Masterarbeit

Operational Concept Development and Evaluation of Pilots Acceptance of the GLASS SBAS to GLS Converter

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Statutory Declaration

I Johann Janes Biernatzki herewith declare that I have completed the present thesis "Operational Concept Development and Evaluation of Pilots Acceptance of the GLASS SBAS to GLS Converter" independently making use only of the specified literature and aids. Sentences or parts of sentences quoted literally are marked as quotations; identification of other references with regard to the statement and scope of the work is quoted. The thesis in this form or in any other form has not been submitted to an examination body and has not been published.

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Abstract

The wide availability of SBAS and the commonness of GLS equipment on commercial air transportation aircraft led to the development and flight testing of the SBAS to GLS converter by DLR. The aim of this thesis is to develop an operational concept, consisting of an approach chart with corresponding operations that can be applied to implement GLASS technology in commercial aviation. Different factors such as safety, pilot's satisfaction and clearness of the chart were used to analyze the quality of the chart and the operation.

Two different charts with the corresponding operations were developed. One is a modified RNP chart, to which the information required for GLASS is added. The other option is a separate GLS chart, with the remark, that is based on LPV. A crew task distribution model with the focus on Airbus A320 aircraft was developed for both variants.

Both charts and the corresponding crew task distribution models were tested with airline pilots in an A320 full flight training simulator. Every pilot flew both approach variants as pilot flying and pilot monitoring. The flight data was recorded for later use and the participants filled in two types of questionnaires.

The recorded data shows that both variants performed well, and the aircraft always remained within operational limits. Only few differences could be found. Most of those differences could not be correlated to the approach operation but to other reasons. Only the final intercept was performed slightly better during the RNP operation. The workload was measured during the simulator flights by using the well-known NASA-TLX. Results of these measurements are in favor of the GLS variant, as it results in lower workload for the flight crews.

Another questionnaire inquired about the pilots' preferences and additional feedback. The results also show an advantage of the GLS, as all pilots prefer this variant. These advantages may be a result of the manual tuning of the GLS channel in the RNP variant of the approach. Unlike other approaches on Airbus A320, the backup tuning must be used during the RNP variant. Overall, the GLS is the better variant for implementation with an A320 fleet.

Further studies should focus on other aircraft types to verify the results and eliminate the influence of backup tuning. A study with more pilots in a Boeing 737 simulator would complement this study well.

Zusammenfassung

Beim DLR wurde aufgrund der großen Abdeckung von SBAS und der weiten Verbreitung von Flugzeugen mit GLS Ausstattung der SBAS to GLS Converter entwickelt. Dieser wurde bereits im Flugversuch erprobt. In der vorliegenden Arbeit wird ein operationelles Konzept zur Nutzung dieser GLASS Technologie in der kommerziellen Luftfahrt entwickelt, welches aus einer Anflugkarte und dazugehörigen Aufgaben der Besatzung besteht. Zur Bewertung wurden verschiede Faktoren wie die Sicherheit, die Zufriedenheit der Piloten sowie die Verständlichkeit der Karte herangezogen.

Es wurden zwei Varianten entwickelt. Bei einer handelt es sich um eine RNP Anflugkarte, auf der die notwendigen Informationen für das GLASS System zusätzlich dargestellt sind. Die andere Variante ist eine separate GLS Anflugkarte, auf der vermerkt ist, dass der GLS durch SBAS zur Verfügung gestellt wird. Für beide Karten wurde ein Arbeitsablauf für die Besatzung am Beispiel einer A320 entwickelt.

Die Karten mit den dazugehörigen Prozeduren wurden von Linienpiloten auf einem A320 Full Flight Simulator erprobt. Dabei flog jeder Pilot beide Varianten als Pilot Flying und Pilot Monitoring. Für die spätere Analyse wurden die Flugdaten aufgezeichnet. Zusätzlich füllten die Teilnehmer zwei verschiedene Fragebögen aus.

Die Ergebnisse zeigen, dass das Flugzeug immer im zulässigen Bereich blieb. Die wenigen Unterschiede sind zudem meist anderen Ursachen zuzuschreiben als den unterschiedlichen Karten und Verfahren. Der Intercept auf das Final wurde während der RNP Variante etwas besser geflogen. Im Simulator wurde die Arbeitsbelastung mithilfe wiederholt ausgefüllten NASA-TLX Fragebögen dokumentiert. Die Ergebnisse sprechen für die GLS Variante, da dort eine geringere Belastung dokumentiert wurde.

Mit einem weiteren Fragebogen wurden die Präferenzen und weitere Rückmeldungen der Piloten eingeholt. Auch hierbei sind die Ergebnisse des GLS Verfahrens besser. Eine Erklärung dafür ist die Nutzung des Backup Systems zum Setzen der Kanalnummer während der RNP Variante. Bei der Implementierung von GLASS mit A320 Flugzeugen ist insgesamt die GLS Variante zu bevorzugen.

Um die Ergebnisse zu verifizieren und den Einfluss des ungewohnten Setzens der Kanalnummer auszuschließen, sollten sich zukünftige Arbeiten auf andere Flugzeugmuster fokussieren. Eine Studie mit einer höheren Anzahl an Piloten in einem Boeing 737 Simulator würde die vorliegende Studie gut ergänzen.

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1. Introduction

Nowadays most approaches in commercial aviation are flown as precision approaches, especially using the Instrument Landing System (ILS). During multiple years of flying in commercial aviation only few non precision approaches were flown or witnessed by the author. For a variety of reasons not every aerodrome can offer an ILS for every runway. At these aerodromes Global Navigation Satellite Systems (GNSSs), for example the Global Positioning System (GPS), can be used to fly approaches. To achieve a higher degree of accuracy, reliability and availability GNSSs can be augmented by either a Space Based Augmentation System (SBAS) or a Ground Based Augmentation System (GBAS) [1–3]. SBAS can be used on Required Navigation Performance (RNP) approaches. This usually allows a lower minimum, than flying these approaches without an augmentation system. The minimum, when using SBAS is called the Localizer Performance with Vertical Guidance (LPV) minimum. Unlike SBAS, GBAS offers a separate precision approach that does not differ much from an ILS approaches in its operation by the flight crew. Both approach types are explained in more detail in the following paragraphs.

While SBASs are available in a wide area, the number of commercial air transportation aircraft, that are equipped with a suitable receiver is relatively small [4]. Particularly airliners that are SBAS capable are rare. At the same time, a lot more aircraft of this category are equipped with GBAS Landing System (GLS) receivers. On the other hand, not many aerodromes have implemented the required ground stations and procedures to enable a GLS approach. The result of these facts is that neither the GLS nor the RNP with LPV minimum is flown often.

To avoid the limitations of both systems the German Aerospace Center (DLR) developed the GLS approach using SbaS (GLASS) technology. It combines the two approaches, making it easier for aerodromes to implement GLS approaches by using SBAS. Therefore all GLS equipped aircraft would be able to use the system [5].

While the technical feasibility has already been tested and verified, the presentation to the cockpit crews and the relating procedures have not yet been developed [6]. This thesis focusses on the operational concept for GLASS approaches and the acceptance of this new approach type by the pilots. For the operational concept, the chart used to present the approach to the flight crew is essential. Flight crew members have different tasks depending on the kind of approach they are flying. These tasks are analyzed and described for different variants of using GLASS in chapter 2.2.The GLASS approach has some particularities that must be considered when developing approach charts and flight deck procedures. This study deals with possible chart representations and ways of operation.

This first chapter introduces the characteristics of the three approach types using GBAS, SBAS and GLASS technology. Additionally, the current chart presentation to pilots and the specifics in operations for GLS and RNP approaches is laid out. After that, the aim of the study and this thesis is stated.

The way to achieve these goals is presented in chapter two. That chapter shows different approach operation variants to utilize the GLASS technology. Additionally, the study that was designed and performed in thesis including the used methods is explained there.

The results of the study, including evaluation of the track recordings and the answers to all questions in the questionnaires are laid out in chapter three. That chapter is followed by an interpretation and discussion of the mentioned results in chapter four. This last chapter also contains an outlook on future research and possible improvements of the study.

1.1. Characteristics and Chart Representation of Different GNSS-Approaches

The following paragraphs give an overview over three types of approaches based on GNSSs. GBAS- and SBAS approaches are operational today and can be flown by different airplanes at various aerodromes. GLASS is a newly developed technology combining elements of GBAS- and SBAS-approaches. The GLASS technology is not yet used in normal operation. It is explained in the paragraphs behind the other two approaches since it is based on those.

All approaches are published by the respective state in its Aeronautical Information Publication (AIP) [7]. To allow pilots the same way of presentation of approaches around the world, different companies use the approaches published in the AIPs and show them in their layout. Their design differs slightly but as the approach is the same, the charts contain mainly the same information. This thesis utilizes charts from the US company Jeppesen Sanderson and charts as they are published in the Austrian AIP by the air navigation service provider (ANSP) Austro Control GmbH.

The next paragraph deals with the GBAS landing system approach followed by paragraphs about the SBAS and GLASS approaches.

1.1.1. GBAS Landing System

The Ground-based Augmentation System (GBAS) Landing System (GLS) is a landing system, that consists of multiple Global Navigation Satellite System (GNSS) reference receivers, a ground facility and at least one Very High Frequency (VHF) data transmitter. All these items are located at an aerodrome with the GNSS receivers being spread out on the aerodrome [8, 9]. Figure 1 shows these elements in a schematic way, including the data streams. A GLS approach additionally requires a GNSS, for example GPS. The system receives the GNSS signal with the reference antennas and calculates correction values as well as integrity information in its control station. It supports approaches to different runways at the same airport by sending data via VHF Data Broadcast (VDB) to approaching aircraft. The provided data contains correction values relevant for this airport, as well as information about the final segment of the approach or multiple approaches [10]. The arriving aircraft still needs to receive the GNSS signal but can improve the accuracy and the integrity with the data received at the VHF-GLS receiver.

In addition to the correction data the GBAS ground station transmits path definitions for the approach paths to all runways with a GLS approach. This information is called the Final Approach Segment Data Blocks (FAS DB). The FAS data is different for every precision approach and contains a set of parameters that identifies the approach and defines the associated approach path as specified in Appendix B of ICAO Annex 10 Volume I [11]. Table 1 shows the different parameters of the FAS DB as specified in the ICAO Annex. Additionally, it shows the bits used, the range of values and the corresponding resolution. The aircraft identifies the FAS DB for the desired approach when the correct channel number is tuned and calculates the final approach path from the received parameters.

