RF leg for departures: One year of successful experience

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ABSTRACT
The Swiss-wide Implementation Programme for SESAR-oriented objectives (CHIPS) aims at implementing new and operationally beneficial technologies and procedures in the Swiss air traffic system. An efficient management of the dense airspace in the vicinity of airports in line with noise protection expectations for the local residents asks for new, tailored procedures. Among these, required navigation performance RNP1 operations including curved segments, the so-called radius to fix (RF) leg functionality, fulfil these demands. RF legs significantly reduce the dispersion of flight tracks.

On 18 October 2012, a first departure procedure with an RF leg has been implemented at Zurich airport. Pilots, depending on aircraft capabilities, may now choose between the conventional and the new RF leg departure. A monitoring system has been established in order to assess the utilisation of the RF leg procedure as well as the navigation performance of the flown flight tracks.

Nearly one year of data with more than 1000 flight tracks are now available. Several aircraft types, covering all seasons and many different weather conditions were recorded. Deviations from nominal tracks have been assessed based on PSR/SSR data as well as on ADS-B information.

In general, the RF leg track distribution changes considerably compared to the conventional departure procedure. A high-precision navigation performance is achieved. Even older airplanes show only small deviations from the nominal track. An analysis has been carried out to determine the statistical parameters on the cross-track error distribution. RNAV/RNP1 requires a 95% accuracy of 1 NM. The achieved 95% accuracy level is roughly 0.1 NM, whereas the maximum errors rarely exceed 0.3NM. Consequently, the accuracy requirements are exceeded by one order of magnitude.

In conclusion, this first RF leg application in Switzerland shows the benefit of advanced RNP operations and will certainly lead to further implementations of departure procedures and also facilitate the introduction of so-called ‘curved’ approach operations. A first curved-approach project has already been initiated at the Swiss Air Force base, Dübendorf.

INTRODUCTION
Performance-based navigation (PBN) allows a more flexible use of the airspace. Often, aircraft may be guided on more direct routes and the lateral separation between aircraft on different routes may be reduced due to the increased performance of the RNAV/RNP environment. In the vicinity of airports, the management of noise is becoming more and more important. PBN allows to narrow the flight track distribution which may be a benefit for airport operators. So far, the PBN concept of ICAO (ICAO, 2008) foresees these advantages only for straight flight segments, whereas for turns, only fly-over or fly-by waypoints exist. Both methods require large protection areas and distribute the flight trajectories over a large area. The effectively flown trajectories are influenced by the aircraft's FMS, flight dynamics, wind conditions and several other factors. Managing the noise pattern is only possible to a limited extent.

The newly introduced RF leg functionality outside of the RNP AR environment (ICAO, 2013) does fill this gap allowing to design constant and predictable turns for approach and departure operations outside of the final approach segment. The RF leg functionality is intended as an optional function within ICAO's RNP1, RNP 0.3 and RNP APCH navigation specifications but required for the A-RNP navigation specification.

The Swiss-wide implementation programme for SESAR-oriented objectives (CHIPS) aims at implementing satellite-based navigation applications in the Swiss airspace. The present RF leg
implementation project has been carried out in the frame of the CHIPS programme to gain experience in terms of airspace densification and noise management. Consequently, the monitoring of the flights using this new RF leg function including the statistical analysis of track deviation is a major task within this project.

**RF LEG IMPLEMENTATION AT ZURICH AIRPORT**

An RF leg is defined as a curved segment between two waypoints. The arc is defined by a radius to be flown from the first to the second waypoint. The RF leg functionality is only foreseen in the RNP environment (RNP1, RNP 0.3, RNP APCH and A-RNP) but not in the RNAV environment which is currently implemented at Zurich airport.

To ease this first implementation - in deviation to ICAO's PBN manual - the RNAV1 navigation specification (ICAO, 2013) has been chosen. In order to still have a sufficient integrity monitoring on board an aircraft, the only accepted navigation sensor to fly this RF leg is GNSS. In that way, a quasi RNP-environment is achieved without the need of additional aircraft certifications.

The RF leg segment has been implemented on a standard instrument departure (SID) towards west from runway 34 at Zurich airport. It consists of a left turn between the waypoints ZH570 and ZH573 starting after the straight segment of the SID (see Fig. 1). The radius of the RF leg is 2.1 NM and the speed is restricted to 210 kt IAS (AIP, 2012; ICAOa, 2012; ICAB, 2012).

