doc 8618 vol II (ICAO 2020). One thing worth noting is that, in section 2.4 "RF TURN METHOD" of ICAO Doc 8618 vol II, the term maximum wind speed at the highest point is used instead of TWC at the highest point to calculate the turn radius, but the same wind speed calculation formula as shown in equation (1) is applied. More importantly, in section 2.4.1.4 of the document, it is clearly stated that, *Maximum wind speed is defined as the ICAO standard wind or, where statistical wind data are available, the maximum wind speed with speed within 95* per *cent probability on an omni-directional basis.* Using this as a guidance, the 95th percentile wind data from the statistical meteorological data is considered in this study. On the other hand, results from omni-directional basis and directional basis have been compared in the presented study. When looking at the statistical wind speed for the different wind direction sectors for a point in space, it typically varies over the 360°. Using 95 per cent probability on an omni-directional basis would normally result in a higher TWC than using directional 95th percentile wind. As lower TWC in procedure design would be generally desirable, using directional basis is preferred if safety and operability of the procedures are ensured.

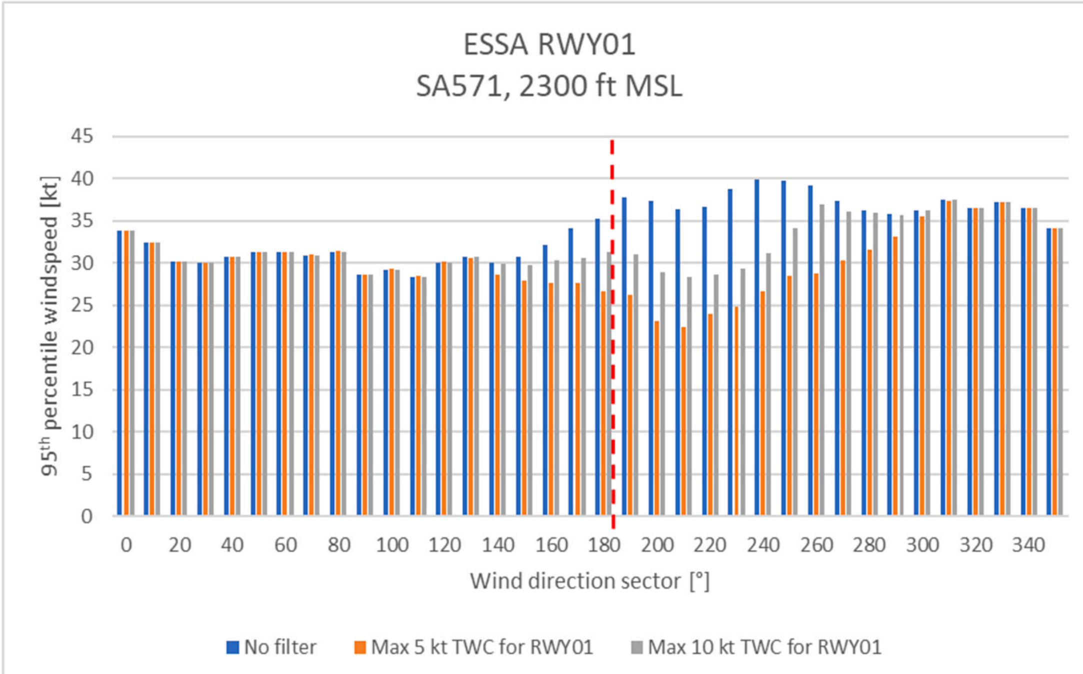


**Fig. 3.** The 95th percentile wind speed calculated for SA571, based on three filtering conditions: no filter, 5 kt and 10 kt TWC threshold at RWY01 of ESSA airport.

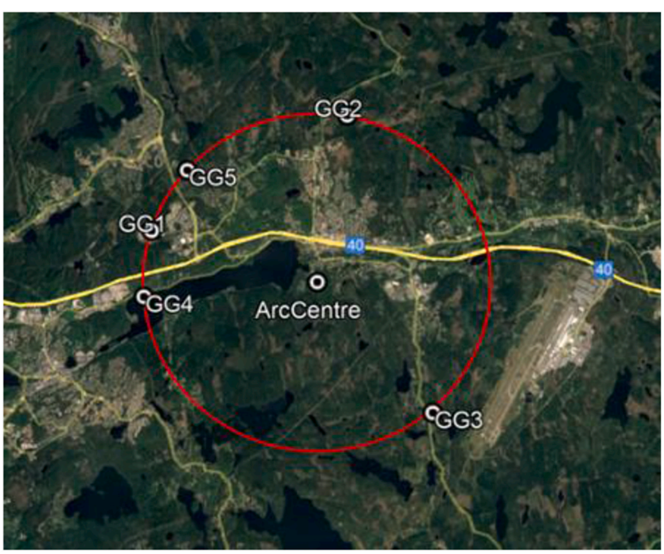


**Fig. 4.** ESGG fictitious descending turn used in the preliminary study of calculating the highest TWC in the turn.

### 2.2. Site-specific meteorological data

Meteorological data was extracted from a regional re-analysis (Kaiser-Weiss et al., 2019) for the two airports, Stockholm Arlanda and Gothenburg Landvetter. As illustrated in Fig. 1, there are 100 and 99 data grid points extracted equally distributed around the two airports respectively. The re-analysis is run with 11 km horizontal resolution leading to an area coverage of about 10,000 km2 centred around each airport. A re-analysis combines past short-range weather forecasts with observations using the same numerical weather prediction system for a very long time period. The process mimics the production of day-to-day weather forecasts giving long consistent data sets with a full three dimensional coverage (Kalnay et al., 1996; Uppala et al., 2005). The meteorological data including wind speed, wind direction, pressure, humidity, and temperature at 20 altitude levels are stored for each grid point. The altitude levels range from 50 feet up to 15000 feet approximately. The re-analysis used is run from 1961 to 2019 but for this study a total time span of 10 years, from 2009 to 2018, has been included with hourly data recorded for the meteorological data variables. The 10-year time span was selected as a result of a preliminary data analysis on different time spans. With a too short period, there is a risk that the results are not representative. On the other hand, including a too long period may also be negative since changes to the climate may affect winds and temperatures over time. Since the work was initiated in 2019,