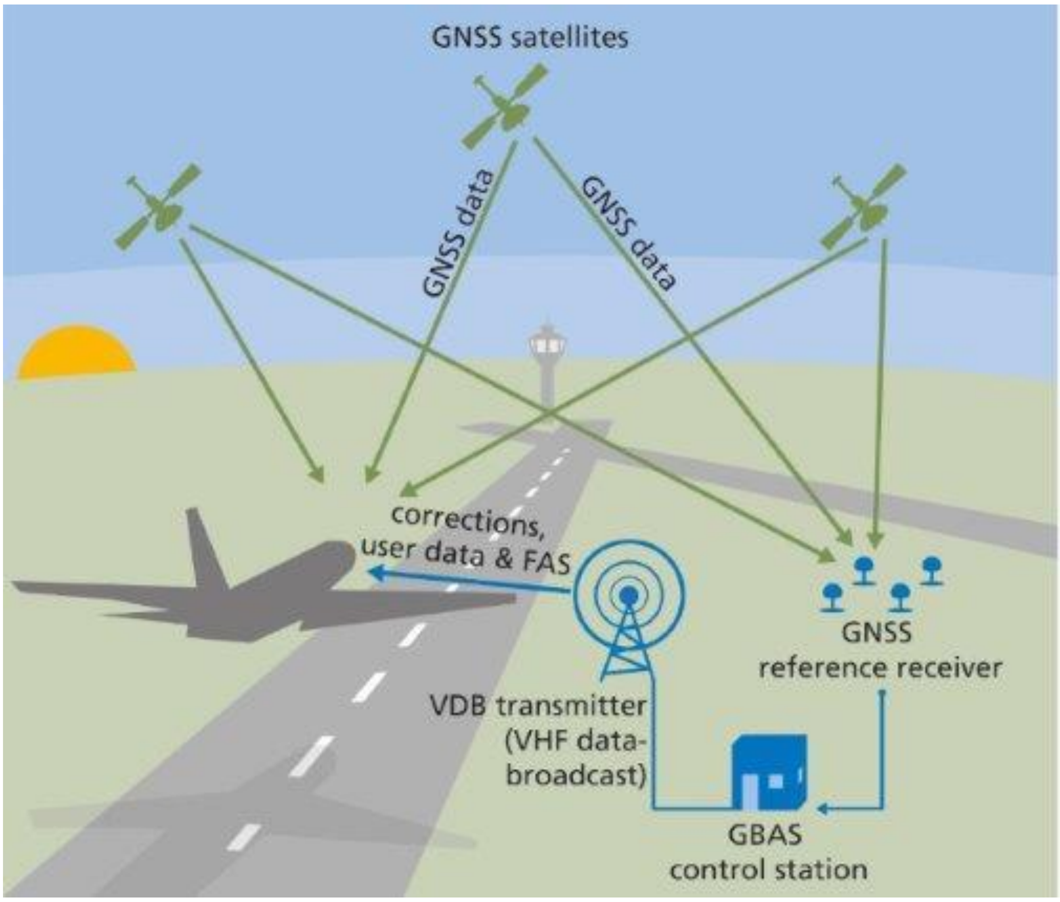
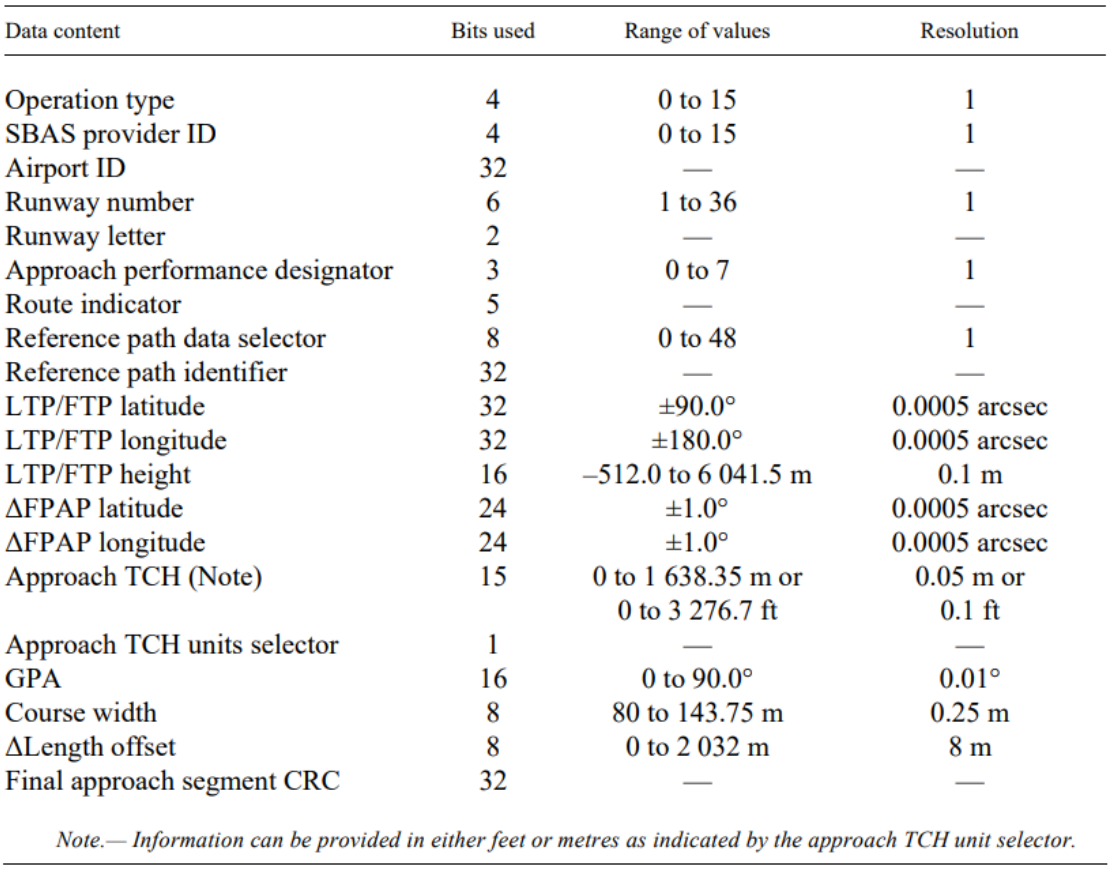


Figure 1 – Current GBAS architecture for GLS approaches. GNSS signals are received by local reference receivers and processed by a control station. The control station generates a signal containing GNSS corrections and information about the approach, that is transmitted via VHF data broadcast to approaching aircraft. (Source: DLR)

One of the parameters important for that calculation is the Landing Threshold Point (LTP). As shown in Table 1 it is transmitted in longitude latitude and height. Together with the Flight Path Alignment Point (FPAP) and the geometric center of the reference ellipsoid, it defines the vertical plane and therefore the course for the aircraft on the approach. The FPAP is given in delta longitude and delta latitude and the center of the ellipsoid is stored in the aircraft. The Glide Path Angle (GPA) defines the vertical part of the approach path and is given in degrees. The aircraft can calculate an exact approach path using these parameters, as vertical as well as horizontal definitions are available [12].

Table 1 - GBAS Final Approach Segment Data Block sent via GLS to Aircraft
(Source: ICAO Annex 10 [11])



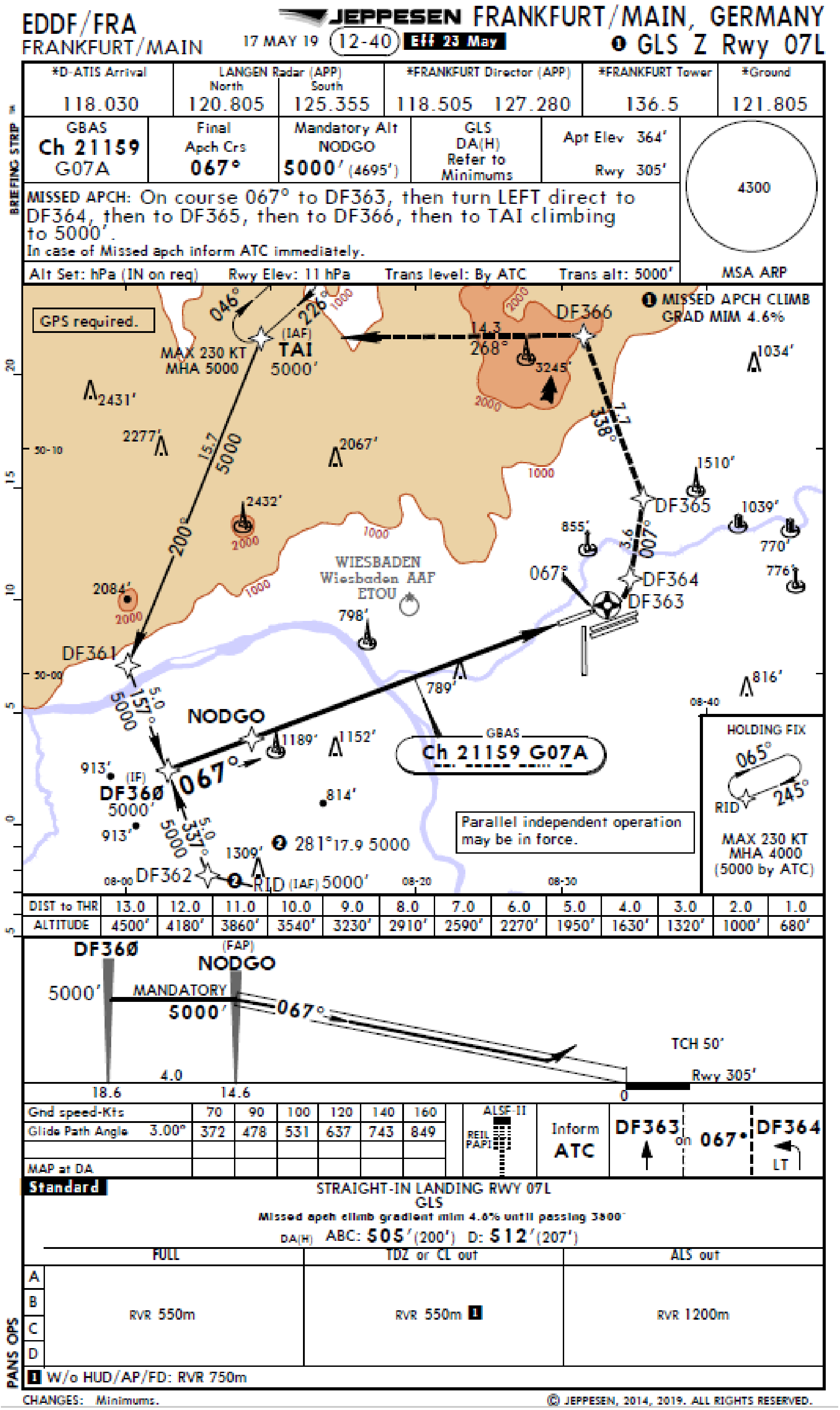
Data content	Bits used	Range of values	Resolution
Operation type	4	0 to 15	1
SBAS provider ID	4	0 to 15	1
Airport ID	32	—	—
Runway number	6	1 to 36	1
Runway letter	2	—	—
Approach performance designator	3	0 to 7	1
Route indicator	5	—	—
Reference path data selector	8	0 to 48	1
Reference path identifier	32	—	—
LTP/FTP latitude	32	±90.0°	0.0005 arcsec
LTP/FTP longitude	32	±180.0°	0.0005 arcsec
LTP/FTP height	16	–512.0 to 6 041.5 m	0.1 m
ΔFPAP latitude	24	±1.0°	0.0005 arcsec
ΔFPAP longitude	24	±1.0°	0.0005 arcsec
Approach TCH (Note)	15	0 to 1 638.35 m or 0 to 3 276.7 ft	0.05 m or 0.1 ft
Approach TCH units selector	1	—	—
GPA	16	0 to 90.0°	0.01°
Course width	8	80 to 143.75 m	0.25 m
ΔLength offset	8	0 to 2 032 m	8 m
Final approach segment CRC	32	—	—

Note.— Information can be provided in either feet or metres as indicated by the approach TCH unit selector.

