Performance Impact of Mountainous Topography for Cloud Break GNSS Procedure

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BIOGRAPHIES

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ABSTRACT

Performance-based navigation allows implementing approach procedures in areas, where conventional procedures are not a feasible solution. This holds especially true for difficult topographic terrain. In case of the Meiringen Air Force base in Switzerland, which is located in a valley surrounded by mountains up to 10'000 ft, a cloud break procedure for rotary wing operations has been developed. This procedure will allow the Swiss Air Force and the local HEMS (Helicopter Emergency Medical Services) operator to fly under adverse meteorological conditions. Due to topographic constraints a required navigation performance (RNP) value of 0.3 NM is envisaged for the whole approach, starting at the initial approach fix until the end of the missed approach.

One of the most critical points is the loss of GNSS navigation capability combined with a one-engine-out situation. In the first part of this analysis, the approach availability for a 30-satellites GPS constellation has been determined. A GNSS simulator has been used to assess different avionics GPS receivers envisaged for this approach.

Based on the mean time between outages (MTBO) of GPS satellites, the probability of a satellite outage, and the effect thereof, has been determined. The discontinuity probability of the received GNSS signals have been considered together with other main technical error sources such as malfunction of navigation equipment and engine problems. Furthermore, statistics on meteorological conditions in the area of Meiringen have been taken into account.

A failure model has been used to determine the probability of the hazardous situations for each helicopter type individually. The resulted probability has then been compared with the required target level of safety. For all helicopter types, the achieved probability values are better than the required TLS, meaning that the minimum level of safety can be maintained.

INTRODUCTION

The aviation community benefits a lot from recent developments in satellite navigation. Previously, conventional navigation using VOR (VHF Omnidirectional Radio range), NDB (Non Directional Beacon) and DME (Distance Measuring Equipment) significantly limited the design of advanced approach procedure in topographical difficult terrain. With the emerging popularity of GNSS in aviation and the introduction of the
performance based navigation (PBN) concept by ICAO (ICAO9613, 2008), the degree of freedom designing advanced approach procedures increased significantly.

In a first phase, PBN did replace conventional flight procedures in order to increase the performance of the air traffic services. In the meantime, the new possibilities raise expectations from the pilot side to have new procedures in an airspace where conventional procedures are not possible at all. In Switzerland, the terrain is often the most constraining aspect while planning new approach procedures.

This study is based on a request for a new approach procedure coming from the Swiss Air Force and REGA, the Swiss HEMS (Helicopter Emergency Medical Services) operator. A rotary wing procedure should be implemented at the Meiringen Air Force base (LSMM). The base is located at the eastern end of Lake Brienz, situated in a valley surrounded by mountain tops up to 10'000 ft northwards and southwards (see Fig. 1). The HEMS operator frequently uses a hospital located at the western end of Lake Brienz in Interlaken. In the past, flights were only possible under visual meteorological conditions (VMC).

In bad weather situations, flights to more remote hospitals are carried out. However, as a common meteorological situation, a fixed cloud cover may prevent flying into the valley while VMC conditions would be more than sufficient above and below. The goal is to have an approach procedure under instrument flight rules (IFR), allowing direct dispatch of flights under IMC.

MEIRINGEN FLIGHT PROCEDURE

Due to the high terrain, flight procedures to the Meiringen Air Force base are difficult to realize, even if using GNSS and PBN. To realize the maximum benefit for both operators, the Swiss Air Force and REGA, a cloud break instrument flight procedure away from the Air Force base to the center of Lake Brienz (a so called point-in-space (PinS) procedure) is envisaged with following VMC segments to the desired final destination.