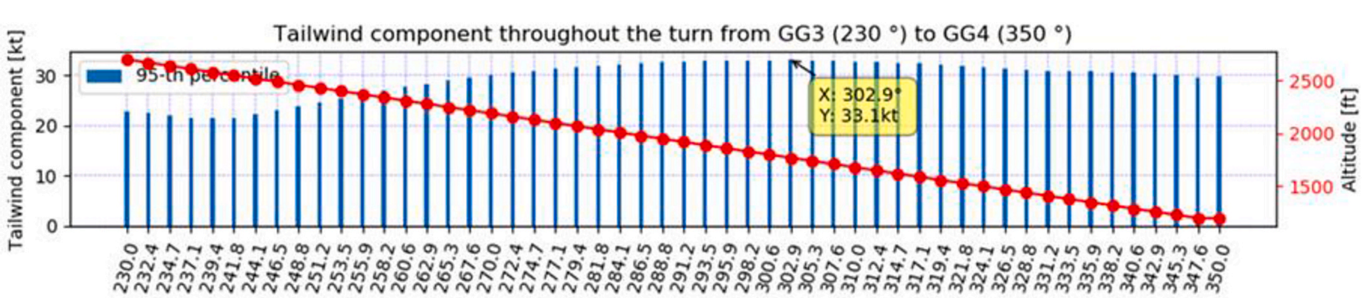


**Fig. 5.** The calculated TWC assuming a 3° descent angle throughout the fictitious turn from point GG3 to GG4 @ESGG.

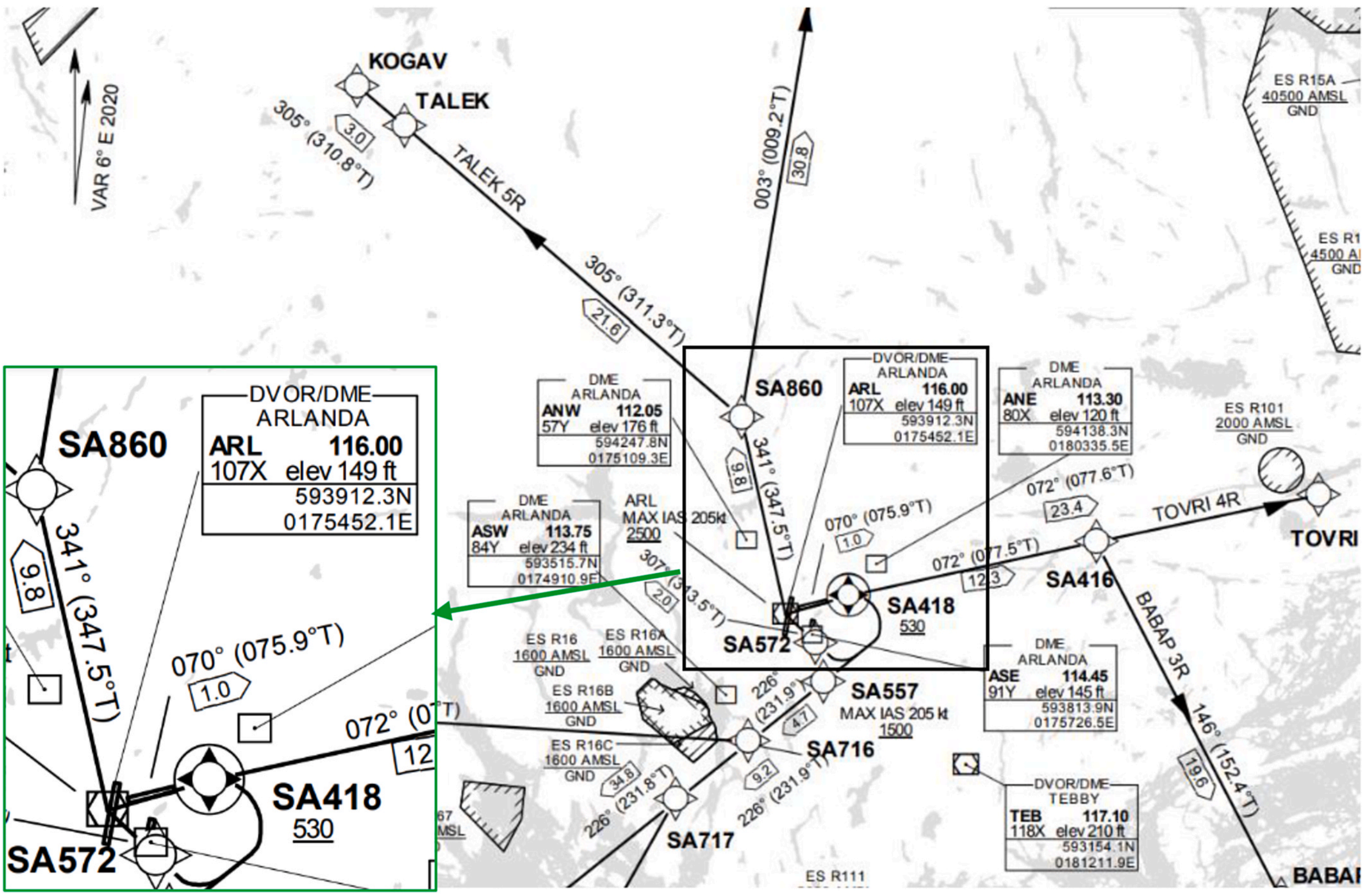


**Fig. 6.** ESSA RNAV SID RWY08 ICAO chart (LFV, 2023b).

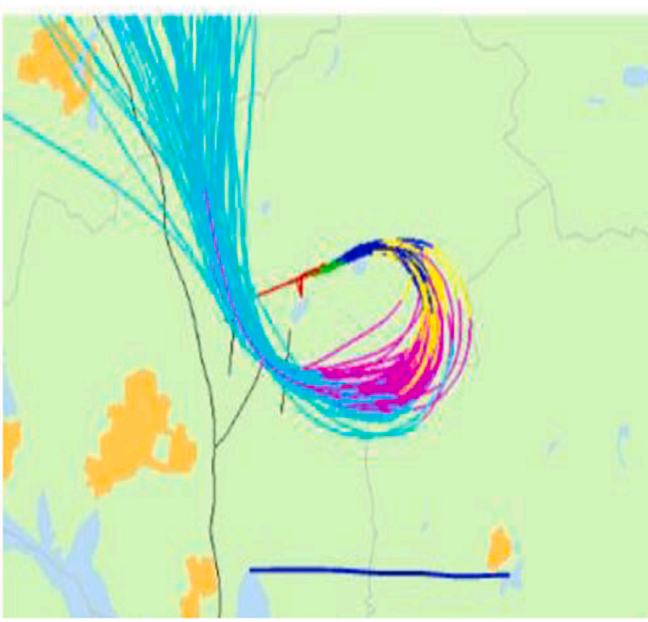

**Fig. 7.** Illustration of flight streams with the current RNAV SID RWY 08 Right Turn procedure at ESSA.

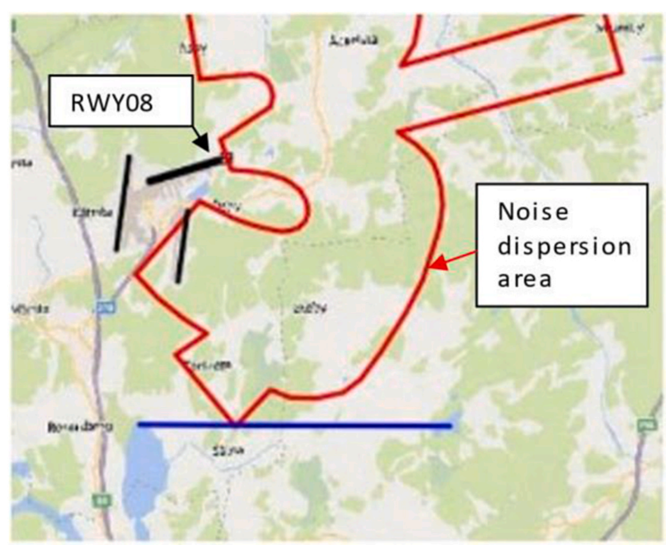


**Fig. 8.** ESSA runway RWY08 noise dispersion area.

the end of the time span was then 2018. Besides the meteorological data mentioned, surface observations close to and at the ariports have also been supplied for the same time period. The observation data have been mainly used for supporting the filtering of the meteorological data in the

**Table 1**
Way points list for ESGG RNP AR RWY03.

| | Way point identifier | Latitude | Longitude | Altitude |
|---|---|---|---|---|
| IAF | GGIAF | 57°45′15.78″N | 012°15′13.09″E | +3200 ft |
| IF | GGXIF | 57°42′36.39″N | 012°12′38.31″E | – |
| RWY | RWY03 | 57°38′58.29″N | 012°16′03.75″E | – |

**Table 2**
RF leg of the Redesigned ESSA RNAV SID RWY08 procedures.

| | Start point | End point | Center of the turn | Radius of the turn | IAS | Bank angle | TWC |
|---|---|---|---|---|---|---|---|
| ICAO standard wind | SA418<br>594006.4N<br>0180054.0E<br>730 ft | SA292r<br>593619.1N<br>0175652.3E<br>8700 ft | ARC292r<br>593716.9N<br>0180217.8E | 2.92 NM | 205 kt | 25° | 65 kt |
| Statistical Wind – directional basis | SA418<br>594006.4N<br>0180054.0E<br>730 ft | SA224r<br>593640.0N<br>0175820.7E<br>6700 ft | ARC224r<br>593756.3N<br>0180158.3E | 2.24 NM | 205 kt | 25° | 34.9 kt |