![Figure 1: RF leg design of the SID runway 34 (segment ZH570 – ZH573).](image)

The RF leg has been designed as an overlay to an existing turn of a conventional SID (AIP, 2012). Thus, pilots may choose between one of both procedures. According to our investigations, the RF leg SID should only be available in FMS of aircraft certified for this application.

**FLIGHT ANALYSIS**

The procedure has been implemented on 18 October 2012. A monitoring has been setup to analyse the use of this SID including the period of 18 October 2012 to 26 September 2013. On a statistical basis, the following information is collected:
• Number of aircraft using the RF leg SID
• Number of aircraft using the conventional SID
• Type of aircraft using the RF leg SID

The number of flights using the RF leg SID was already high since the implementation of the procedure (see Fig. 2). Approximately 60% of the flights were using the RF leg procedure. This number seems to stay constant during the monitoring period.

![Figure 2: Number of aircraft using the RF leg SID vs. the conventional SID.](image)

The runway 34 as departure runway has daily time limits. A majority of the flights are performed with long-haul aircraft. Nearly half of the flights using the new procedure have been carried out with the A340 family (see Fig. 3). 30% of the flights were performed with the A320 family and 14% with the Avroliner RJ-100 (RJ1H). However, the RF leg SID was also used by several other aircraft types.

![Figure 3: Distribution of aircraft types using the RF leg SID for the total of 1368 flights observed.](image)
The flight trajectories have been analysed based on radar data. Latter trajectories are assumed as the true flight path. For aircraft sending ADS-B information, this data has also been analysed. ADS-B data is assumed to represent the navigation system flight path. Radar data is usually less accurate than ADS-B data, however, for the present analysis, both data sets are assumed as accurate enough. The analysis includes the deviation from the radar data to the nominal track, the so-called total system error (TSE) and the deviation from the ADS-B data to the nominal track, the so-called flight technical error (FTE).

The flight trajectories of all flights using the RF leg segment have been analysed. Depending on the altitude of an aircraft, the RF leg segment may not be flown to its end, a direction change may be enforced by the ATC by giving a vector or using a direct-to clearance to a consecutive waypoint. Such trajectories must be excluded from the statistical analysis. It is assumed that track deviations are generally small close to the waypoints. Consequently, a method has been applied to evaluate the track deviation at the two waypoints ZH570 and ZH573. If a trajectory deviation of more than 0.2 NM is observed at one of these waypoints it is seen as evidence that the RF leg segment has not been flown out completely and the flight trajectories are disregarded for the statistical analysis. Such trajectories are given in green in the following figures. However, aircraft leaving the RF leg segment shortly before ZH573 may not be excluded from statistics with this method. An example of such trajectories is given in Fig. 4.

![Figure 4: Track distribution for Embraer E190 based on radar data. On several flights, it seems that the RF leg segment was not completely flown, i.e. the ATC enforces a track change before ZH573. Some of these trajectories are included in the statistical analysis (blue trajectories).](image)

The distribution of all flight trajectories using the RF leg SID is shown in Fig. 5. Blue trajectories are used to determine the bounds whereas green trajectories – identified using the method described above - have been disregarded from statistical analyses.
Figure 5: Distribution of real flight trajectories for the RF leg segment based on radar data. Green trajectories show flights where the RF leg segment has not been flown out completely. The blue trajectories have been used to determine the statistical analysis including the error bounds.

The deviation of the tracks to the nominal path is very small. The mean of all tracks (50% bound) corresponds to the nominal track. Also the 5% and 95% bounds are close to the nominal track. A few rare cases have been found where the aircraft did obviously not follow the nominal track. An example is given in Fig. 6. The aircraft seems to fly a straight segment using the two RF leg waypoints (ZH570 and ZH573) as fly-by waypoints. The appropriate airline or aircraft owner of each identified flight has been informed. Feedback has been received partially.
Figure 6: Example of an aircraft’s trajectory which seems not to fly the RF leg correctly.

The track distribution of the conventional SID is given in Fig. 7. The nominal track of the conventional procedure is identical to the nominal track of the RF leg procedure. Comparing Fig. 5 and 7, it is clearly seen visually that the track distribution is much wider by using the conventional procedure.

Figure 7: Track distribution of the conventional SID based on radar data.
The track deviation from the nominal path of the RF leg procedure has been analysed in further detail. The deviation corresponds to the total system error. Fig. 8 shows the results for all trajectories. A statistical analysis has been performed using the blue trajectories. The green trajectories have been rejected using the method described above. The error bounds are given together with some statistical numbers. The maximum track deviation is 0.65 NM to the left of the nominal track and 0.36 NM to the right. The 95% accuracy percentile is 0.1 NM. Consequently, the RNAV1 requirement of the 95% bound within 1.0 NM is exceeded by a large margin.

