Curved Approach Segments for Noise Abatement

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BIOGRAPHIES

Dr. Marc Troller is a navigation expert at the Swiss Air Navigation Services Ltd., Skyguide, Switzerland. He received M.S. and Ph.D. degrees in Geodesy and Geodynamics from the Swiss Federal Institute of Technology (ETH) Zurich in 2000 and 2004 respectively. He has been involved in several GNSS approach implementation projects in the Swiss airspace in the last years.

Romano Germann is an instrument flight procedure expert at the Swiss Air Navigation Services Ltd., Skyguide, Switzerland. Romano joined Skyguide's predecessor in 1997 where he followed two and a half years of ATCO training in Area Control. As a project manager, he is currently in charge of GNSS instrument flight procedure projects like the introduction of RNAV 1 at regional airfields, the implementation of RF leg SID at Zurich or the development of RNAV approach at Buochs airfield.

André Frik is the EASA part 21J Head of Design Organization at Cessna Zurich Citation Service Center GmbH (former Jet Aviation AG, Zurich Airport Branch). He received Dipl. El. Ing. Bsc degree in Electrical Engineering and Information Technology from the Zurich University of Applied Sciences 2005-2009 and the exec. MBA in General Management from the University of Applied Sciences in Business Administration Zurich in 2009-2011. He was responsible for development and certification of the test aircraft’s avionic suite as well as development and conductance of flight tests for RF legs. This included also the development and approval of an EASA accepted certification review item outside RNP-AR.

Captain Marc Bertschi is a Swiss Air Force pilot, flying helicopter (AS332 Super Puma and EC635) and fixed wing aircraft (Super King Air and Beech 1900D). He has been involved in several GNSS approach implementation projects for the Swiss Air Force, especially RNAV approaches for helicopters in mountainous areas. As a technical pilot he was involved in the upgrading of the Swiss Air Force Super King Air, including RF leg capability.

Dr. Pascal Truffer is a navigation expert at the Swiss Air Navigation Services Ltd., Skyguide, Switzerland. He received M.S. and Ph.D. degrees in Electrical Engineering and Information Technology from the Swiss Federal Institute of Technology (ETH) Zurich in 1994 and 2001 respectively. He has been involved in several GNSS approach implementation projects in Switzerland and is currently managing the GBAS project in Zurich.

Dr. Maurizio F. Scaramuzza is head of expert team on Communication, Navigation and Surveillance at the Swiss Air Navigation Services Ltd., Skyguide, Switzerland. He received his Diploma in Geomatics at the Swiss Federal Institute of Technology (ETH) Zurich in 1995. Then he joined the Institute of Geodesy and Photogrammetry at the ETH Zurich, where he received the doctorate in technical sciences in the field of satellite based flight approaches and landings in 1999.

ABSTRACT

Noise protection has an increased importance for approach and departure procedures in vicinity of airports. A possible option is to concentrate flight tracks over sparsely populated areas to the greatest extent possible. Switzerland has many congested and extensively fragmented airspace due to the various user requirements. ICAO's latest update on performance-based navigation will allow Radius-to-Fix (RF) legs during initial and intermediate segments of an approach. The latter are a major enabler to minimize airspace use and to optimize fuel consumption.

In the frame of the Swiss-wide implementation program to promote GNSS procedures and applications (CHIPS), test flights were carried out to analyze the use of various RF leg applications in an approach procedure. Two different approach scenarios were developed. The first scenario was designed according current ICAO standards with one RF leg and a straight stabilization segment of 2 NM before the final approach segment. The second scenario included three RF legs, the first one to the right, followed immediately by a second and third leg, both, to the left. The latter ended directly at the start of the final approach segment. A maximum bank angle and wind conditions without safety margins tailored to the deployed aircraft were applied, pushing the system to the envelope limits. Both scenarios were designed with an ILS and RNAV final approach segment.

Test flights have been carried out with a Super King Air of the Swiss Air Force. This aircraft is equipped with a
Pro Line 21 system having RF leg capability and a Rockwell Collins GPS4000S GPS/SBAS receiver.