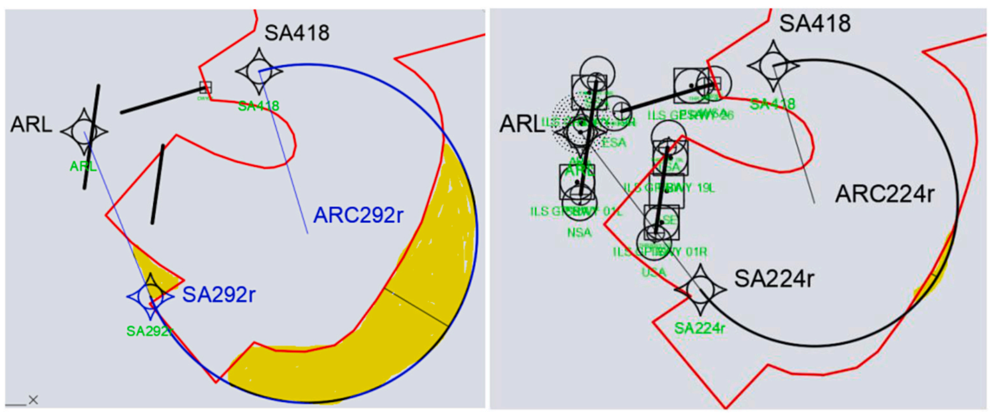


**Fig. 9.** Departure procedure design example - ESSA RNAV SID RWY 08.

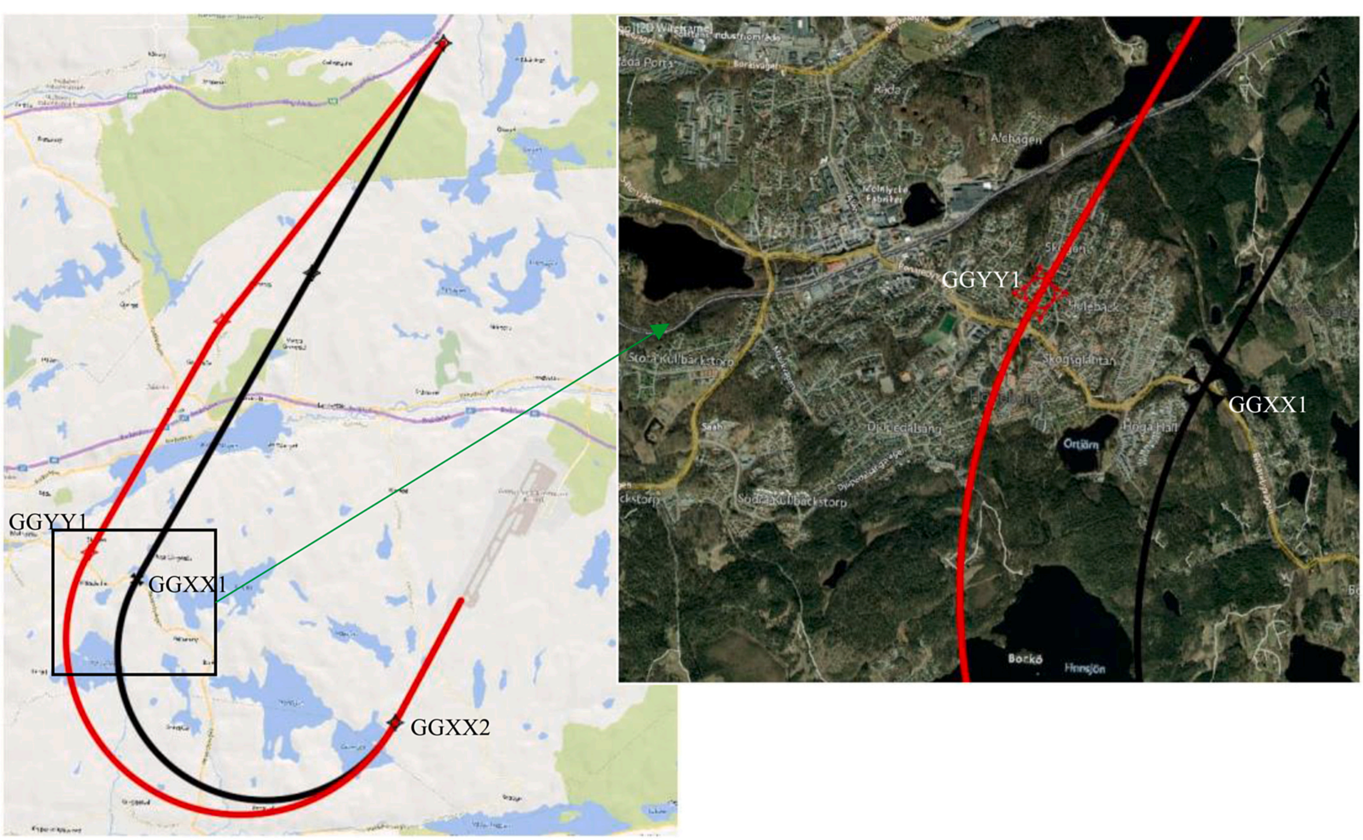


**Fig. 10.** Flight path plot (Left) and a zoom-in (Right) of the ESGG RNP AR RWY 03 procedures: with statistical wind data (black solid line); with ICAO standard wind (red solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 3**
RF leg of the designed ESGG RNP AR RWY03 procedures.

| | Start point | End point | Center of the turn | Radius of the turn | IAS | Bank angle | TWC |
|---|---|---|---|---|---|---|---|
| ICAO standard wind | GGYY1<br>57°39′20.65″N<br>012°08′11.14″E<br>3035 ft | GGXX2<br>57°37′33.78″N<br>012°14′46.98″E<br>1029 ft | GYARC<br>57°38′25.78″N<br>012°11′27.74″E | 1.985 NM | 185 kt | 25° | 52.44 kt |
| Statistical Wind – directional basis | GGXX1<br>57°39′03.76″N<br>012°09′12.79″E<br>2720 ft | GGXX2<br>57°37′33.78″N<br>012°14′46.98″E<br>1032 ft | GGARC<br>57°38′17.66″N<br>012°11′58.87″E | 1.676 NM | 185 kt | 25° | 33.9 kt |

air space, which will be discussed later.

### 2.3. Meteorological data processing and subsetting

In order to enable a fast processing and obtain the 95th percentile data for any arbitrary location within the air space structured by the data grid points, the 95th percentile data of all the data grid points for the 10-year time span was calculated and stored first. After that, the 95th percentile wind speed at a certain location can be interpolated from a cubic spline formed by the data of the surrounding grid points. Except the basic interpolation of the data, the study has introduced a filter to exclude the data which is considered invalid for the purpose, as well as a different algorithm other than considering only the TWC for the highest altitude within the turn.

#### 2.3.1. Filtering the meteorological data based on the surface wind of each runway

Take-off and landings are normally performed in a runway direction that gives a headwind component, but low level of TWC, for example less than 10 kt, may be acceptable in certain situations. When take-off/landing on the intended runway is not allowed due to high TWC for the runway direction, the meteorological data reading at the same time may be inappropriate to be included in the data subset. Therefore, filtering the meteorological data based on the surface wind at the airports, so that only the data when take-off/landing on the intended runway was realistic are included, may improve the quality of the data subset. This filter has been implemented and related analyses have been performed in the presented study. In order to determine the threshold of the filter, the distribution of the headwind/tailwind component for the landings at ESSA and ESGG in the period of 2019–2021 was analyzed. From the data provided by LFV 202,247 landings at ESSA and 59,500 landings at ESGG performed within the two years were plotted in Fig. 2. At both airports, there were 9% of the landings performed with TWC, while only 0.43% and 0.66% of the landings were performed with a TWC higher than 5 kt for ESSA and ESGG respectively. Therefore, using 5 kt as the threshold value for filtering on runway surface wind could cover more than 99% of the flights and is considered a suitable value.