Standard ICAO criteria (ICAO8168, 2006) would require a straight-in approach to the point-in-space as well as a straight missed approach procedure (ICAO standard RNP APCH to LNAV minima). Both requirements are not feasible for the given terrain. For the approach, the only solution is to follow Lake Brienz until the point-in-space, including two track changes of 45° and 15°. Under normal conditions, the approach ends at a minimum of 830 ft above the lake followed by a visual flight to the final destination (see Fig. 1). If a missed approach must be initiated, a short straight segment is followed by two turns with 27° track change each, to get out of the valley and to reach a sufficient altitude. ICAO standard criteria would ask for a required navigation performance (RNP) 1 (NM) for the initial, intermediate approach and the missed approach and RNP 0.3 for the final approach. The required airspace for such a standard approach is, however, not available due to the challenging terrain. Thus, RNP 0.3 performance has to be maintained during the whole procedure up to the end point of the missed approach (Delétraz, 2012).

![Fig. 1: Approach procedure to the PinS and subsequent missed approach.](image)

The result is an approach procedure which is flyable, but requires a special assessment of the available helicopter platforms and an extra instruction to the pilots.

OPERATIONAL FLIGHT SAFETY

To cover the various aspects due to the deviation from standards, a so-called flight operational safety assessment (FOSA) has been performed (NLR, 2011). The safety assessment includes both, operational hazards and technical failures. The results allow a risk based approach for the parties involved in accordance with standards and recommendations promulgated by ICAO. As a guideline, EASA airworthiness criteria (EASA, 2009) has been used.

In a first step, the operator has to declare its target level of safety (TLS), which defines the operational risk accepted for flight operations (ICAO9859, 2009). Rotorcraft operations in general and Air Force and HEMS operations in particular accept a higher risk than commercial airlines (Raju, 2010; Boeing, 2009; Marwinski, 1998). For the current project, based on empirical data, a target level of safety of $10^{-4}$ per flight hour has been identified as acceptable (Wipf, 2012).

The safety assessment identified all major hazards and technical failures of this procedure as developed by an interdisciplinary project team. The loss of unexpected navigation capability has been identified as a major hazard. Usually, in case of insufficient GNSS accuracy, a safe missed approach is carried out with the less challenging RNP 1 specification, or alternate navigation aid such as VOR or DME or dead reckoning. None of these options, however, are possible. Due to terrain, RNP
0.3 NM is required for the whole missed approach and the reception of VOR or DME signals is not given. Dead reckoning is critical because of the constant RNP 0.3 performance requirements and the turn in the missed approach procedure.

However, as long as only one failure occurs, operations are always still safe. For instance, in case of only a GNSS failure, the missed approach can be flown with a larger climb gradient to maneuver the helicopter out of the critical area even before the missed approach turn must be initiated.

Consequently, in the next step of the assessment, potential failures have been linked together to evaluate their impact. A reliability diagram has been identified as critical for the implementation of the approach. The simultaneous unexpected loss of GNSS navigation capability and a malfunction of one engine will lead to an unsafe flight (Fig. 2). To assess this safety issue, the probability of this event has been determined.

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case, however, the implemented P-RAIM check is inappropriate to decide on the approach availability.

The approach availability considering the terrain has been analyzed using the software package GeoSTARS. For a 24 hours timeframe, the "worst-case" horizontal dilution of precision (HDOP) values have been determined. "Worst-case" HDOP values are obtained by simulating an unpredicted outage of the most critical GPS satellite. These HDOP values are denoted as HDOP$_{n-1}$. The horizontal protection level (HPL) is derived with receiver-dependent RAIM algorithms. Depending on the RAIM algorithms implemented in the GNSS receivers, HDOP$_{n-1}$ may be a major contributor for the determination of the HPL. As a very rough estimation, a simplified relation between the HPL and HDOP$_{n-1}$ has been used (Truffer, 2011):

$$HPL = 60 \cdot HDOP_{n-1}$$

(1)

This formula is an estimate only and valid for RAIM receivers aware that the artificial GPS signal degradation SA (Selective Availability) is not active anymore. The rough approach availability has been determined as of 99.1% of the day.