A total of 13 approaches have been flown. The aircraft has been equipped with a geodetic GNSS receiver in order to record raw GPS measurements. These measurements have been post-processed to determine the true flight path at decimeter level accuracy. The navigation system flight trajectory has been determined by recording ADS-B messages.

The test flight results have been analyzed concerning compliance to the ICAO RNP 1 specification. The flights have been performed with different autopilots and flight director settings. Furthermore, configurations with deselected GPS and deselected DME have been tested.

The performance boundaries of RNP 1 were maintained for all flights. Even abnormal conditions with dead reckoning (DR) navigation only, resulted in an acceptable performance. The transition with a single RF leg did never show any significant deviation from the designed flight track. The transition with three RF legs in an S-shape, however, showed significant lateral deviations of up to 0.3 NM.

INTRODUCTION

The implementation of ICAO’s performance-based navigation (PBN) concept allows a significantly more flexible route design. For the terminal area, approach and departure, the design of enhanced procedures are planned to be published in the near future. Curved segments, the so-called Radius-to-Fix (RF) legs, are a major enabler and allow to better avoid densely populated areas and to significantly narrow the flight track distribution. Consequently, the noise impact can be managed much easier.

So far, RF leg applications have mainly been limited to RNP AR APCH procedures. With the publication of the latest version of the ICAO PBN manual (ICAO, 2013), RF legs are now also applicable in the initial and intermediate segments of an approach procedure. The design criteria are currently being developed by the ICAO Instrument Flight Procedure Panel (IFPP) and intended to be published in autumn 2014.

The terminal maneuvering area of Zurich has congested and extensively fragmented airspace. Noise protection is a major aspect to operate with the goodwill of local residents. Consequently, the introduction of RF leg segments is a major enabler for future operations. To cope with these requests, a Swiss-wide implementation program to promote GNSS procedures and applications (CHIPS) has been setup. All major aviation stakeholders are taking part in this program.

In the frame of this program, curved approach test flights have been carried out with several RF leg segments at the airfield of Dübendorf. A Hawker Beechcraft B300C King Air of the Swiss Air Force has been used, equipped with a Rockwell Collins GPS 4000S GPS/SBAS receiver and the Pro Line 21 system including RF leg functionality.

INSTRUMENT FLIGHT PROCEDURE DESIGN

Two RNP 1 transitions with RF leg segments in the initial and intermediate part of the approach have been designed (see Fig. 1) based on two ICAO working papers for RF leg design criteria (ICAOa, 2012; ICAOb, 2012).

The first transition includes one single RF leg with standard conditions in respect of wind (59 kt omnidirectional) and maximum bank angle. A radius of 2.1 NM and an IAS (Indicated Air Speed) of 180 kt (maximum for CAT B aircraft) resulted. A 2 NM stabilization segment
has been included between the RF leg and the final approach segment.

The second transition includes three RF legs. A maximum wind component of 30 kt has been assumed. The S-shape RF legs have rather narrow radiiuses of 1.7 NM for the first two legs and 2.55 NM for the third leg. The latter is followed by the final approach segment immediately, i.e. without any stabilization distance.

In the final approach segment of both transitions the aircraft makes use of the existing ILS or RNAV approach (to LNAV minima). In the case of an ILS approach, the currently published conventional missed approach based on a conventional turn at an altitude is used. In the case of an RNAV approach, a missed approach procedure with one RF leg has been designed based on standard conditions and a radius of 1.5 NM.