In the chart shown in Fig. 3 below, the directional 95th percentile wind speeds calculated for the final approach point (FAP) SA571 as defined in an existing RNP AR procedure (LFV, 2023a) are given as an example. Please note, the wind direction is given by the direction from which the wind originates, and a wind blowing from the true north has a wind direction of 0°. The wind direction sectors given in the chart are defined with 10° interval. Unfiltered winds are illustrated by the blue bars in the chart while the orange bars illustrate the 95th wind speed calculated from the statistical data where a surface wind filter of maximum 5 kt TWC for the runway 01 (RWY01) has been applied. The grey bars added the case where a surface wind filter of maximum 10 kt tailwind component for RWY01 has been applied for comparison. The red, dotted, vertical line illustrates the runway contra course. As can be seen, when filtering the meteorological data by the surface wind for the specific runway, a valley is created with lower wind speeds in sectors centred slightly to the right of the contra-course of the runway. The reason for the affected sectors not being centred around the runway contra course is that the wind veers approximately 30° to the right statistically in the northern hemisphere. As the difference between 95th percentile wind speed calculated from filtered and unfiltered data is pronounced, i.e. can be more than 10 kt, the impact would be significant. It is believed that this is a critical factor to be considered when applying the statistical meteorological data in procedure design. For all the other runways in ESAA as well as the runways in ESGG, similar results were observed, but are not shown in the paper because of length limit.

#### 2.3.2. Calculating the highest TWC in the turn

An RF turn in departure or arrival procedure normally involves a continuous variation in flight altitude, while wind speeds tend to increase with higher altitude above the ground. This trend is also indicated by equation (1) as the TWC is linearly increased with altitude from the equation. However, the TWC is a function of the wind direction, the wind speed, and the aircraft course. As the statistical wind data could have a notable difference from location to location despite the altitude levels, combining the variations in the wind direction and the aircraft course during a turn, a higher TWC can be expected anywhere during the turn than the one at the highest point. Within the study, when determining the statistical TWC to be used for a turn, the fast processing of the meteorological data enables two options.

- To calculate the statistical TWC for the highest point in the turn, or
- To calculate the statistical TWC for the point where the TWC is the highest in the turn.

In order to assess the differences from applying the two options, a study performed is given below. It is an example for a fictitious descending turn executed at ESGG from point GG3 (passed at altitude 2700 ft) to GG4 (passed at altitude 1200 ft), see Fig. 4 for the locations of the points and the fictitious turn. The inbound course at GG3 is 230° and the outbound course from GG4 is 350°.

In Fig. 5 below, the calculated TWCs for all aircraft courses throughout the turn with the surface wind filter for ESGG RWY21 are given. Assuming a 3° descent angle between the start and the end point of the turn, the altitude variation throughout the turn is illustrated by the red dots with line in the figure, associated with the secondary y-axis. For each aircraft course, the TWC has been calculated with the statistical meteorological data corresponding to the location of that point. As can be seen, the TWC for the highest point in the turn calculated for the inbound course (22.8 kt) is significantly lower than the highest TWC experienced through the turn (33.1 kt) at 302.9° which is highlighted with yellow label in the figure. Identifying the highest TWC of the turn taking into account the altitude variation associated with each aircraft course through the turn is hence considered the most appropriate way of applying the meteorological data.

### 2.4. Procedure design practices

#### 2.4.1. ESSA RNAV SID RWY08 right turn

The ESSA RNAV SID RWY 08 Right Turn (LFV, 2023b) which has a large right turn towards north (approximately 250° angle difference) has