In a further analysis, it was investigated if the deviation from the nominal track is varying along the RF leg segment. The segment preceding the RF leg segment, DER34 – ZH570 is a straight RNAV segment. Thus, it is expected that the aircraft can follow the nominal path with at least the same accuracy than the RF leg segment and, consequently, near ZH570 the spreading of the flight trajectories should not be larger than on the RF leg. As the statistical analysis may cover flights which changed direction shortly before the end of the RF leg, a larger spreading of the flight trajectories may be present close to ZH573.

The track deviation from the nominal track at the beginning of the RF leg (ZH570), on four further steps and at the end of the segment (ZH573) is given as a cumulative probability distribution function in Fig. 9. It is visible that the 50% distribution is slightly above the nominal path. At the beginning of the RF leg, the track deviation is the smallest. A slight increase of the track distribution is visible for the second part of the RF leg segment and at the end (ZH573).
The track deviation may also depend on the aircraft type. This behaviour has been analysed in the middle of the RF leg segment (2NM after ZH570). However, as the equipment in the individual aircraft is not known in detail, only the different aircraft types have been considered. Fig. 10 shows the statistical track deviation. The RJ1H does have the most accurate trajectories followed by the E190 and the A332.

Figure 9: Cumulative probability distribution function of all flights at the beginning, at four steps in between and at the end of the RF leg segment.

Figure 10: Statistical track deviation 2.0 NM after ZH570 for the individual aircraft types. The green boxes show the 5%/95% boundaries, the bars indicate the minimum/maximum values.
All analyses did investigate the track deviation based on radar data to the nominal path, i.e. the total system error. The individual components of the total system error, the flight technical error and the navigation system error have not been analysed so far. A rough estimate to evaluate the individual error components is shown in Tab. 1. Maximum left (negative) deviation, maximum right (positive) deviation and the 95% error bound values of all aircraft and the individual aircraft types are given for the total system error (based on radar data) and the flight technical error (based on ADS-B data). The numbers for the total system error and the ones for the flight technical error are nearly identical which indicates a small navigation system error.

<table>
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<tr>
<th>Aircraft type</th>
<th>Total System Error (TSE)</th>
<th>Flight Technical Error (FTE)</th>
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<tr>
<td></td>
<td>No</td>
<td>Left max</td>
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<tr>
<td>RJ1H</td>
<td>183</td>
<td>-0.11</td>
</tr>
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</table>

Table 1: Comparison of statistical parameters of the total system error and the flight technical error. As not all aircraft are equipped with ADS-B, the number of flights is smaller in case of the flight technical error analysis.

CONCLUSION

An RF leg segment has successfully been implemented on a SID of runway 34 at Zurich airport. A monitoring has been setup to closely investigate the number of aircraft using the new procedure as well as to analyse the flight trajectories of the individual aircraft.

After the implementation of the new procedure, the majority of the aircraft departing from runway 34 towards the west did fly the new GNSS-only RF leg SID. Nearly half of the RF leg flights have been performed with the Airbus A340. Significant contributions of roughly 30% stem from the Airbus A320 family and 14% of the Avroliner RJ-100.

The track analysis showed an overall excellent fit of the flight tracks with the nominal track. Compared to the conventional procedure, the track distribution did much better follow the nominal track and the spreading of the flight trajectories is much narrower in the case of the RF leg procedure.

A few cases with large deviations from the RF leg nominal track occurred, mainly because an aircraft’s FMS was not able to follow the RF leg’s nominal path. For these cases, the aircraft operator has been informed.

The track deviations of all aircraft were well within the RNAV1 defined boundaries of +/- 1 NM. A mean track deviation of 0.02 NM resulted. All tracks lay between -0.65 NM and +0.36 NM deviation of the nominal track, the accuracy of the 95% bound was 0.1 NM.
The statistical analyses did not show a significant change in the statistical behaviour of the trajectories for the different parts of the RF leg segment. Furthermore, only a small significant deviation between the different aircraft types is seen.

The implementation of the RF leg SID runway 34 did show the expected benefits in respect of flight trajectory distribution and the noise pattern. Such enhanced functionalities will allow more tailored procedures in the future. A next implementation is planned in the frame of an approach procedure in the intermediate segment for the Swiss Air Force base, Dübendorf. Flight trials (Troller, 2013) have already been carried out successfully.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

AIP, (2012), Aeronautical Information Publication Switzerland, Skyguide (WEF 18 October 2012), 2012