The duration of the approach including the missed approach is around 15 minutes. The approach procedure can not be initiated less than 15 minutes before an approach unavailability. Consequently, the availability of an individual approach is given as 97%.

**GNSS AVAILABILITY SIMULATIONS**

The approach procedure will only be available for the Swiss Air Force and REGA and selected types of helicopters. To check the "real" availability of the approach, GNSS simulations have been carried out with four different GPS receivers used in the various helicopters.

As a GNSS signal source, an IFEN-NavX-NCS GNSS signal generator has been used. All simulations have been performed during 24 hours and using an identical GPS constellation including the terrain masking. In case of GPS/ SBAS receivers, two simulations have been performed, the first with GPS signals only and the second one with GPS and EGNOS signals. Fig. 5 shows the HPL of the CMC CMA-5024 and the CMA-3024 receiver. A significant difference is visible for these two receivers. As the CMA-3024 receiver is not aware of SA withdraw, much larger safety margins have to be taken into account to determine the protection levels.

Receivers using GPS/EGNOS do generally show a horizontal protection level which is significantly better than one obtained with GPS/RAIM (see Fig. 5). Tab. 1 shows the approach availability of the investigated receivers. It is concluded that the approach availability derived from the rough estimate has been confirmed with the present simulations. Running a GeoSTARS simulation before initiating an approach, will provide the approach availability with a good precision.

![Fig. 5: Horizontal protection level (HPL) during 24 hours at the PInS for CMA-5024 (GPS/RAIM and GPS/EGNOS) and CMA-3024 (GPS/RAIM). A HPL value of 0.3 NM (i.e. 550m) is the upper limit for an approach availability.](image)

**Tab. 1: Approach availability of the investigated avionics GNSS receivers.**

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Technology</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMA-5024</td>
<td>GPS/RAIM</td>
<td>98.5%</td>
</tr>
<tr>
<td>CMA-5024</td>
<td>GPS/EGNOS</td>
<td>100%</td>
</tr>
<tr>
<td>CMA-3024</td>
<td>GPS/RAIM</td>
<td>56.5%</td>
</tr>
<tr>
<td>Chelton Beta-3</td>
<td>GPS/RAIM</td>
<td>98.7%</td>
</tr>
<tr>
<td>Chelton Beta-3</td>
<td>GPS/EGNOS</td>
<td>100%</td>
</tr>
<tr>
<td>LN 100 G SAASM</td>
<td>GPS/RAIM</td>
<td>99.1%</td>
</tr>
</tbody>
</table>

Assuming a conservative average availability of 98%, the probability that the approach cannot be completed leads to $2.0 \cdot 10^{-2}$.

**GNSS SIS CONTINUITY**

The loss of navigation capability during the approach due to the failure of a GPS satellite is also a critical topic. This scenario is called a continuity event as the continuity of the approach availability is not given anymore (ICAOA10, 2006).

The probability of a GPS satellite outage has been assessed by analyzing the outages of all satellites launched from 1989-2010. This includes all GPS block II generation satellites. Satellites of the GPS block I generation, launched before 1989, have already been decommissioned and are not considered in this study. The investigations distinguish between unpredicted outages and predicted outages, as announced by NANU's (Notice Advisory to Navstar Users). Fig. 6 shows the mean time...
between outages (MTBO) for all GPS space vehicles (SV).

Fig. 6: Mean time between outages (MTBO) for all GPS space vehicles. The average MTBO values adds to 780 days for all outages and 172 days for unpredicted outages only (marked with the dotted lines).

Given the time of an approach $t_{\text{approach}}$ and the MTBO of GPS satellite vehicles $MTBO_{\text{GPS}}$, the probability of a satellite outage during an approach $\omega_{\text{MTBO}}$ can be determined:

$$\omega_{\text{MTBO}} = \frac{t_{\text{approach}}}{MTBO_{\text{GPS}}} \quad (2)$$

A satellite outage may lead to an increased HPL. Considering again the 30 satellites constellation, and the possible failure of one satellite at a time, 30 different HPL time series result. The software package GeoSTARS has been used to determine the HDOP$_{n-1}$ values for each of the 30 constellations with the outage of one satellite. Thereof, the resulting HPL values has been calculated. Fig. 7 shows an overlay of all 30 calculated HPL series.