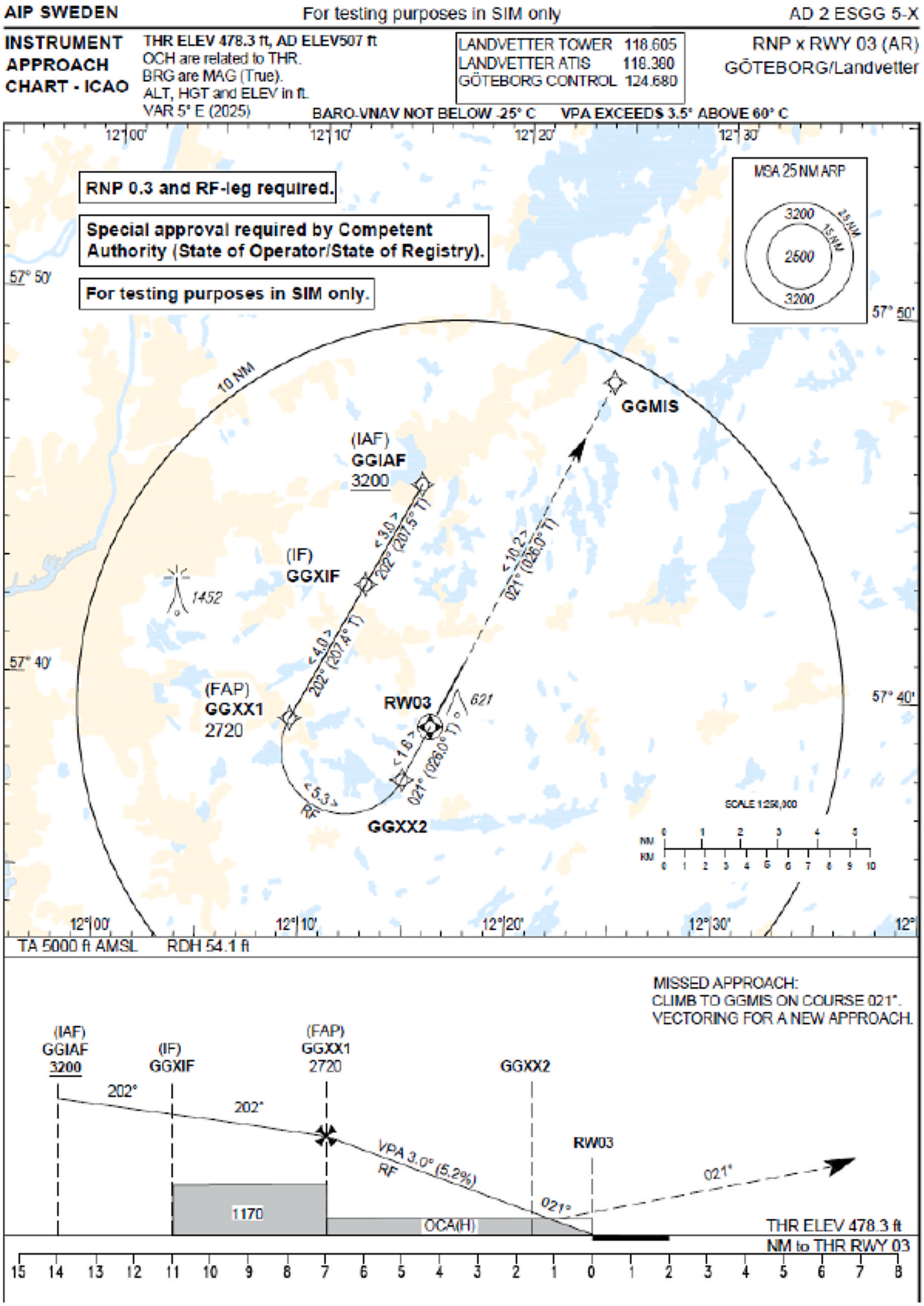


**Fig. 11.** Issued ESGG RNP AR approach procedure chart – for testing purposes in simulator only.

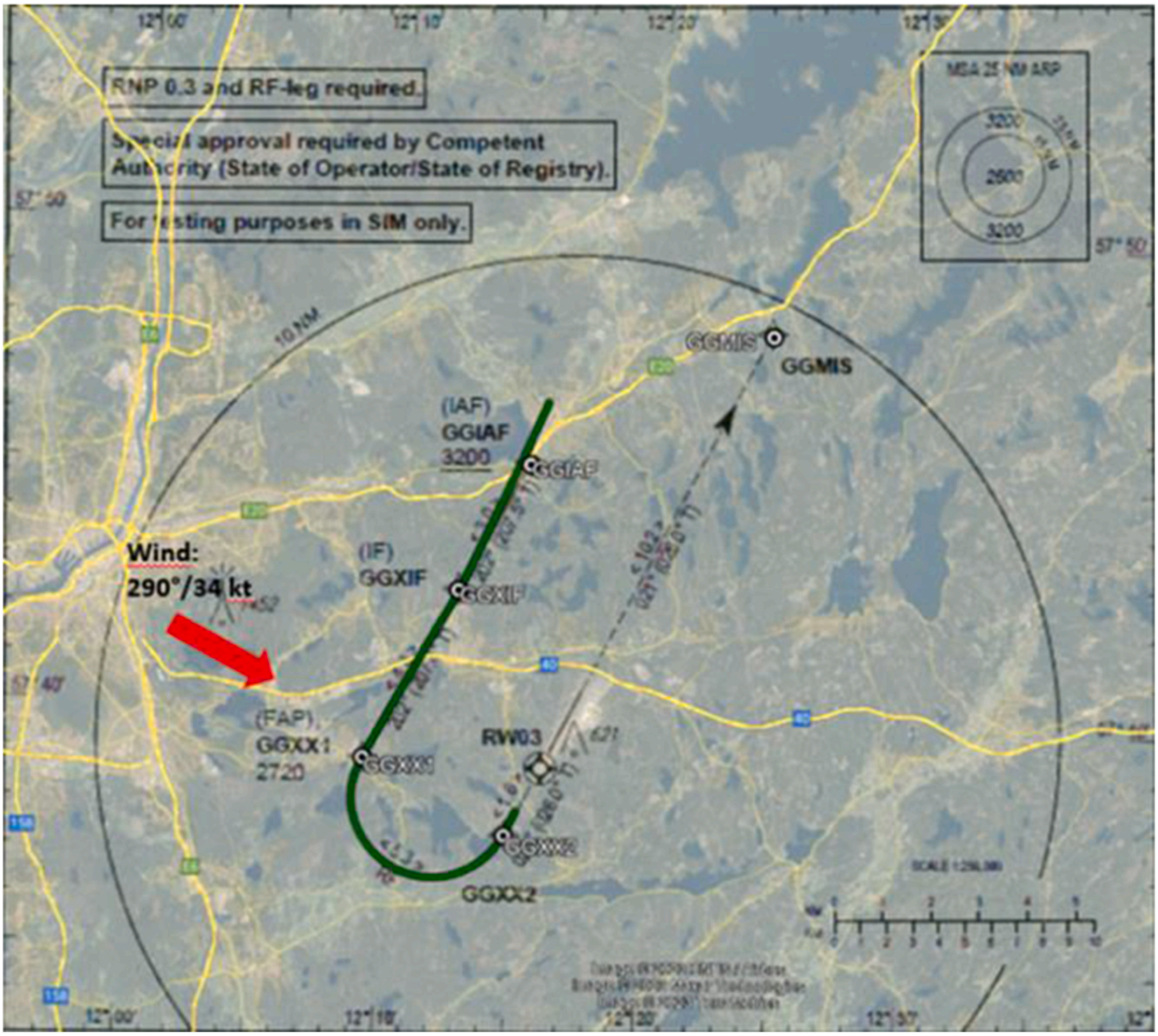


**Fig. 12.** Level flight between GGXX1 and GGXX2 at 2700 ft MSL, IAS 185 kt, CONF 1 with wind of 290°/34 kt.

been selected as one of the two design practices. Current right turn from ESSA RWY 08 towards KOGAV, as shown in Fig. 6, has the following description up to ARL: straight ahead via Course to a Fix (CF) leg towards SA418 defined as fly-over way point and Course to an Altitude (CA) leg +530 ft followed by right turn via Direct to a Fix (DF) leg to SA572 and on to point ARL. The maximum indicated air speed (IAS) of 205 kt applies up to ARL. The fixed way points of the procedure are listed in Table 2.

With the use of statistical meteorological data, the aim of the design practice is to establish an RF-leg between SA418 and ARL. The big difference between the current SID encoded with a CF-leg followed by a DF-leg comparing to a SID encoded with a RF-leg is that the aircraft could fly more freely with the current SID. This has ended up with a more diverse flight streams as illustrated in Fig. 7. Whilst aircraft which could comply with RF-leg will be able to fly the turn very precisely. This procedure in certain circumstances would be beneficial. On the other hand, the constructed RF-leg turn must be within the permitted noise dispersion area where the departures from RWY08 must follow, as shown in Fig. 8. This has been an impossible task with the ICAO standard wind constructed RF-leg.

#### 2.4.2. ESGG RNP AR RWY03

For the airport ESGG, a design practice of constructing a completely new approach procedure RNP AR RWY03 was performed. The fixed way points of the procedure are listed in Table 1 which includes the initial approach fix (IAF) point, the RWY03 point and the missed approach point. Way points and segments in between are to be determined by the design regulations together with the statistical wind data. As the paper focuses on the use of statistical meteorological data in procedure design, details of the procedure design in terms of obstacle assessment and protection area calculations are not reported here. Only the results of the procedures constructed from different wind data are given.

## 3. Results and discussion

### 3.1. ESSA RNAV SID procedure design results

Key parameters of the RF leg of the two redesigned SID procedures, with 95th statistical wind data and ICAO standard wind equation respectively, are given in Table 2. In this procedure design practice, the TWC calculated from ICAO standard wind equation is 65 kt for the highest altitude of 8700 ft. This results in a turning radius of 2.92 NM. The total flight distance between the departure end of runway (DER) to the point ARL through this flight path is about 17.5 NM (32.45 kM). When using the STATMET demonstrator, the calculated TWC became 34.9 kt which in turn results in a smaller turning radius of 2.24 NM and a lower end point altitude of 6700 ft. The flight distance between DER and ARL in this case is 13.8 NM (25.57 kM). The flight distance is thus 3.7