The 5-digit channel number must be dialed in the receiver on the flight deck, to allow it to receive the GBAS signal and use the appropriate FAS DB. The correct number for the specific approach is shown on the respective approach chart. The aircraft receiving the path definition and the GPS corrections calculates its own position relative to the path and displays the deviation to the flight crew. The auto flight system then receives the information on deviations, which allows it to intercept and follow the correct path. GLS approaches are precision approaches comparable to the Instrument Landing System (ILS) CAT1 approach. The guidance provided by the GLS is also angular, like the guidance of an ILS. That results in higher precision close to the runway and less precision further away. Nowadays GLS approaches only support CAT 1 approaches, but the system is designed to allow approaches with lower minima in the future [9, 13]. The presentation to the flight crew is shown and explained in the following paragraph.

1.1.1.1. GBAS Chart Representation

Approaches utilizing GBAS are presented on a GLS approach chart. It shows the lateral and vertical approach procedure for example as shown in Figure 2. The approach is based on waypoints that are programmed into the aircrafts Flight Management System (FMS). Until the final segment the aircraft navigates to these using GNSS and other area navigation sources. For the final approach segment of an GLS approach the aircraft must receive the GBAS data from the ground as explained in the previous subchapter. To enable the reception of this data, the correct channel number must be set on the GLS receiver. This channel number can be found in the upper left-hand corner and on the final approach segment drawing in the middle of the Jeppesen GLS approach chart. At the same places, the identifier is shown. In Figure 2 the identifier is "G07A". The identifier is used by the pilots to verify that the correct channel number is tuned. It is received by the receiver and displayed on the Primary Flight Display (PFD). The flight crew can than compare it to the identifier on the chart and verify the correct data is received. The other information presented on the chart is the same as for other approach types. Depending on the chart provider the location of channel number and identifier varies, but both must be displayed on the chart.



EDDF/FRA
FRANKFURT/MAIN

JEPPESEN 17 MAY 19 (12-40) Eff 23 May

FRANKFURT/MAIN, GERMANY
❶ GLS Z Rwy 07L

*D-ATIS Arrival	LANGEN Radar (APP) North	LANGEN Radar (APP) South	*FRANKFURT Director (APP)	*FRANKFURT Tower	*Ground
118.030	120.805	125.355	118.505 127.280	136.5	121.805

GBAS	Final Apch Crs	Mandatory Alt NODGO	GLS DA(H)	Apt Elev	Rwy
Ch 21159 G07A	067°	5000' (4695')	Refer to Minimums	364'	305'

MISSED APCH: On course 067° to DF363, then turn LEFT direct to DF364, then to DF365, then to DF366, then to TAI climbing to 5000'.
In case of Missed apch inform ATC immediately.

Alt Set: hPa (IN on req) Rwy Elev: 11 hPa Trans level: By ATC Trans alt: 5000'

MSA ARP 4300

❶ MISSED APCH CLIMB GRAD MIM 4.6%

GPS required.

HOLDING FIX
065°
245°
RID
MAX 230 KT
MHA 4000
(5000 by ATC)

Parallel independent operation may be in force.

DIST to THR	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0
ALTITUDE	4500'	4180'	3860'	3540'	3230'	2910'	2590'	2270'	1950'	1630'	1320'	1000'	680'

Gnd speed-Kts		70	90	100	120	140	160
Glide Path Angle	3.00°	372	478	531	637	743	849
MAP at DA							

ALSF-II
REIL
PAPI

Inform ATC | DF363 | on 067° | DF364 LT

Standard

STRAIGHT-IN LANDING RWY 07L
GLS
Missed apch climb gradient mim 4.6% until passing 3800'
DA(H) ABC: 505'(200') D: 512'(207')

	FULL	TDZ or CL out	ALS out
A B C D	RVR 550m	RVR 550m ❶	RVR 1200m

❶ W/o HUD/AP/FD: RVR 750m

CHANGES: Minimums.

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Figure 2 - Example of a Jeppesen GLS chart. The GLS channel number, together with identifier, is shown in the upper left-hand corner and on the drawing in the middle. Shown is the GLS Z 07L in Frankfurt (EDDF) (Source: Jeppesen)

1.1.2. SBAS Approaches

Satellite-based Augmentation System (SBAS) is a system to improve accuracy, reliability, and integrity of Global Navigation Satellite Systems (GNSSs). Different regions in the world are covered by their own SBAS.

The European Geostationary Navigation Overlay Service (EGNOS) consists of more than 40 ground stations and three satellites on geostationary orbits. The general architecture is shown in Figure 3. The ground stations of EGNOS are mainly Ranging Integrity Monitoring Stations (RIMS), that measure the incoming GNSS signals. There are 40 RIMS, and they are spread out over the covered region of EGNOS. The southernmost RIMS are in northern Africa and the northernmost RIMS is located at the Svalbard Airport. Every second the RIMS transmit the raw data to the Central Processing Facilities (CPF). The CPF are part of the two Mission Control Centres (MCC), called master control station in Figure 3. In the CPF different corrections are calculated and sent to the three EGNOS satellites. These satellites are positioned on different locations in geostationary orbits to cover mainly the European area. The signal containing the different correction data is forwarded via transponders on the satellites to the users. Aircraft with suitable receivers can use the signal to improve the accuracy and integrity of their GNSSS navigation [14, 15].

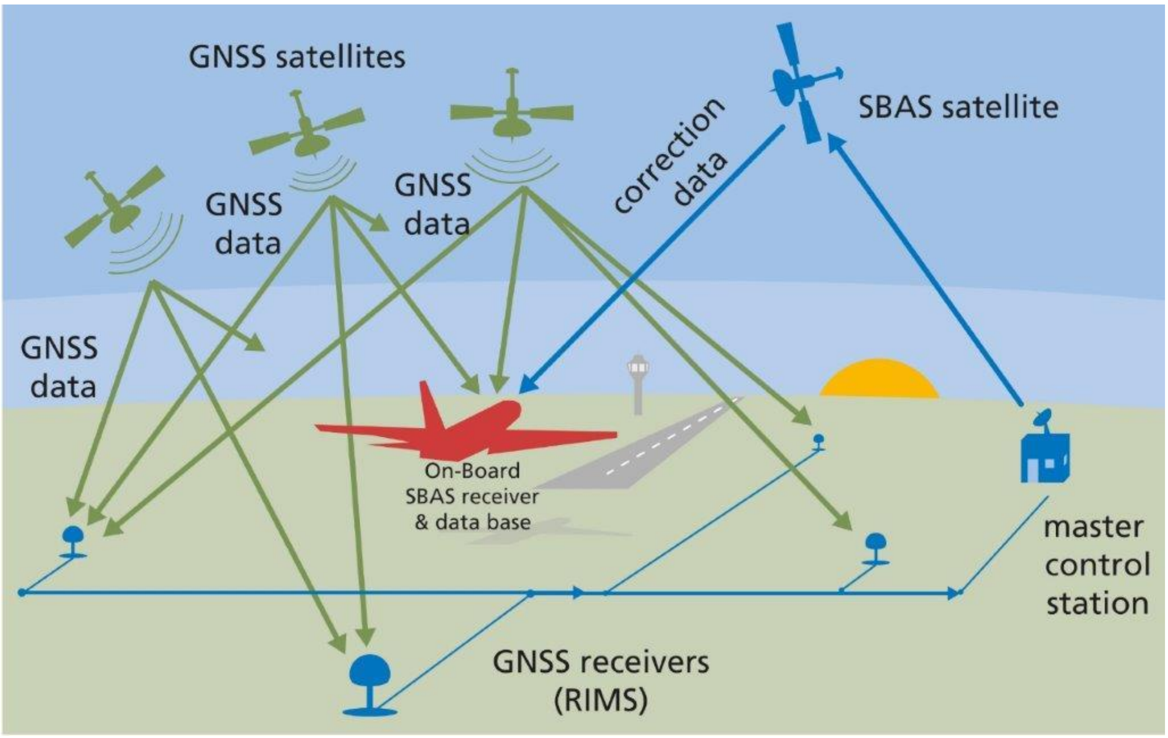


Figure 3 – Current SBAS architecture for RNP LPV approaches. GNSS signals are received by Ranging Integrity Monitoring Stations (RIMS) all over the European area and processed by control stations. The control station generates a signal containing GNSS corrections, that is transmitted to SBAS satellites and forwarded to approaching aircraft. The approach information is stored in an on-board data base. (Source: DLR)

An approach to the Localizer performance with Vertical Guidance (LPV) minimum is an Approach with Vertical guidance (APV) in which the lateral and vertical guidance is based in GNSS and augmented by SBAS. The guidance is angular, resulting in higher precision closer to the runway. The desired approach, and the corresponding Final Approach Segment Data Block (FAS DB) must be stored in the FMS [16, 17]. The reason for that is that unlike the GBAS signal, the SBAS signal does not contain the FAS DB. Therefore, only approaches that are stored in the database can be flown by the equipped aircraft. The FAS DB that is stored in the FMS is similar to the FAS DB of a GLS approach as described in chapter 1.1.1. In addition to the data in the GBAS FAS DB the SBAS FAS DB contains values for the Horizontal Alert Limit (HAL) and the Vertical Alert Limit (VAL). All data in the FAS data block can be seen in Table 8 in the appendix.

In the FAS DB, the last segment is defined for the aircraft. All waypoints prior to the interception of the final segment are flown out of the FMS database and only the final segment is flown calculated with the definitions out of the FAS DB. The standard LPV minimum used to be 250 ft Above Ground Level

(AGL). With LPV CAT 1 an LPV approach can qualify for a precision approach nowadays, with a minimum as low as 200 ft AGL. That is the same minimum as during a standard ILS CAT 1 [18–20]. No ground equipment is required at the aerodrome to enable the SBAS LPV approach.

The downside of this augmentation system is, that most aircraft used in commercial air transport are not equipped with a suitable receiver to fly SBAS approaches. The European manufacturer Airbus planned to start offering SBAS in their A320 and A330 in 2020 as an option. For Airbus aircraft only the A350 had SBAS capability options prior to that [21].

Like during an GLS approach the receiver must be fed with the correct channel number to enable the aircraft to receive the SBAS signal and follow the final calculated out of the FAS DB. Some aircraft can tune the channel number automatically when the approach is loaded from the FMS database. When the correct channel number is dialed in, the corresponding identifier should be displayed on the Primary Flight Display (PFD) or other devices depending on the equipment. This indicates that the aircraft gets improved navigation accuracy and has loaded the path definitions, allowing it to fly to the lower LPV minimum instead of using one of the other higher RNP minima that is usually displayed on the same chart. More information about the chart presentation is given in the following subchapter.

1.1.2.1. SBAS Chart Representation

The type of approach that can utilize SBAS is the RNP approach. There is no separate SBAS approach and therefore it is usually not shown on a separate chart. The LPV minima and other specialties of an approach using SBAS are displayed on the standard RNP chart. In some cases, an RNP approach is only authorized to be flown with SBAS. If that is the case it is shown as “LPV only” on the chart.