**TEST FLIGHT SUMMARY**

A total of 13 flights have been carried out (JetAviation, 2012):

- 2 flights with the single RF leg transition and ILS final
- 2 flights with the single RF leg transition and RNAV final
- 2 flights with the S-shape RF leg transition and ILS final
- 7 flights with the S-shape RF leg transition and RNAV final

Usually, the approaches have been flown with autopilot and full navigation capability. On some flights, special configurations have been applied:

- Deselection of both GPS receivers (3 flights)
- Deselection of both GPS receivers and the DME receivers (1 flight)
- Disengagement of the auto-pilot (1 flight)
- Disengagement of the flight director (1 flight)

**DATA RECORDING AND ANALYSIS METHOD**

A JAVAD Sigma GNSS receiver has been used to record raw GNSS data during the flights. The Super King Air is equipped with an additional fixed-installed GNSS antenna which was used for this purpose. Recordings have been made with 1 Hz data rate in the L1/L2 band. Data of the automated GNSS network for Switzerland (AGNES) have been used as reference station recordings. Post-processed, the reference trajectories of all flights have been determined with a carrier-phase solution to an accuracy level of roughly 10 cm RMS. These flight trajectories have been determined independently of avionics GNSS receiver recordings.

Additionally, position information of the avionics system has been recorded thanks to the ADS-B out transmitter of the aircraft. With a Kinetic SBS-3 ADS-B receiver, raw data has been recorded and processed resulting in position information.

The flight trajectories determined with phase solution represents the true flight path, i.e. the path where the aircraft actually flew. The navigation system flight path is the flight path as indicated by the aircraft avionics and gathered by the ADS-B receiver. Finally, the desired flight path is the path indicated on the flight charts (see Fig. 2).

![Fig. 2: Relation between different flight path determinations and its associated errors.](image)

Different errors are derived from these flight paths. The navigation system error (NSE) is the difference between the true flight path and the navigation system flight path, i.e., the error of the avionics navigation solution. The flight technical error (FTE) is the difference of the navigation system flight path and the desired flight path and, the total system error (TSE) is the difference between the true flight path and the desired flight path or the sum of the FTE and the NSE.

Each of the 13 flights has been analyzed individually. The lateral components of the FTE and the TSE have been determined. The analysis has been performed for each flight segment (Skyguide, 2012; Skyguide, 2013).

**SINGLE RF LEG TRANSITION FLIGHTS**

Flights using the single RF leg transition showed normal behavior. The flight tracks of one of these flights are given in Fig. 3. The aircraft is flying precisely on the nominal track with a track deviation of less than 0.02 NM. The intercept to the RNAV final approach segment as well as to the ILS final approach segment was always successful. Furthermore, the difference between the true flight path and the navigation system flight path is negligible.

One flight was performed by deselecting GPS/SBAS. Thus, the aircraft reverted to DME/DME operation. The deviation to the nominal track increased to roughly 0.1 NM, however, the transition was possible and still accurate enough with a large margin.
The limits of the aircraft were checked by omitting waypoint MD752 and proceeding directly to MD751 (see Fig. 4). As the aircraft did not pass MD751 tangential to the RF leg arc, a large track deviation occurred until the FMS was able to correct the track to the nominal path. The largest deviation was roughly 0.3 NM shortly after MD751 and decreased constantly until the end of the RF leg segment. The intercept to the ILS final approach segment has been performed without any difficulties.

**S-SHAPE TRANSITION FLIGHTS**

The S-shape transition flight tracks obtained under normal conditions are shown in Fig. 5. The nominal track is accurately followed in the first straight segment (MD703-MD702) and the first RF leg (MD702-MD701). Subsequently, a significant track deviation of up to 0.3 NM was observed in the opposite RF leg. The aircraft corrected the track by applying the maximum bank angle of 25°. As the prevailing tailwind was roughly 29 kt and...
the procedure has been designed for a tailwind of maximum 30 kt, the track correction took a relatively long time and the aircraft was aligned on the nominal track not before VIBAX. Two flights with identical conditions have been performed and this behavior was reproduced.

To verify that the S-shape design is the reason for the significant track deviation, a further flight has been carried out omitting the S-shape segments (MD703-MD701), thus, proceeding directly to MD701 and flying the RF leg segment until VIBAX (see Fig. 6). This flight did not show a significant track deviation, the maximum lateral displacement was less than 0.1 NM.