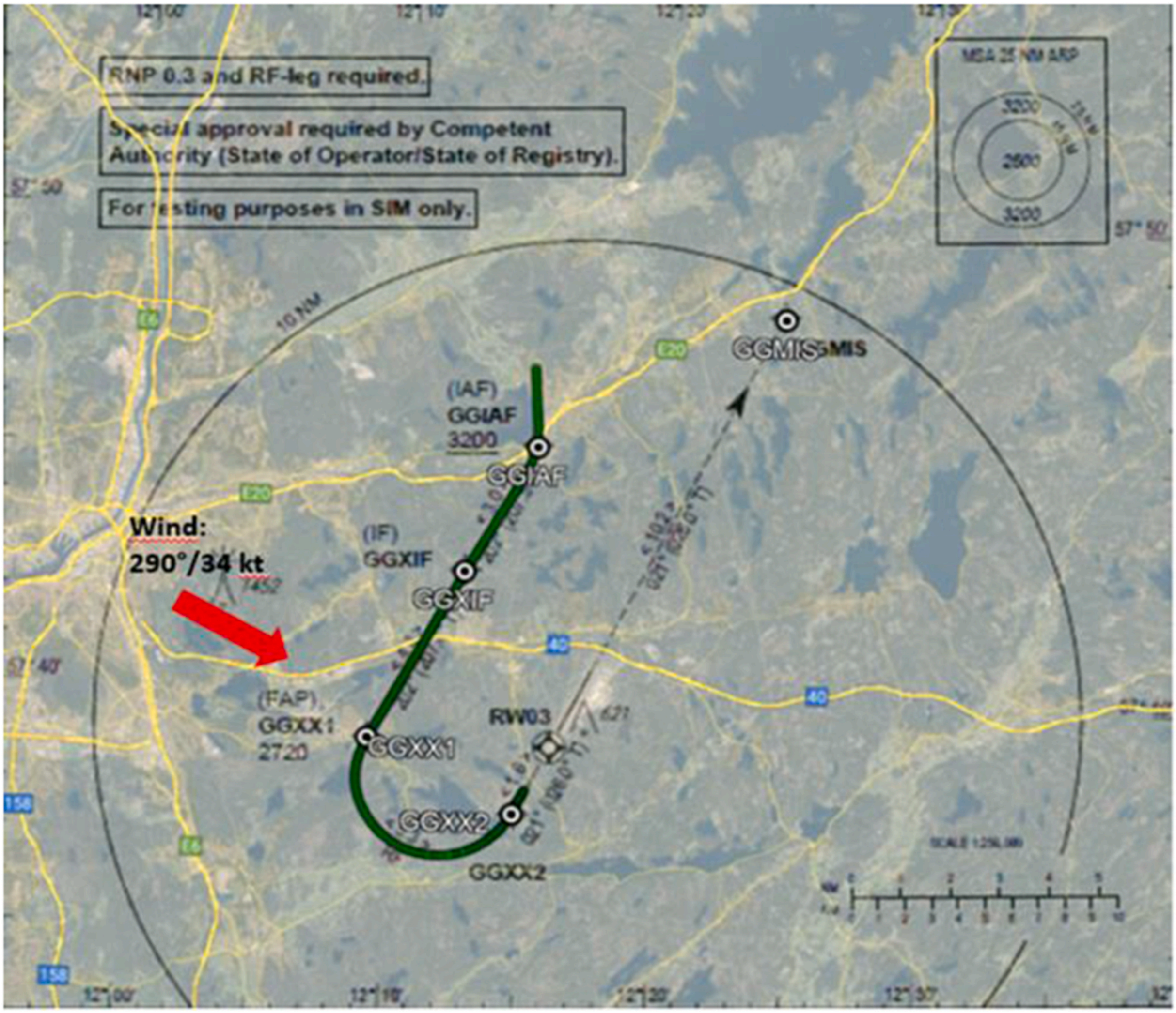


**Fig. 13.** Descending with a 3° from FAP/GGXX1, IAS 185 kt and CONF 2 with wind of 290°/34 kt.

NM shorter when using the TWC from the statistical wind data in the procedure design. This is very positive in several aspects - reduced fuel consumption, less emissions to the ambience and a shorter flight time which is positive for air traffic control in terms of traffic management and separation. In the simulations of a A320 aircraft model flying the two procedure design conditions using a commercial aircraft preliminary design software Pacelab APD version 8.1 (PACE GmbH, 2023), a fuel burn reduction of 111.3 kg was obtained when flying the statistical wind designed procedure compared to the one designed with ICAO standard wind. Considering a jet fuel combustion CO2 emissions index of 3.16 (kg of equivalent CO2 per kg of jet fuel) as introduced in (ICAO, 2024), this equals to a CO2 emissions reduction of 350 kg which can be even higher if considering the jet fuel life cycle CO2 emissions. The simulations performed have assumed the same take-off weight, the same rate of climb, the same calibrated air speed, and the start/end point as specified in Table 2, for a direct comparison.

In the current RNAV SID RWY08 Right Turn procedure without RF-leg published by the Air Navigation Services of Sweden (LFV, 2023b), the instruction limits the maximum indicated air speed to 205 kt and a minimum altitude to 2500 ft. Removing the SID speed constraint would benefit the fuel consumption and CO2 emissions as demonstrated in (Mitchell and Ekstrand, 2011), and one possible way to lift the speed limit proposed in the study is to use statistical meteorological data instead of ICAO standard wind table for the procedure design. However, in our current study, especially the design practice of the new ESSA RNAV SID procedure with RF-leg, the first target was to keep the RF-leg inside the noise dispersion area as regulated by the authorities. While lifting the speed limit would increase the RF turn radius, the flight speed constraint was hence retained. While the climb rate has been also fixed for both cases, engine power and high lift devices deployment would be similar for the two cases, the only difference is then the end altitude that the aircraft will achieve at the end point. Altitude is normally more critical with respect to noise emissions, higher altitude level in general means lower noise emissions to the ground. As we can see the end point altitude for both procedures are well above the minimum altitude of 2500 ft, the noise emitted to the ground has been recognized as a minor issue to consider in the study.

The RF-legs of the two cases are plotted in Fig. 9 with the noise dispersion area outlined by red line. Looking at the left plot, the result of the case using ICAO standard wind is that the turn of the RF-leg, which is outlined by blue line, ends up far outside the permitted noise dispersion area with approximately 2400 m (marked in yellow area). On the other hand, the right plot shows that the part of the RF-leg outside the permitted noise dispersion area is significantly reduced when statistical wind data is applied. However, the RF-leg is still failed to achieve the target as there is a small part of the turn outside the border of the noise dispersion area about 200 m. To further reduce the RF-leg turn radius in order to keep the turn inside the dispersion area, one may choose to tighten the speed limit. A more comprehensive study would be needed to investigate the feasibility of this option as it involves trade-offs/conflicts

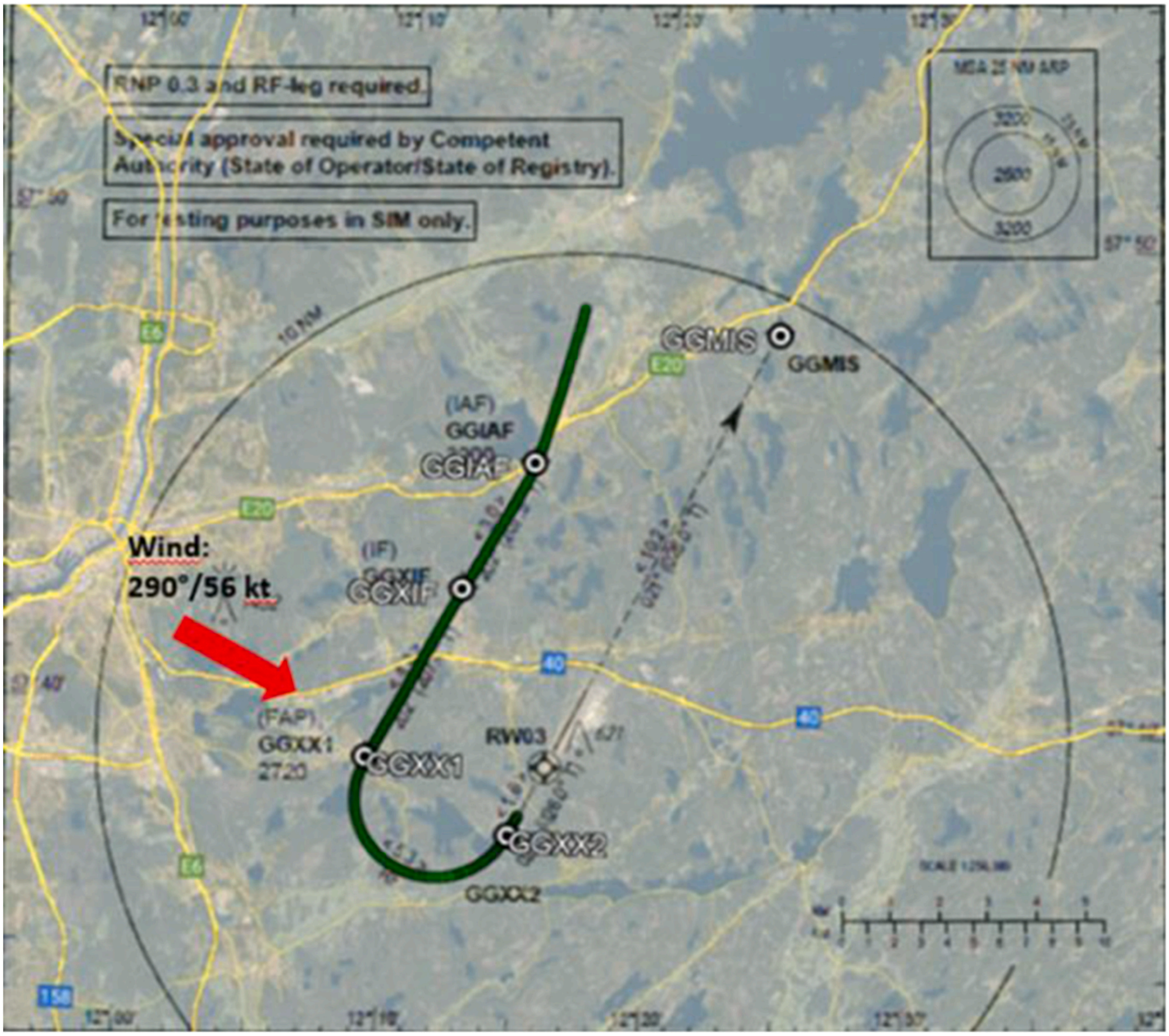


**Fig. 14.** Descending with a 3° from FAP/GGXX1, IAS 165 kt and CONF 2 with wind of 290°/56 kt.

between different aspects, such as engine noise and airframe noise due to lowered engine power and prolonged high lift devices deployment, aircraft noise and fuel burn/emissions as tightened speed constraint is unfavourable in fuel burn and emissions, etc.