Required Navigation Performance (RNP) is a family of navigation specifications which allow aircraft to operate along a precise flight path. An RNP approach offers different minima. The Lateral Navigation (LNAV) and LNAV/Vertical Navigation (VNAV) minima can be flown with GNSS providing the lateral navigation and barometric altimeters providing the vertical navigation. SBAS can be used additionally to fly the LNAV/VNAV minimum as the SBAS increases precision. But an aircraft is only allowed to continue to a Localizer Performance with Vertical Guidance (LPV) minimum, if it receives the SBAS augmentation data required for the approach. The LPV minima are usually the lowest on an RNP chart [22–24]. Which minimum an arriving aircraft uses on the approach depends on its capability and the availability of the augmentation system.

Figure 4 shows a Jeppesen chart of an RNP approach in EDVE. The minima can be found in the lower third of the approach plate. To the very left of the different minima the LPV minimum is stated. During this approach it is 575 ft for a category C aircraft.

The channel number required for the reception of the correct signal and identification of the correct FAS DB for the chosen runway can be found in the upper left-hand corner of the approach plate. In the same field above the channel number, it states also the SBAS system used for the approach, as these vary in different parts of the planet. In this case it is EGNOS because the approach shown is in Brunswick, Germany. The identifier presented below the channel number is also shown to the flight crew on the PFD, when the setting is correct. It can also be displayed at another location on the flight deck, depending on the used equipment. It allows the flight crew to verify the correct setting of the approach and channel number. In this case the identification is "E26A" as shown in Figure 4. Additionally, the channel number, the inbound course, and the identifier are displayed next to the drawing of the final approach in the middle of the Jeppesen chart shown in the figure.

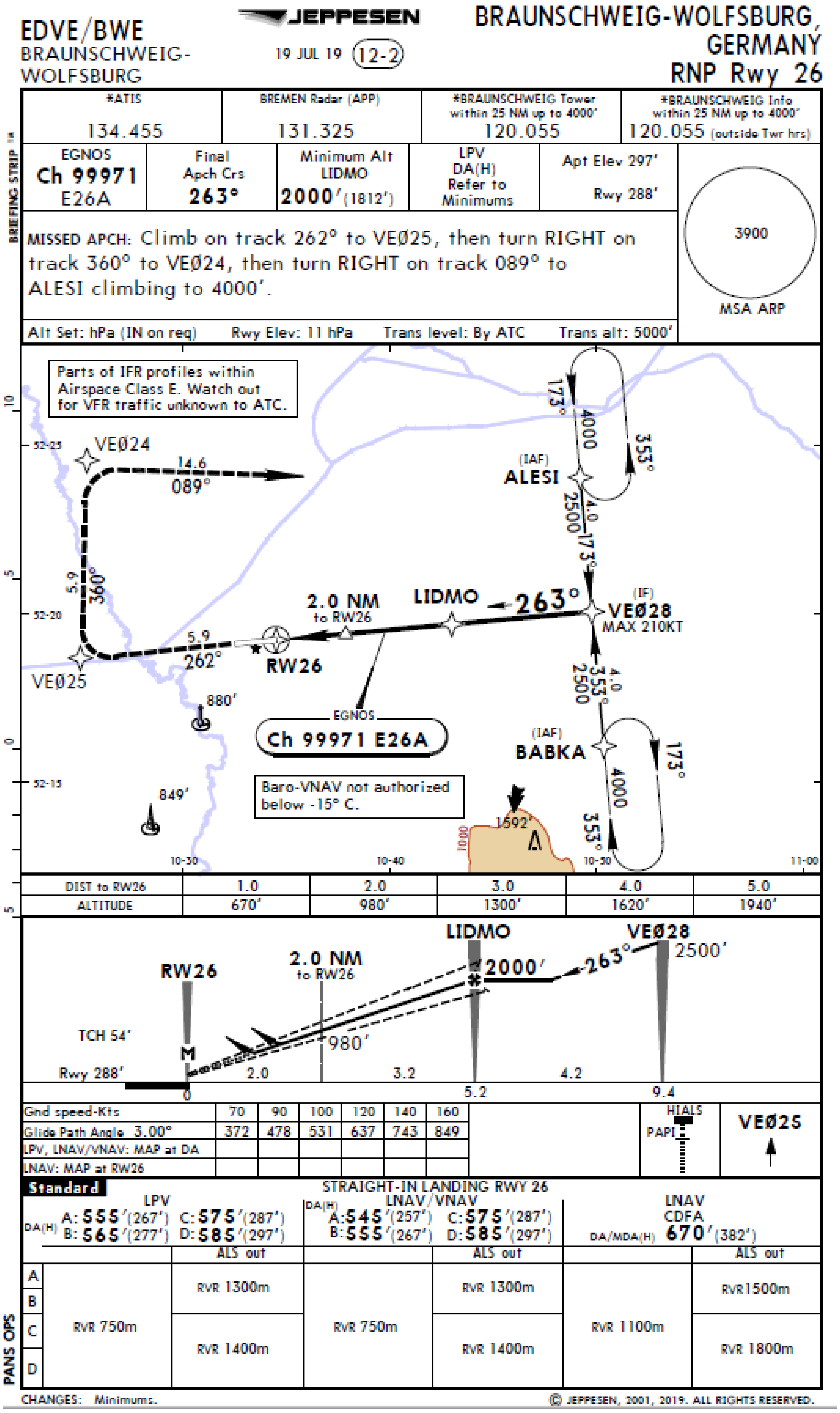


Figure 4 - Example of a Jeppesen RNP Chart including LPV minimum and EGNOS information. The channel number is shown in the upper left-hand corner and on the drawing in the middle together with the identifier. The LPV minimum is displayed in the lower third on the left side. This chart is the RNP 26 in Brunswick (EDVE) (Source: Jeppesen)

1.1.3. GLASS Approaches

The newly developed GLS approach using SbaS (GLASS) technology enables GLS like approaches by using a ground station that converts SBAS data into GBAS data and transmits it to arriving aircraft. The ground segment of GLASS does not require multiple antenna locations since it does not need to calculate correction values of locally received GPS data. It receives the signal from the SBAS satellite, in this case EGNOS and calculates the correction values for the GLS signal. The FAS DB generated in the system together with the identifier for the approach. The data is combined and a GLS signal is generated and transmitted via VDB the same way as by a standard GLS [5, 6]. Figure 5 shows the described GLASS ground segment and the architecture required for approach.

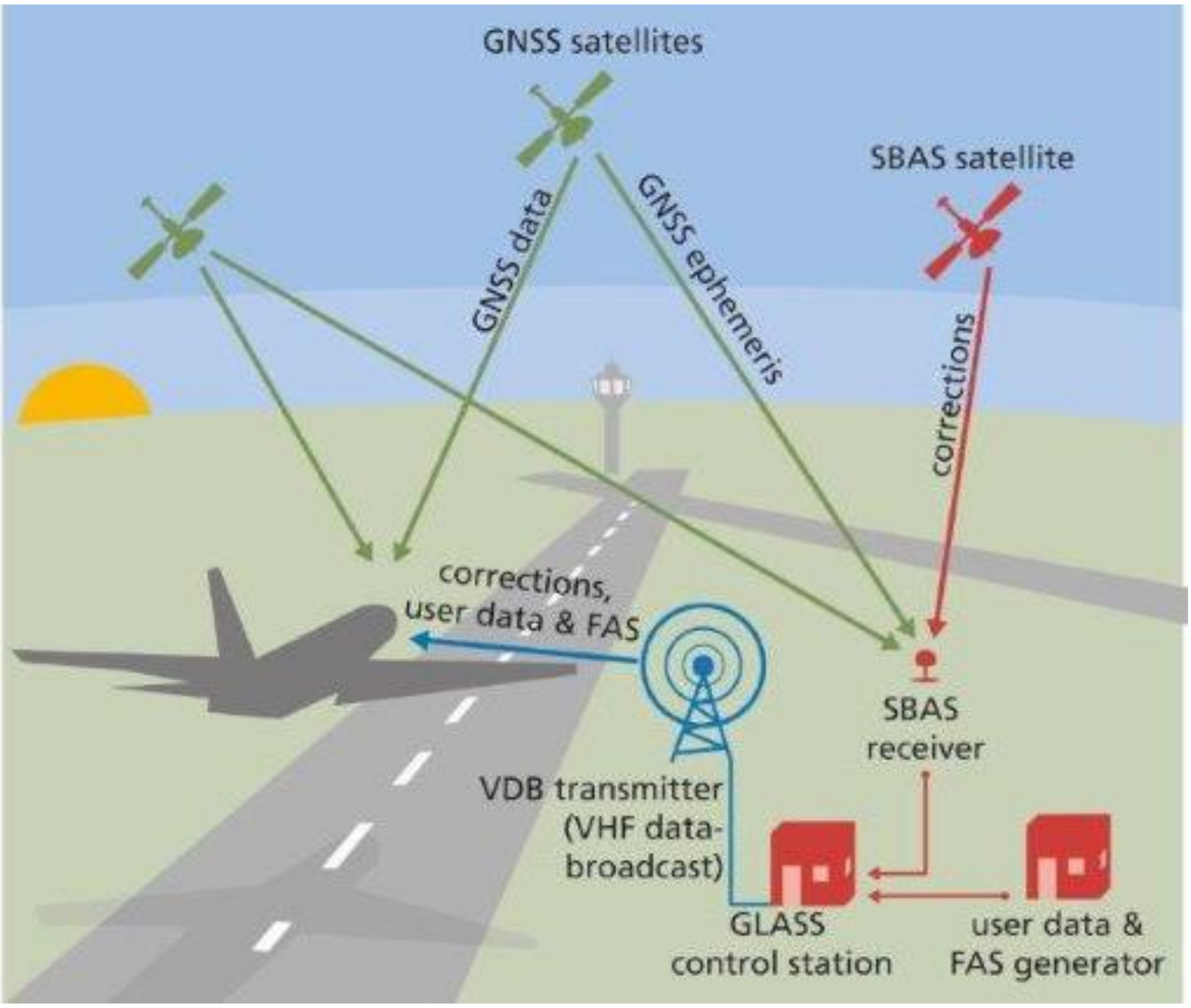


Figure 5 – DLR developed GLASS architecture enabling GLS equipped aircraft flights to LPV minimum. The SBAS receiver on ground receives the SBAS signal and GNSS ephemeris. With these and the Final Approach Data Block (FAS DB) the control station calculates a GLS signal that is transmitted via VHF data-broadcast to the approaching aircraft. (Source: DLR)

The advantage compared to a regular GLS is the much simpler ground infrastructure and no additional equipment beside an antenna and a computer. This system is planned to be set up on the ground allowing all approaching aircraft, that are GLS equipped to use it. This is the way it has been flight tested by DLR [25]. In theory the GLASS system could also be on the approaching airplane instead of the ground. The SBAS antenna and computer would be on board and transmit the information directly to the GLS receiver. An advantage of this setup would be the flexibility for the aircraft operator, as he would be independent of the airport operator and the ground infrastructure.

In the first case with the GLASS system being on the ground the approaching aircraft receives the GLASS signal just like it would receive a GLS signal. Any aircraft able to fly GLS approaches can fly this approach. The approach is still based on SBAS and therefore it is the RNP approach down to the LPV minimum, but the signal can be received with the GBAS receiver.