A further flight has been carried out to verify the auto-pilot performance. The first two segments until MD701 have been flown with auto-pilot, subsequently, the auto-pilot has been disengaged and the pilot tried to follow the nominal track manually. Nevertheless, the resulted track deviation was similar to the previous flights with a maximum track deviation of 0.35 NM (see Fig. 7).

Another two flights have been carried out completely without auto-pilot. In the first flight, the pilot flew in plan mode and the second flight in CDI (course deviation indicator) mode (see Fig. 8). Both flights have been performed without significant deviations on the critical RF leg segment (MD701-MD700). The maximum track displacement for the plan mode was 0.4 NM and for the CDI mode 0.15 NM. The pilot judged the CDI mode as easier to follow, which has also been observed from the track deviation analysis. The intercept to the RNAV final approach segment was achieved successfully in both approaches with a high accuracy.

The last part of the S-shape test flights investigated the track deviations in degraded navigation modes (see Fig. 9). For the first flight, GPS/SBAS was deselected and the aircraft reverted to DME/DME navigation. The resulted track deviation due to the S-shape design was slightly larger than in the nominal condition but did not exceed 0.35 NM. The RNAV approach was aborted after VIBAX as GPS, required for this segment of the approach, still was deselected. For the second flight, GPS/SBAS and DME was deselected, consequently, the aircraft had to revert to the AHRS (Attitude Heading Reference System), i.e. it had to navigate in DR (dead reckoning) mode. A significantly larger deviation to the nominal track was present with a maximum of 0.7 NM. However, even in DR mode, the aircraft’s avionics was capable to fly the S-shape transition with a successful intercept to the ILS final approach segment.
**MISSED APPROACH RF LEGS**

The RNAV missed approach procedure with one RF leg has been flown four times, twice with auto-pilot (see Fig. 5) and twice manually (see Fig. 7 and Fig. 8). All flights did accurately follow the nominal tracks. The highest flight track deviation was observed with disengaged autopilot with a maximum deviation of 0.15 NM.

**CONCLUSION**

Curved approach procedures with RF legs have been tested flown to assess the performance and the potential of advanced RNAV procedures for the avoidance of noise-critical areas in the approach segment. Current ICAO approach design criteria include an S-shape design of the RF legs but foresee a straight segment between the last RF leg and the final approach segment.

The flight analyses of the single RF leg transition showed that all flights accurately followed the nominal tracks. The differences between the true flight path and the navigation system flight path were negligible. The flight track deviations were less than 0.05 NM. Even reverting to DME/DME navigation resulted in a flight track deviation of less than 0.1 NM. Consequently, the requirements for ICAO’s RNP 1 navigation specifications were always reached with a large margin.

The analysis of the S-shape transition showed a different picture. The intercept of the final approach segment, be it ILS or RNAV, was successfully possible directly from the RF leg segment. However, the S-shape design, which is based on published ICAO criteria, did show significant lateral track deviations of up to roughly 0.3 NM. The different flight configurations showed that these deviations appeared because of the two RF legs immediately following each other with a turn direction change. It is assumed that the aircraft did finish the first RF leg not before the waypoint MD701 and entered in the second RF leg with some delay, as time was needed to physically roll into the opposite turn. To correct the deviation, the aircraft applied the maximum bank angle of 25°. The present tail wind component was nearly the maximum considered in the RF leg design, consequently, the correction took a relatively long time. However, the transition was designed according ICAO’s RNP 1 navigation specification and the significant lateral deviations were always within the limits of RNP 1. Even in degraded navigation mode, using DR, the maximum observed lateral deviation only reached 0.7 NM, fully compliant with the RNP 1 requirements.

The test flights showed the potential of RF leg segments for curved approaches. Such operations will significantly narrow the flight track distribution and allow avoiding noise-sensitive areas in the future. A first operational implementation of a curved approach is being planned at the airfield of Dübendorf. A monitoring of the flights will be performed to statistically analyze the track distribution.
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