### 3.2. ESGG RNP AR approach procedure design results

In Fig. 10 shown below, the flight path for the ESGG RNP AR approach procedure designed on ICAO standard wind as well as the flight path designed on the statistical wind data are plotted over map. The reduction in fuel burn, according to the simulations performed in Pacelab with the procedure details as specified in Table 3 and an A320 aircraft model, is however mild because the shortening of flight distance is just 1 NM in this case. About 4.9 kg for the statistical wind designed procedure was obtained from the simulations and this is equivalent to about 15.5 kg CO2 emissions. More importantly, the flight paths show that with the statistical meteorological wind data it could avoid flying directly over an inhabited area (Mölnlycke, as can be seen in the zoom-in image of Fig. 10), which therefore would lead to a reduced environmental impact with regard to noise and emissions to the ambient. Conflict of interest may exist when flying the new path as noise impact is not eliminated as flight altitude, speed, and aircraft configuration settings are similar between the two procedures, but moved from one area to another. It has been investigated in Thoma et al. (2024) that, by re-constructing the lateral flight profile and allowing the aircraft to turn away from a dense population area, a significant reduction of over 1/3 in the number of people initially affected by noise exceeding 70 dB(A) in terms of sound exposure level can be achieved.

### 3.3. Validation – A320 full flight simulator

Based on the ESGG RNP AR approach procedure constructed with the statistical meteorological data, a standard ICAO instrument approach chart has been issued for testing purpose, as presented in Fig. 11. A simulator evaluation of the procedure was then performed on the April 18, 2023 in an A320 full flight simulator in Essen, Germany. The aim of the simulator session was to validate the RNP AR approach procedure for RWY03 at ESGG that was developed with statistical meteorological data, and to investigate the operability of the procedure with different wind conditions. Five different cases of the RNP AR approach test procedure were flown, and focus was on flyability, crew workload and aircraft drift. In conclusion, no issues were identified, and the procedure was deemed flyable and acceptable from an operational perspective in all cases. Below, the setups and results of the five simulator evaluations are presented case by case. For each case, the flight path from the simulator have been plotted in Google Earth together with the coordinates for the procedure waypoints, see Figs. 12–16. The instrument approach chart has then been superimposed on the Google Earth map

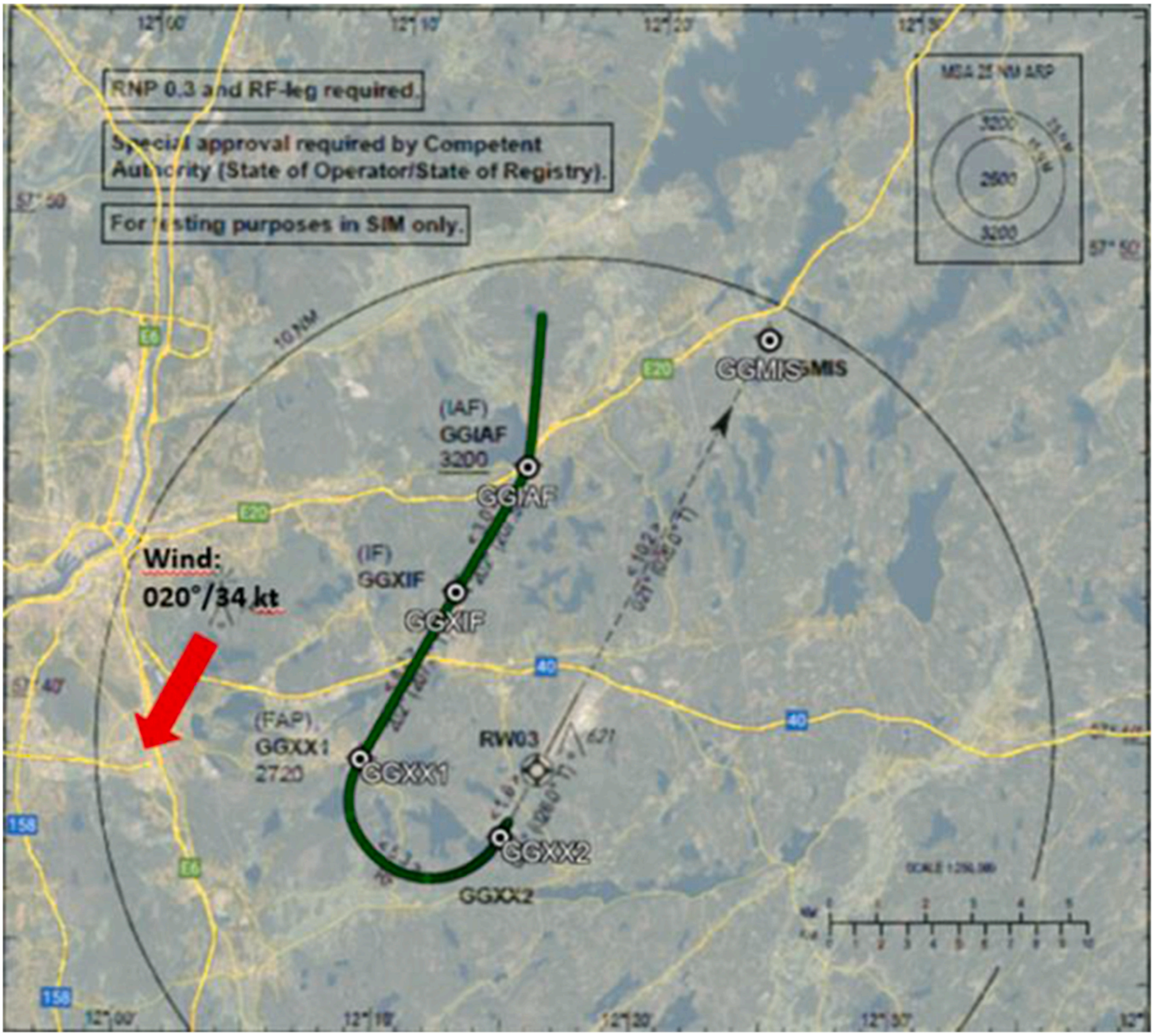


**Fig. 15.** Descending with a 3° from FAP/GGXX1, IAS 185 kt and CONF 2 with wind of 020°/34 kt.

with partial transparency to display the details together with the flight path from the simulator. A red arrow in the figures indicates the wind direction and above the arrow, the wind direction and wind speed used in the case are stated.