As the aircraft receives it as a GLS approach, the representation by the on bord equipment to the flight crew is the same as for the GLS approach, unless some modifications are made. If the build in equipment remains unchanged all differences between the GLS approach and the RNP approach must consequently be shown on the approach chart. Additionally, the specialties of the GLASS approach must be communicated to the flight crew using the approach chart. Procedural characteristics of a GLASS approach and differences to a normal GLS approach must be known by the flight crew. On a possible approach chart all required information for the approach must be presented, peculiarities for this approach type should be highlighted, and the adequate procedures should be triggered by the chart.

1.2. Aim of Thesis

The development of an operational concept including the corresponding chart representation of the GLASS approach is the focus of this thesis. Different variants of representation including the required crew tasks are shown in Chapter 2 and discussed in the remainder of the thesis.

The aim of this study is especially to find the best way to fly an SBAS LPV approach using the newly developed GLASS system. To achieve that, a good way to present the required information to the flight crew must be found. At the same time, the required amount of crew training for the new approach shall be kept as low as practicable. A possible new or adapted chart should trigger all the necessary procedures for this kind of approach and aid the crew to maintain a good situational awareness.

Additionally, pilot's acceptance of this new kind of approach shall be analyzed and the kind of operation and its associated chart, shall not hinder the acceptance.

It is important to show the differences to other approaches. Any differences that result in different actions or influence the approach in other ways, must be displayed or highlighted on the approach chart. It is important that the crew identifies it as a SBAS LPV approach received by GBAS. Additionally, the crew must get all the necessary information to safely carry out the approach.

To determine the best way of operation and chart-representation it must be defined how the quality of the operation and representation is measured. Different factors will be identified and are used for that purpose in this thesis. The goal is to find factors, that possibly show how the ways of representation differ and help to determine which way might be superior to the other. The following factors are described in this chapter and used for the identification of the better approach-chart representation.

- Safety
- Satisfaction of pilots with representation/pilot's acceptance of new approach type
- Difference to currently coded aircraft procedure
- Speed of implementation
- Indication of required equipment

1.2.1. Safety

Safety should always be the number one priority. That is especially true for aviation and has been enforced by the aviation authorities during the years. Consequently, safety should also be the number one factor in evaluation of this new kind of approach. This study deals with the chart representation, way of operation, and pilots' acceptance of the new approach. Therefore, the safety generated by the flight crew on the flight deck should be maximized. As safety cannot be easily measured, different other factors are analyzed to get an understanding of the safety. The focus lies only on factors that can be influenced from the flight deck.

Safety in the aviation does depend on human factors. Especially Crew Resource Management (CRM) plays an important role. CRM is the optimal use of all available resources for the achievement of safe and efficient flight operations by an air crew [26]. CRM has been studied and analyzed for multiple years and every aspect potentially influencing CRM shall be analyzed for threads [27]. As the workload correlates with the performance of the flight crew it has a potential impact on CRM and safety. An optimum workload doesn't overwhelm but also doesn't underchallenge the flight crew [28]. Since the workload during approach is enough to assure the crew is not underchallenged [29], the focus lies on not to overwhelm the crews.

The following factors are measured or discussed and are expected to have an impact on safety:

- Crew Workload
- Proneness to Error
- Ease of Understanding
- Track deviation

The following paragraphs contain a short description of each of the different factors.

1.2.1.1. Crew Workload

The workload of the crew during a flight and during the approach phase depends on multiple factors. External factors such as the terrain or weather cannot be influenced by the chart and the kind of operation. Nevertheless, the design of the approach chart and the operation should be in such a way that it facilitates a safe approach without additional workload for the crew. During the approach different tasks must be performed and these tasks compete with each other [30]. By utilizing a good task management, the crew can complete these tasks and ensure high safety. To guarantee save approach operation in the future, the crew workload shall be measured during the trial approaches. By comparing the workloads during different approach types, the safer variant in respect to crew workload can be identified.

1.2.1.2. Chance of Flight Crew Error

As with all approaches it might sometimes happen, that pilots make a mistake and misinterpret or misread data from the approach chart. Due to the additional information that needs to be on a chart of an SBAS LPV approach with the final segment received by GBAS, the likelihood of misinterpretation might be increased. To ensure safe operation it is important to keep the number of errors in reading data at an acceptable level. An approach chart should therefore be designed in such a way that misinterpretation is unlikely. For the GLASS approach some of the important information that is depicted on the chart and should especially not be misread are:

- the required equipment
- the equipment setting and the
- allowed minimum.

The required equipment for an approach using GLASS technology is the same as for a GLS approach. The aircraft must be able to receive the GBAS signal and interpret it. That allows it to calculate and follow the final approach track. This equipment must be set correct. That means the channel number and inbound course must be inserted, and therefore easy to access on the chart. The minimum as the third item listed, should also be clearly identified by the flight crew. Approach charts may have multiple minima depending on the aircraft category and equipment. It is important, that the flight crew can easily determine the appropriate one.

Additionally, all data that is required for the approaches needs to be shown on an approach chart. A lot of this information needs to be read for every approach everywhere. Since pilots are used to read this data from charts for every approach, the likelihood of misinterpretation of this data is already low and not affected by a new kind of approach operation.

The chance of flight crew error is closely related to misinterpretation of data, but in a multicrew cockpit usually the other flight crew member catches the error and advises the pilot misinterpreting the chart. Additionally, pilot error could occur due to other factors than misinterpretation of approach chart. Wrong knowledge of the relating procedures could lead to a mistake. For example, an RNP approach could accidentally be flown to the LPV minimum without receiving the required augmentation data. If the crew did not know that the GLS receiver needs to be utilized during an approach using the GLASS system to receive the correct signal such a mistake could happen.

The design of the approach chart should be in such a way, that it minimizes the chance of any error. Therefore, it might be required to show additional information on the chart. This information might not be essential for the execution of the approach, but it could help to prevent errors by reminding the pilots to set a certain instrument or follow a specific procedure. This additional information should be presented in such a way, that it aids in good Crew Resource Management (CRM). To improve CRM the chart should support the flight crew in conducting approach briefings by presentation of all required information. Preferably all required information should be visible on a single page. The risk of flight crew error might additionally be mitigated by establishing adequate checklists and procedures for this approach variant.

1.2.1.1. Ease of Understanding

The ease of understanding is important so a pilot that is flying the new approach for the first time in a real aircraft understands the chart, the approach, and the required equipment. All information should be available but also digestible during flight for a normal flight crew member. Some background information is always required to understand a new approach type, but it should not be necessary to spend hours in advance to be able to understand this new way of receiving the SBAS LPV approach data. The chart should not contain any contradictions. A pilot that received the required background information about the approach type and its operation should be able to grasp the approach without consultation of additional manuals.

1.2.1.2. Track Deviation

The deviation from the nominal track shall be kept as low as possible, even though a certain deviation is unavoidable and normal. The Total System Error (TSE) has three components. The Path definition error (PDE), the Navigation System Error (NSE) and the Flight Technical Error (FTE) [31]. The PDE is an error that occurs when the path defined in the system does not correspond to the desired path [32]. This error cannot be influenced by the flight crew as approaches are stored in the FMS. The flight crew could influence this only if they are manually edit the approach. To reduce the risk of PDE the flight crew can verify the waypoint location and path direction with the locations and directions on the approach chart. The error in flight is mainly composed of the NSE and the flight technical error FTE [33]. The NSE is the error resulting from inaccuracies in the navigation system [10]. And the FTE is the error resulting from the performance of auto flight system when flying with engaged autopilot or by the pilot's abilities when flying manually.

Since SBAS LPV approaches are validated and used nowadays and the GLASS system only converts SBAS in GBAS signal, the NSE will be neglected in this thesis. There is no significant increase in the NSE expected due to the new system and the system has been verified in flight trials [25].

The FTE on the other hand is influenced mainly by the pilots or auto flight control inputs and the current weather situation. When using the Automatic Flight Control System (AFCS) the turbulence has an influence on the FTE. Increased turbulence results in larger deviations from ideal track. [33]. Additional influence has the path steering capability of the aircraft and the aircraft energy state. An example for the influence of the energy state is that the turn radius is larger with higher speed.

During manual flight, the flight crew's skill to fly the airplane has a big influence on the FTE. An increased workload might lead to larger deviations. Unusual or unknown approaches may lead to increased workload and therefore increased FTE. Additionally, complicated approaches might lead to higher FTE than simple straight in approaches.

Even during approaches using the AFCS the workload can impact the FTE. When the crew is performing other tasks and does not pay attention to the current setting of the autopilot the FTE might increase, due to not optimal use of the autopilot. While the crew has high situational awareness and monitors the autopilot the track deviation is usually less.

1.2.2. Satisfaction of Pilots with Representation and Perceived Safety

Another factor to be analyzed in this thesis beside the safety is the acceptance by Pilots of the approach variant. The perceived safety plays an important role in the acceptance of a new approach variant. Pilots are selected to be very safety minded and therefore prefer a safe approach over an unsafe one. In the experience of the author the perceived safety of an approach plays an important role in pilots' acceptance of a new procedure or technique. Additionally, pilots are often part of the airline management and therefore also participate in selection of new approach types. Consequently, a high perceived safety by the pilots is important to implement this new approach variant around the world.

Usually, pilots have multiple years of experience flying different aircraft to many different countries and airports around the world. The knowledge and expertise these people have shall be used to determine the perceived safety during these approaches.

Additionally, pilots can offer valuable feedback for a new kind of approach and its chart representation. It is therefore important to give the flight crews the possibility to provide feedback. This possibility shall be structured in such a way that even topics that were not considered in beforehand can be addressed by the participating pilots. Pilots' acceptance is used as a factor to generate an overall grading for the new kind of approach and its approach plate. The flight crew can rate their satisfaction with the chart, its corresponding operation, and their happiness with the new approach type.

1.2.3. Additional Coding of Aircraft Procedures

When evaluating the best representation of the new approach type, the already coded aircraft procedures should be considered. In the case of the GLASS system the RNP approach to LPV minimum is already coded and would allow an implementation without additional coding of procedures. The approach procedures to the different runways on different airports are coded in the Flight Management System (FMS) of the aircraft. Pilots select the runway and approach type they intend to fly, and the respective waypoints are loaded from the database. The name of the approach on the approach chart and in the FMS are the same, so it is easy to make sure the correct approach is selected. All current approaches are already coded for the various FMS`s. The complexity of implementation is considered in the discussion of the thesis in the chapter 4 Interpretation, Discussion, and further Research.

1.2.4. Speed of implementation

The newly developed GLASS technology is planned to be implemented at different aerodromes where it can play its benefits over current approach types. To make sure a certain chart design does not delay the implementation due to different regularities, the speed of possible implementation should be considered when selecting a chart. Nevertheless, there should be no compromise on safety for the benefit of a faster implementation.

1.2.5. Clearness of Chart

As stated in the description of the approaches the airplane must be equipped with a suitable receiver to fly GLS approaches and therefore to be able to use the GLASS technology. It is necessary to state the required GLS onboard equipment on the approach chart to ensure pilots verify the correct equipment of the aircraft before planning the approach.

In addition to the waypoints marking the lateral profile and the depicted vertical profile, the required channel number and identifier must be shown on the chart. To allow the aircraft to receive and therefore track a GBAS signal, the correct 5-digit channel number must be set. The flight crew can than verify the reception of the correct signal with the shown identifier. It is therefore important to show the identifier and the channel number on the chart in a clear way.