Fig. 7: Horizontal protection level (HPL) for all 30 constellations, each with one satellite failure (displayed with different colors). HPL 0.3 NM is the upper limit for an approach availability.

Based on these time series, the number of events with HPL exceeding 0.3 NM ($n_{\text{SAT}_{\text{HPLex}}}$) has been determined. The time resolution $\Delta t$ of one event has been set to 1 second. Hence, the probability of an unavailability of an approach $\omega_{\text{approach_u/a}}$ is equal to the number of events with HPL exceeding 0.3 NM during the investigated time period $T$ and for the number of satellite constellations $n_{\text{PRN}}$, multiplied with the probability of a satellite outage during an approach $\omega_{\text{MTBO}}$.

$$\omega_{\text{approach_u/a}} = \frac{\omega_{\text{MTBO}}}{T \cdot n_{\text{PRN}}} \sum_{i=1}^{T} n_{\text{SAT}_{\text{HPLex}}} \cdot \Delta t \quad (3)$$

Tab. 2 shows the probability of an unavailability of an approach. The difference between predicted and unpredicted outages and unpredicted outages only is not significant.

Tab. 2: Overview of the probability of a continuity outage.

<table>
<thead>
<tr>
<th></th>
<th>Predicted and unpredicted outages</th>
<th>Unpredicted outages only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$5.4 \cdot 10^{-7}$</td>
<td>$1.2 \cdot 10^{-7}$</td>
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**APPROACH FAILURE MODEL**

Considering the results of the four components navigation, engine, ceiling and visibility (see Fig. 2), a model is developed for each helicopter platform to determine the probability of the different conditions.

All individual parts of the navigation component have been processed in an own model. Considering predicted and unpredicted outages caused by a GPS satellite unavailability, the navigation risk leads to $2.1 \cdot 10^{-2}$ for one of the helicopter platforms. If the unavailability of the approach due to terrain masking is being checked in advance and consequently not anymore being part of the hazard analysis, the navigation risk is reduced to $1.9 \cdot 10^{-4}$.

The navigation results are now incorporated in the overall risk model for each helicopter platform. A hazardous situation occurs in case of navigation failure and engine failure including insufficient visibility and/or a low ceiling (Fig. 8). Depending on the helicopter platform, this probability leads to around $5.5 \cdot 10^{-5}$ if terrain masking is considered as hazardous situation or $2.0 \cdot 10^{-2}$ in case terrain masking is mitigated by a pre-approach check. As the target level of safety has been set to $10^{-4}$ per flight hour for rotorcraft operations, it is concluded that for both options and all helicopter platforms, the operation is acceptably safe.

**CONCLUSION**

To improve the accessibility of the Meiringen/Interlaken region, an approach procedure is being implemented.
Given the narrow valley surrounded by high mountains, a standard approach is not possible. As the only option, a cloud break GNSS procedure has been identified as feasible. Several deviations to ICAO standards have been taken into account. For this reason, the flight operational safety has to be assessed in detail. A potential major hazard is identified: The simultaneous failure of the navigation capability and one engine.

With the aid of a failure model, all probabilities have been considered to determine the probability of a hazardous event. Depending on the helicopter platform, a probability in the order of $10^{-4}$ per flight hour for rotorcraft operations. Consequently, the approach procedure is identified as an acceptably safe operation.

The study presents a practicable way to implement a GNSS approach procedure in mountainous areas, where the application of common aviation standards may not be feasible. Nevertheless, the implementation of such an unorthodox approach does considerably increase the safety of aviation in comparison with marginal or difficult VMC.

ACKNOWLEDGMENTS

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