- **Case 1:** the turn between GGXX1 and GGXX2 was flown in level flight at 2700 ft mean sea level (MSL), IAS 185 kt and flap configuration (CONF) 1. The wind was 290°/34 kt giving the highest TWC halfway through the turn, where 34 kt is the TWC that was used in the procedure design and corresponds to the 95th percentile TWC for the turn filtered on maximum 5 kt TWC for RWY03. As can be seen Fig. 12 below, the lateral flight path follows the RF-leg perfectly.
- **Case 2:** in this case and all the following cases, the procedure was flown as a normal approach, i.e. descending with a 3° vertical path angle from the FAP (GGXX1). The aircraft configuration at the FAP was CONF 2 and the IAS was 185 kt. Landing gear was extended at 2300 ft followed by CONF 3. The IAS at GGXX2 was 140 kt. The same wind was used as in case 1 (290°/34 kt). Also for this case, as can be seen in Fig. 13 below, the lateral flight path follows the RF leg perfectly.
- **Case 3:** a higher wind speed of 56 kt, which corresponds to the 100th percentile TWC for the turn filtered on maximum 5 kt TWC for ESGG RWY03, was used at the wind direction of 290°. A vertical path angle of −3° was flown from the FAP (GGXX1) and the aircraft configuration at the FAP was CONF 2 with an IAS of 165 kt. The reason for the lower speed over the FAP (165 kt instead of 185 kt as in the previous cases) was to fly the approach in a manner that is realistic from an operational point of view. With such strong winds, a more conservative deceleration and configuration of the aircraft is what can be expected. Landing gear was extended at 2300 ft followed by CONF 3. The IAS at GGXX2 was 140 kt. As can be seen in Fig. 14 below, the lateral flight path follows the RF leg perfectly also in this case. The highest bank angle reached during the turn is 22° which is well below the aircraft maximum bank angle limit.
- **Case 4:** the procedure was flown with the TWC that was used for the procedure design and with a wind direction giving full tailwind on the course flying into the turn, i.e. 020°/34 kt. A vertical path angle of −3° was flown from the FAP (GGXX1) and the aircraft configuration at the FAP was CONF 2 with an IAS of 185 kt. Landing gear was extended at 2300 ft followed by CONF 3. The IAS at GGXX2 was 140 kt. In this case the maximum bank angle 30° is reached in the beginning of the turn for a few seconds when the full TWC is experienced. There was a slight drift, reaching a cross track of 0.04 NM at the most, which is hardly to be seen from Fig. 15 while the rest of the flight path follows the RF leg well.
- **Case 5:** the procedure was flown with a high wind speed giving a full TWC on the course flying into the turn (020°/56 kt). Despite the very strong tailwind on the course inbound to the FAP, the IAS passing the

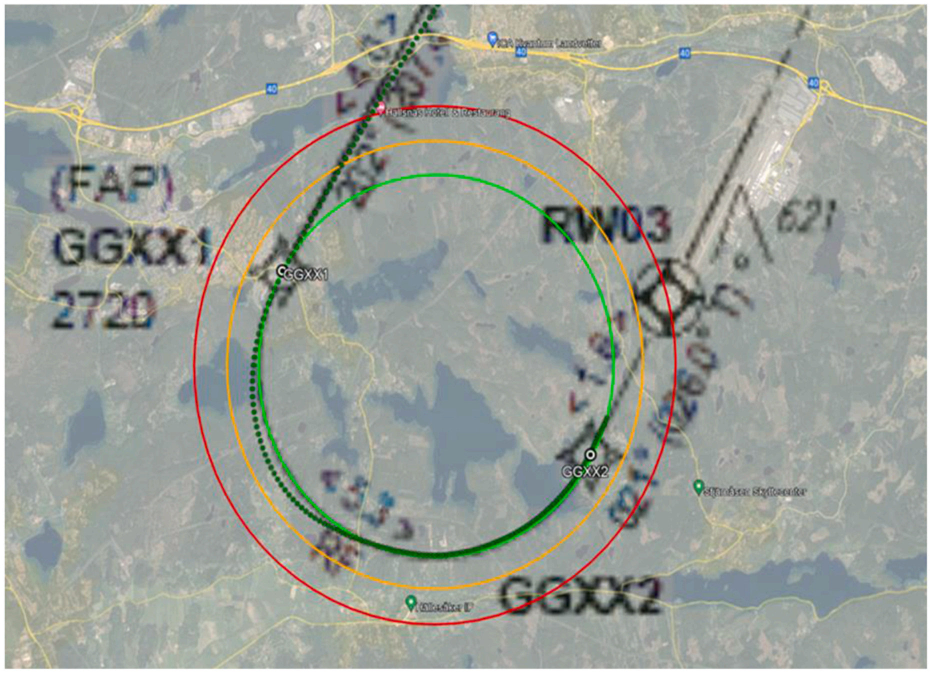


**Fig. 16.** Descending with a 3° from FAP/GGXX1, IAS 190 kt and CONF 2 with wind of 020°/56 kt; the radius of the RF leg (green circle), the outer limit of the RNP0.3 corridor (orange circle) and the outer limit of the protected area (the red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

FAP was kept high in order to evaluate a worst-case scenario. The IAS at the FAP was 190 kt in CONF 2. The landing gear was extended at 2300 ft followed by CONF 3. The IAS at GGXX2 was 176 kt. In this scenario, the aircraft drifted off the intended radius during the first part of the turn, as can be seen from Fig. 16, where the ground speed was the highest (255 kt when passing the FAP). The use of a 30° bank angle during approximately 20 s at the mean time. The cross track at the point of maximum drift was 0.13 NM. In this figure, circles have been plotted illustrating the radius of the RF leg (the green circle), the outer limit of the RNP corridor (radius of the RF turn + 0.3 NM, the orange circle) and the outer limit of the protected area (radius of the RF turn + 0.6 NM, the red circle) where obstacle clearance is guaranteed.

## 4. Conclusion

Applying site-specific statistical meteorological data in constructing curved flight procedures has been performed with two procedure design practices at two Swedish airports. Firstly, to determine an appropriate subset of the statistical meteorological data to be used, a filter has been introduced to exclude the meteorological data when take-off/landing on the intended runway is not allowed due to high TWC for the runway direction. Secondly, the highest TWC during the curved flight turning derived from the statistical meteorological data has been used instead of using the TWC at the highest altitude during the turn. Study has shown that the highest TWC throughout the turn can be higher than the TWC at the highest altitude, since the wind speed/TWC from statistical meteorological data is not simply linear to the altitude. Using the TWC at the highest altitude during the turn when applying statistical wind data would be risky that a higher TWC encountered later in the turn would be missed.

Although one of the procedure design practices, the construction of the RNAV SID has failed to keep the RF-leg completely inside the noise dispersion area. The potential of using it instead of ICAO standard wind is still significant as the flight path outside the noise dispersion area has been greatly reduced. In addition, the smaller turning radius designed on the statistical wind data has shortened the flight distance in this case by 3.7 NM which is 21% of the flight distance of the procedure designed on ICAO standard wind. Another design practice, which is the construction of the RNP AR approach, has been a success in all aspects. Compared to the procedure designed on ICAO standard wind, the RNP AR approach procedure designed on the statistical wind data has achieved a 1 NM shorter flight distance, and more importantly, the lateral flight path has been shifted away from the centre of an inhabited area near the airport. Nevertheless, future studies would be required to quantify these potentials in fuel burn and emissions reductions as well as noise impact evaluations, with accurate modelling techniques or ideally real flight tests. More practical cases need to be sorted out by different stakeholders who have access to local historical meteorological databases and with procedure design capabilities, case by case as every airport and procedure can be different. One can argue if removing speed constraint or shortening the RF turning path would be more beneficial through adopting statistical meteorological data in procedure design. Conflict of interest may exit when shortening the RF turning path as noise impact is not eliminated but moved from one area to another, while removing speed constraint could substantially increase engine noise in the exchange of the noise caused by the aircraft high lift system.

As safety is always the top priority in aircraft operations, the RNP AR procedure designed on statistical wind data has been validated through tests in an A320 full flight simulator. It has been proved in the simulator tests that, even at the worst scenario where the 100th percentile wind from the statistical wind data and a higher IAS were applied, modern aircraft with the capability of operating at 30° bank angle would be able to fly the procedure without challenging the outer limit of the RNP0.3 corridor. The presented study encourages the use of site-specific statistical meteorological data in constructing curved flight procedures, which could bring down the environmental impact near the airports, and enhance the flexibility and predictability of ATM.

## CRediT authorship contribution statement

**Xin Zhao:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ulrika Ziverts:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Henrik Ekstrand:** Validation, Resources, Methodology, Formal analysis, Conceptualization. **Maria Ullvetter:** Visualization, Methodology, Formal analysis. **Peter Lukic:** Visualization, Methodology, Formal analysis. **Anette Näs:** Supervision, Resources, Methodology. **Esbjörn Olsson:** Resources, Methodology, Data curation. **Martin Ridal:** Resources, Methodology, Data curation. **Åke Johansson:** Resources, Methodology, Data curation. **Martin Wall:** Writing – review & editing. **Olivier Petit:** Resources, Methodology, Funding acquisition, Conceptualization. **Tomas Grönstedt:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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