Different types of representation offer different ways of showing the required equipment. It must be clear what the required equipment is and how to set it. The following chapter deals amongst other things with different options to present an approach using GLASS technology to the pilots and the corresponding operation.

2. Material and Methods

To evaluate the factors determined in Chapter 1.2 two different kinds of operation with the associated charts are developed. The evaluation is done in a simulator study with multiple pilots flying the GLS approach using SBAS (GLASS). The flight crew members rate the different chart designs and give feedback. The chosen chart designs are shown and explained in the following paragraphs followed by an explanation of the operation. At the end of the chapter a description of the simulator study design is given.

2.1. Approach Operation Variants

Two different ways to use the GLASS technology have been considered for this thesis. One is the GLS approach chart as a basis and the other is the RNP SBAS LPV approach chart. Both approach types, the associated charts, and the necessary changes as well as additions are described in this subchapter.

The task distribution between the flight crew members is shown in the subchapter after that.

2.1.1. GLS Chart for GLASS

One option for the representation of the GLASS approach is a modified GLS chart. For the flight crew, it would be a standard GLS approach. The only difference on the chart would be a remark stating that the GLS is based on SBAS. The operation of such a GLS approach does not differ from other GLS approaches and does not differ much from a standard ILS approach. A more detailed description of the crew tasks is given in Chapter 2.2. It must be verified that the correct channel number is tuned by the aircraft and the correct identifier is received. Apart from that the operation is very similar to a normal ILS. In case of missed approach during a GLS approach the aircraft has the correct missed approach procedure coded and can fly it using its Flight Management System and internal navigation systems.

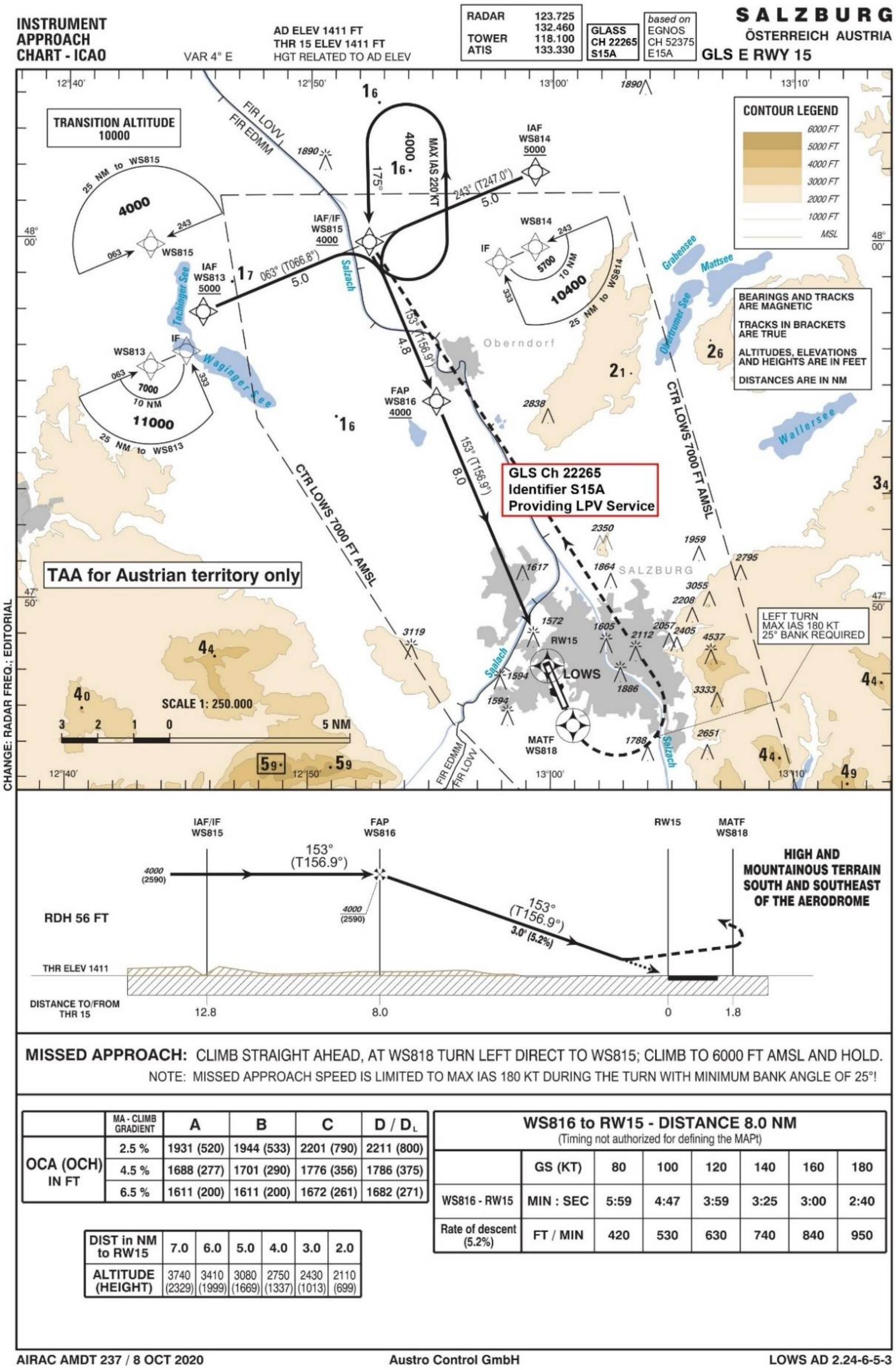
Figure 6 shows a possible GLASS supported GLS approach chart for Salzburg. This approach chart is based on the RNP E approach for runway 15 in LOWS. The RNP E approach is a LPV only approach and can therefore not be flown without SBAS equipment. It is based on the chart published in the AIP by Austro Control GmbH. The GLASS technology enables GLS equipped commercial transportation category aircraft to fly this approach.

In a red square box in the drawing in the middle of Figure 6 it shows the remark:" GLS Ch 22265 Identifier S15A Providing LPV Service". Therefore, the flight crew flying the approach knows, that the

GLS is unlike a standard GLS. It provides LPV service, that is usually provided by SBAS. Additionally, the information about the channel number and identifier are shown at the top of the chart next to the information that the GLS is based on the SBAS LPV approach. The flight crew knows out of this information that the limitations of an RNP to LPV minimum exist. For example, automatic landings are certified for GLS but not allowed during RNP approaches. Additionally, an offset of the final approach track to the runway orientation is limited to 5° during GLS approaches. As RNP approaches are usually non-precision approaches the final approach track alignment is not limited, but only the Obstacle Clearance Altitude (OCA) is increased, if the track is not aligned with the runway [34].An RNP approach which is offset does not offer a low minimum since the pilots must perform the maneuver to align the aircraft visually. Therefore, the advantage of an SBAS augmentation would not be large, for offset approaches. It is consequently unlikely that the GLASS technology will be used for approaches whose final is not aligned with the runway.

A separate chart such as the displayed GLS chart has the advantage, that only the information required for this approach are shown.

If this variant is used for an implementation of the GLASS system, every approach that shall be enabled to be flown using GLASS technology must receive a new GLS chart depicting it. The approach chart would be based on the already published RNP approach chart but be converted to a GLS chart. The FAS DB and the correction data are sent from the GLASS ground equipment and received by the aircraft using the onboard GBAS receiver. A disadvantage is, that a separate chart must be produced, and an additional approach must be coded and uploaded to the FMS of all aircraft that are supposed to fly this approach.



MISSED APPROACH: CLIMB STRAIGHT AHEAD, AT WS818 TURN LEFT DIRECT TO WS815; CLIMB TO 6000 FT AMSL AND HOLD.

NOTE: MISSED APPROACH SPEED IS LIMITED TO MAX IAS 180 KT DURING THE TURN WITH MINIMUM BANK ANGLE OF 25°!

	MA - CLIMB GRADIENT	A	B	C	D / D$_L$
OCA (OCH) IN FT	2.5 %	1931 (520)	1944 (533)	2201 (790)	2211 (800)
	4.5 %	1688 (277)	1701 (290)	1776 (356)	1786 (375)
	6.5 %	1611 (200)	1611 (200)	1672 (261)	1682 (271)

DIST in NM to RW15	7.0	6.0	5.0	4.0	3.0	2.0
ALTITUDE (HEIGHT)	3740 (2329)	3410 (1999)	3080 (1669)	2750 (1337)	2430 (1013)	2110 (699)

WS816 to RW15 - DISTANCE 8.0 NM
(Timing not authorized for defining the MAPt)

	GS (KT)	80	100	120	140	160	180
WS816 - RW15	MIN : SEC	5:59	4:47	3:59	3:25	3:00	2:40
Rate of descent (5.2%)	FT / MIN	420	530	630	740	840	950

AIRAC AMDT 237 / 8 OCT 2020 Austro Control GmbH LOWS AD 2.24-6-5-3

Figure 6 – New GLS chart for GLASS operation to LOWS. This chart triggers GLS procedures. It is adapted from AIP LOWS RNP E 15 chart by Austro Control. The GLS channel number and the identifier are shown in the top row and in the drawing in the center of the chart. Additionally, a note informing about the service being LPV is shown. (Adapted from Austrian AIP chart [35])

2.1.2. RNP SBAS LPV Chart for GLASS

Another possibility for a chart presentation of the GLASS system is using an adapted RNP chart. Since the GLASS system requires a different operation in the flight deck than other RNP approaches these must be adapted. The biggest difference is that the correct GLS receiver setting must be checked to ensure the reception of the FAS DB and correction data. Using the RNP approach chart there will be no new chart, but the existing chart will be updated, for approaches that shall use GLASS technology. All required information for the LPV minimum to be flown using GLS is added to the chart.

There is a risk of pilots flying the RNP approach to the LPV minimum without tuning the GLS to the correct channel number and receiving the required information. It is therefore important to clearly mark the GLASS specialties. In particular that means the GLS receiver and its setting.

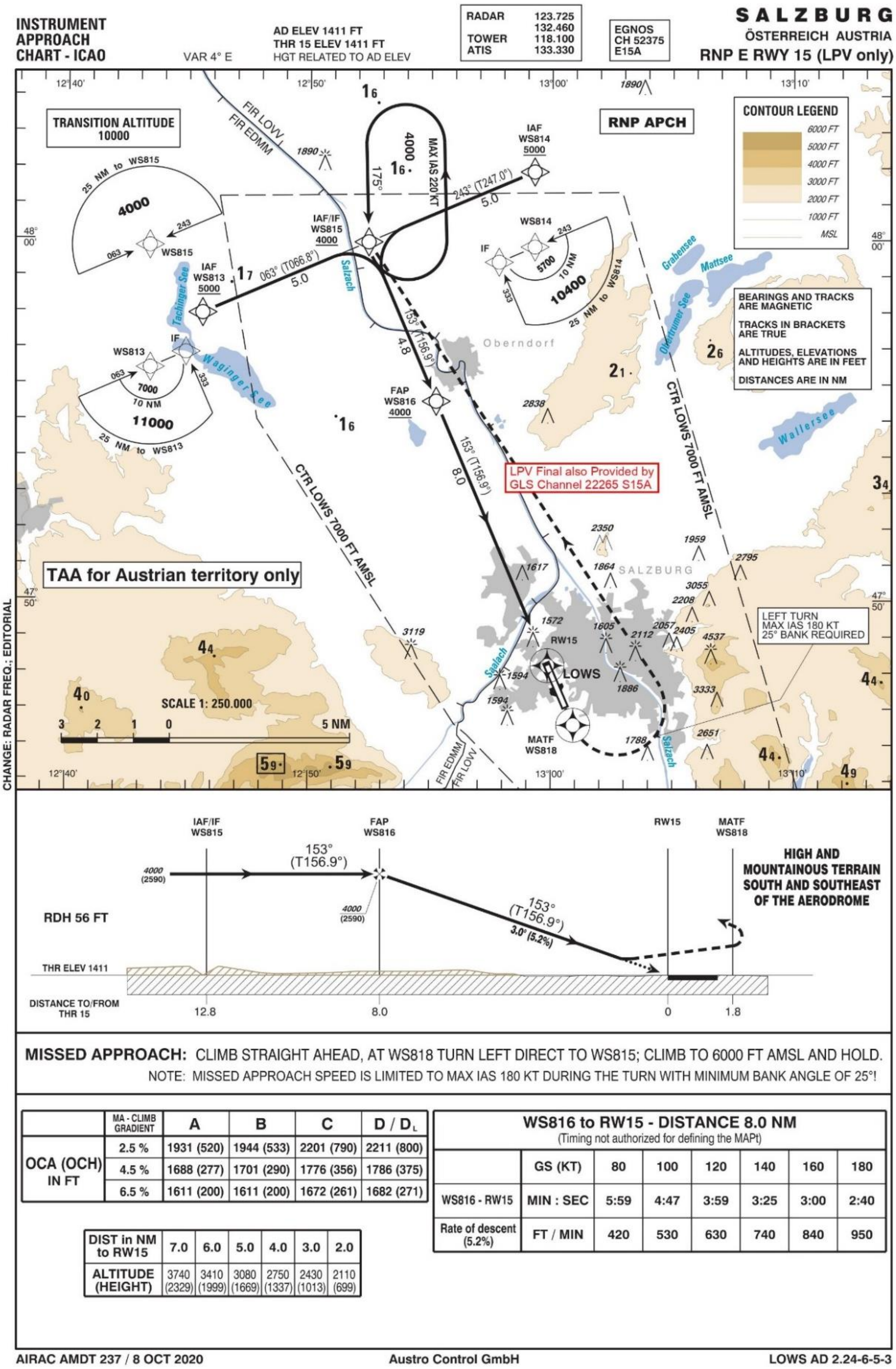
The GLS receiver must be part of the aircraft equipment. Since many airlines operate different versions of an aircraft family, it is possible that within the fleet of an operator there are aircraft that are equipped for GLS and others that are not. It is therefore important for the flight crew to verify that the aircraft used for that approach is equipped with a serviceable GLS receiver, to fly an RNP LPV with GLASS technology.

In terms of setting of the receiver, it is necessary that the channel number is dialed in correctly. Additionally, the final course must be set on some systems and the identifier must be received and verified to be correct Consequently the channel number, the final course and the identifier must be shown prominently on the chart. The reason to highlight this is, that normally RNP approaches are flown with FMS guidance only. The FMS calculates the current position with the help of GNSS-receivers and build in inertial reference units (IRUs). With the help of the current position, it follows the precalculated approach.

Using the GLASS technology on the other hand the correct GLS channel must be set. This allows the aircraft to receive the final approach information from the ground station. The FMS still calculates the current position and compares it with the received flight path. When receiving GBAS signal and being on the approach it can use the correction data it receives to improve the accuracy of the calculated position. The usage of the data depends on the system architecture of the used aircraft and its setting. The A320 does only use the signal if a GLS approach is loaded in the system or the backup tuning is used to override the system.

Figure 7 shows an example of an RNP chart for using GLASS technology. Presented is the RNP E approach for runway 15 in Salzburg. It is a modified chart based on the one published in the AIP of Austria by the Austro Control GmbH. This approach is LPV only, therefore it can usually only be used by aircraft equipped with an SBAS receiver. To enable the operation using GLASS technology the chart additionally presents the following remark in the middle of the drawing in Figure 7: "LPV Final also Provided by GLS Channel 22265 S15A".

Apart from that this chart does not differ from the standard RNP (LPV only) approach plate. This box provides the flight crew with the necessary information to tune the GLS receiver and verify the correct tuning with the identifier. To highlight the remark, it is shown in red with a red square box around it.



INSTRUMENT APPROACH CHART - ICAO

AD ELEV 1411 FT
THR 15 ELEV 1411 FT
HGT RELATED TO AD ELEV

RADAR	123.725 132.460
TOWER	118.100
ATIS	133.330

EGNOS
CH 52375
E15A

SALZBURG
ÖSTERREICH AUSTRIA
RNP E RWY 15 (LPV only)

LPV Final also Provided by GLS Channel 22265 S15A

MISSED APPROACH: CLIMB STRAIGHT AHEAD, AT WS818 TURN LEFT DIRECT TO WS815; CLIMB TO 6000 FT AMSL AND HOLD.

NOTE: MISSED APPROACH SPEED IS LIMITED TO MAX IAS 180 KT DURING THE TURN WITH MINIMUM BANK ANGLE OF 25°!

	MA - CLIMB GRADIENT	A	B	C	D / D_L
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Rate of descent (5.2%)	FT / MIN	420	530	630	740	840	950

DIST in NM to RW15	7.0	6.0	5.0	4.0	3.0	2.0
ALTITUDE (HEIGHT)	3740 (2329)	3410 (1999)	3080 (1669)	2750 (1337)	2430 (1013)	2110 (699)

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LOWS AD 2.24-6-5-3

Figure 7 – Adapted RNP-Chart for LOWS RNP E 15 including GLASS technology information. The chart is still an RNP chart but has the information that the LPV final is also provided by GLS added. The GLS channel number and the identifier are shown in the middle of the chart. (Adapted from Austrian AIP chart [35])

2.2.Crew Task Distribution Model

This chapter deals with the tasks of Pilot Flying (PF) and Pilot Monitoring (PM) during the different approach variants and the distribution of these tasks. The study explained in the following subchapter takes place in a A320 Simulator. Therefore, the task distribution in this chapter is based on the required tasks in an A320 aircraft.

The task distribution is given for two variants using the GLASS technology. First the tasks required when flying an approach using a GLS chart and its FMS coding is shown. Second the crew tasks for the same approach using an RNP chart and its FMS coding is given. Both variants are possible ways to utilize the GLASS technology. The crew task distribution shown in the following paragraphs starts with the descent preparation phase of the flight and continues until the minimum altitude. The reason these boundaries have been chosen is that it is assumed all tasks prior and after that interval are the same for both variants. The task distribution models presented in this chapter are based on approaches in managed speed mode. During the managed speed mode, the correct speeds are displayed and flown based on internal calculations by the FMS. The approaches could also be flown in manual speed mode where the pilots chose their preferred speed during the different phases of approach. The chosen speed would be selected by either the PF or the PM. With Autopilot (AP) engaged the PF selects the speeds in the Flight Control Unit (FCU). During manual flight the PM sets the speeds. For the sake of clarity only the managed version is shown below.

The tasks that are specific for this kind of approach and operation are shown in bold and italics. The task distribution is based on the industry standard for the operation of Airbus A320 family aircraft and derived partially from the Quick Reference Handbook for A320 operation [36].

2.2.1. GLS Approach Using GLASS

Prior to initiating descent, the flight crew starts with the approach preparation. The first part of that is the descent preparation. The flight management system (FMS) is prepared for the expected approach, the landing performance is calculated or confirmed, and the appropriate display settings are selected. When the aircraft is prepared for the approach and before initiation of the descent the pilot flying shall perform the approach briefing.

On the following pages, for every part of the approach, a list of tasks is given, followed by an explanation of the different steps.

Table 2 – Proposed Descent Preparation Task List using GLASS technology and GLS operation. The list includes most items to be performed by the flight crew in preparation of the descent. Items that are specific for an approach using GLASS technology and GLS operation are shown in bolt and italic.
(Derived from A320 QRH [36])

DESCENT PREPERATION	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
	Obtain Weather and Landing Information
Prepare Nav Charts.	Prepare Nav Charts
Confirm Landing Performance	Check Landing Performance
Insert GLS approach in FMS	***Verify Correct Approach Set***
Set GLS Minimum	***Set GLS Minimum***
Check Landing Elevation	
Set Autobrake as Required	
Perform Approach Briefing	
Set Terrain on Navigation Display as Required	Set Terrain on Navigation Display as Required
Adjust Weather Radar as Required	
	Set Anti Ice System as Required
	Obtain Descent Clearance
Set Cleared Altitude in Flight Control Unit	

During the descent preparation the flight crew prepares for the approach. In a first step the Pilot Monitoring (PM) obtains the current weather and landing information of the arrival airport. The flight crew knows of the current runway in use from the landing information. With this information both pilots prepare the required navigation charts. In case of an intended use of the GLASS technology, the crew prepares the expected arrival route chart and the GLS chart especially published for the approach using GLASS technology. In the next step the landing performance data, that is calculated by the FMS, is checked, and confirmed by the pilots. This data is composed of different elements. For example, the required landing distance and speeds are calculated by the system.

After that, the Pilot Flying (PF) selects the GLS approach in the FMS and inserts it in the route. The PM verifies the correct selection and compares the name and order of the inserted waypoints with the chart. When the FMS is programmed correctly both pilots set the applicable GLS minimum.

Upon completion of that the PF checks the landing elevation, sets the autobrake as required and performs the approach briefing. Depending on the weather, either both pilots set their navigation display to show the surrounding terrain, or the pilot flying choses the weather radar and the PM the terrain option for his navigation display.

In preparation for the descent and depending on the weather, the PM switches the engine anti ice system and the wing anti ice system on. The PM also requests the descent clearance on time and confirms it to the ATCO.

Once the descent clearance is obtained the PF sets the cleared altitude in the Flight Control Unit (FCU) and initiates the descent.

Table 3 – Proposed descent task list using GLASS technology and GLS operation. The list includes the items to be performed by the flight crew during the descent until the initial approach. Items that are specific for an approach using GLASS technology and GLS operation are shown in bolt and italic.
(derived from A320 QRH [36])

DESCENT	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
Monitor Descent	
Set and Crosscheck Barometric Reference when Cleared for an Altitude	Set and Crosscheck Barometric Reference when Cleared for an Altitude
	Check ECAM Status
	Switch on Landing Lights and Seat Belt Signs when Passing 10.000 ft
Press Landing System Button on EFIS Control Panel	Press Landing System Button on EFIS Control Panel
	Verify Correct Channel Number and Identifier
Complete Approach Checklist	Complete Approach Checklist

During the descent, the PF monitors and adjusts the descent, as necessary. Once the clearance to an altitude instead of a flight level is received, both pilots set their altimeters to the setting received from the ATCO. The PM checks the Electronic Centralized Aircraft Monitoring (ECAM) status on the ECAM display. The PM also switches the landing lights on once the aircraft passes 10.000 ft altitude. Latest at this moment the PM switches on the fasten seatbelt signs.

Prior to the beginning of the approach both pilots press the Landing System (LS) button on their Electronic Flight Instrument System (EFIS) control panel to show the deviations of the landing system on their Primary Flight Displays (PFD). Because the approach is stored as an GLS approach and selected in the FMS, the aircraft automatically sets the channel number loaded from the database. The aircraft therefore receives the GBAS-Signal from the GLASS transmitter and calculates the deviations. These deviations are displayed on the PFDs once the LS button is pressed. The channel number and identifier are also displayed on the PFD and are compared to the channel number and identifier on the approach chart by the PM. After that, the flight crew completes the approach checklist.

Table 4 – Proposed aircraft configuration for approach task list using GLASS technology and GLS operation. The list includes the items to be performed by the flight crew in between the initial approach and the minimum altitude. Items that are specific for an approach using GLASS technology and GLS operation are shown in bolt and italic. (Derived from A320 QRH [36])

AIRCRAFT CONFIGURATION FOR APPROACH	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
On Initial Approach Adjust Flight Plan Sequencing	
Approximately 15 NM before Touchdown Activate Approach Phase	
Check Managed Speed	
Monitor and Adjust Flight Path as Required	Monitor Navigation Accuracy
Adjust Weather Radar as Required	
	Readback Approach Clearance when Received
Press Approach Button on FCU	
Check LOC and GS Armed	
Call out LOC* when Intercepting GLS LOC	
Check Correct Lateral Intercept of Approach	***Check Correct Lateral Intercept of Approach***
Callout GS* when Intercepting GLS GS	
Check Correct Vertical Intercept of Approach	***Check Correct Vertical Intercept of Approach***

AIRCRAFT CONFIGURATION FOR APPROACH	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
Set Go Around Altitude	
At Green Dot Speed Order Flaps 1	Select Flaps 1 when Ordered
Check S Speed	
Order Flaps 2 Minimum 2000ft AGL	Select Flaps 2 when Ordered
Check F Speed	
Order Landing Gear down when Flaps are 2	Select Landing Gear Lever Down when ordered
	Confirm Auto Brake
	Arm Ground Spoilers
	Set Exterior Lights
Order Flaps 3 when Landing Gear is deployed	Select Flaps 3 when ordered
	Check ECAM Wheel Page
Order Flaps FULL when Flaps are 3	Select Flaps FULL when ordered
Check Speed Target	Check Auto Thrust on Speed Mode or Off
	Turn Wing Anti Ice System off if not Required
Stow Sliding Table	Stow Sliding Table
	Check Landing Memo no Blue on ECAM Display
Receive Cabin Report	Receive Cabin Report
	Advise Cabin Crew

AIRCRAFT CONFIGURATION FOR APPROACH	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
Complete Landing Checklist	Complete Landing Checklist
Call Out any Flight Mode Annunciator Change	Monitor Flight Parameters
Continue or Go Around at GLS Minimum	Monitor One Hundred Above and Minimum call

The aircraft configuration for approach includes all steps starting on the initial approach until reaching the minimum. On the initial approach the PF checks the Flight Plan page in the FMS and adjusts it according to the expected sequence. When the remaining distance from touchdown is approximately 15 NM the PF activates the approach phase. This phase is also activated automatically when the lateral mode is "NAV" and the "DECEL" pseudo waypoint is passed. This is the point where the FMS calculated deceleration starts. From this moment on the aircraft flies its calculated approach speed schedule. The PF checks that the aircraft is in managed speed mode and verifies that the aircraft flies the correct speed. In addition to the correct speed, the PF also monitors the flight path and adjusts it as required. This may include the usage of speed brakes to dissipate energy. The PM monitors the accuracy of the navigation system. Depending on the weather the PF adjusts the weather radar to get optimal overview of the cloud situation.

Once the approach clearance is received from ATC, the PM reads it back to confirm it and the PF arms the approach mode by pressing the "APPR" labeled approach button on the FCU. The FMA now shows LOC and GS in cyan below the active mode indicating that these modes are armed. Once the aircraft is at the correct distance from the GLS localizer it will start intercepting it. This mode is indicated by the LOC* and called out by the PF. Both pilots check the correct interception of the GLS localizer. Once the aircraft is established on the localizer the mode changes to LOC, which is also called out by the PF. When initiating the GLS glideslope intercept the vertical mode changes to GS*, which is called out by the PF. Both pilots check the correct intercept of the GLS glideslope. Once established on the glideslope the active mode changes to GS. As all FMA changes this mode change is also called out by the PF.

The following steps may be partially occurring before the intercept described above. The exact order depends on the approach and the current situation of the flight. For better clarity, the two parts are separated in the description. The interception of the final approach path is shown above and the configuration for landing including the speed reduction is shown below.

On the intermediate or final approach, when flying green dot speed and deemed appropriate by the PF, flaps 1 are ordered by the PF and selected by the PM. Once the flaps are extended to position 1 the commanded speed changes "S-Speed" This speed is the recommended speed to select the next flap setting [37]. When reaching the S-Speed and minimum in 2000 ft Above Ground Level (AGL) the PF orders flaps 2 and the PM selects the flap lever to 2. After extension of the flaps to position 2, the managed speed changes to "F-Speed". The F-Speed is the managed speed target with flaps in position 2 or 3 and is the recommended speed to select the next flap setting [37]. The PF checks that F-Speed is commanded and orders landing gear down once the F-Speed is reached. When receiving this order, the PM selects the landing gear lever down, confirms the autobrake setting, arms the ground spoilers and sets the exterior lights to the appropriate setting. Next the PF orders Flaps 3 once the gear is deployed. The PM selects the Flap lever to 3 and checks the wheel page on the ECAM display. To finish the aircraft configuration, the PF orders Flaps Full and the PM selects it. The managed speed changes to the approach speed and remains there until touchdown or go around. While the PF checks the new speed target the PM verifies that the auto thrust is in speed mode or off, if the PF uses manual thrust. If the weather permits the PM turns of the wing anti ice system at this point.

In preparation for landing both pilots stow the folding table, and the PM verifies that the landing memo on the ECAM display shows no open items. As open items are shown in blue the wording at that point is "no blue". Once the cabin has informed the flight deck, that they are ready for landing and the cabin is informed about the imminent landing, the landing checklist is performed by the pilots. After that, the PM monitors the flight parameters and calls out deviations, while the PF calls out any FMA changes and flies the aircraft manually if the autopilot is turned off. 100 ft above the minimum altitude the aircraft gives the call: "One hundred above" and at minimum: "Minimum". If those calls are not given by the automatics the PM takes over that task. At minimum, the PF decides whether to continue to land or go around and announces the decision accordingly.

2.2.2. RNP Approach using GLASS

The previous subchapter explained the tasks to be completed on an approach when utilizing the GLASS technology using GLS chart and operation. This chapter deals with the differences in the procedures when using RNP charts and operation instead while utilizing the GLASS technology. Most of the actions performed are the same, therefore not all explanations are given again. The tables containing the tasks are shortened where the actions do not differ from the GLS operation. All differences are highlighted and shown in bold and italic.

Table 5 – Proposed descent preparation task list using GLASS technology and RNP operation. The list includes the items to be performed by the flight crew in preparation of the descent, that differ to Table 2. Items that are specific for an approach using GLASS technology and RNP operation are shown in bolt and italic. (Derived from A320 QRH [36])

DESCENT PREPERATION	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
	Obtain Weather and Landing Information
Prepare Nav Charts.	Prepare Nav Charts
Confirm Landing Performance	Check Landing Performance
Insert RNP approach in FMS	***Verify Correct Approach Set***
Tune GLS Channel Number	***Tune GLS Channel Number***
Select Inbound Course	***Select Inbound Course***
Set LPV Minimum	***Set LPV Minimum***
Check Landing Elevation	
Continued as Shown in Table 2	

The descent preparation starts similar for all approach types. Again, the weather information is obtained by the PM and the required charts are prepared by both pilots. When using RNP operations the corresponding RNP chart must be opened in addition to the arrival chart with the expected arrival route. The calculation of the landing performance is done as explained in chapter 2.2.1.

The difference in the tasks start after that. Table 5 gives an overview over the tasks during the descent preparation phase. The Airbus A320 usually tunes the required navigation systems to the correct settings such as frequency, inbound course, or channel number. During the GLS variant of the approach it does exactly that and the crew only has to verify the correct setting. Since the system is not programmed to tune a GLS channel number during an RNP approach, the automatic setting does not work when using an RNP approach utilizing the GLASS technology. Therefore, the channel number and inbound course must be set manually. This is the largest difference between the two variants of operation. When a frequency is manually entered in an A320 the crew usually uses the RADNAV page of the FMS. Unfortunately, this way does not work for the GLASS system. Even though the deviations of the calculated track are displayed in the PFD the AFCS does not use it. The desired modes do not engage as desired. The required modes are shown in Table 7.

To enter the correct setting and allowing the autopilot to use it, the backup navigation switch on the COM/NAV panel must be set to on. This is marked with "1" in Figure 8. After that, the GLS must be selected and the channel number and inbound course according to the chart must be tuned using the knob ("2." and "3." in Figure 8). The channel number and inbound course are shown in the display of the COM/NAV panel. Tuning the GLS as described on both sides enables the reception of a GBAS signal even though an RNP approach is selected in the FMS. This way of tuning the GLS also allows the auto flight system to receive the GBAS signal and fly the final accordingly.

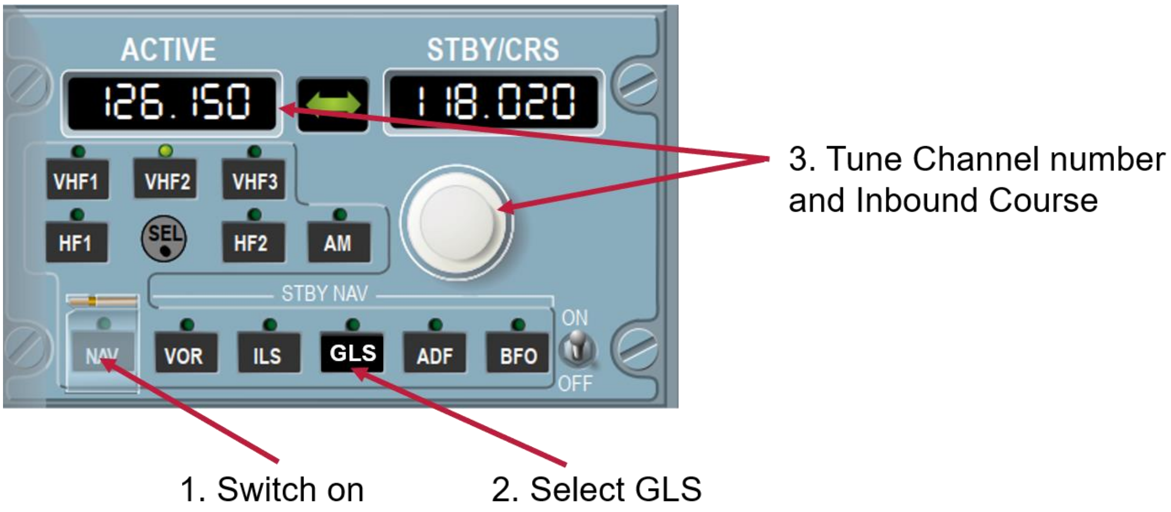


Figure 8 - GLS-channel and inbound course tuning to utilize GLASS during RNP approach using COM/NAV Panel in Airbus A320 (Adapted from: Airbus, 2004)

In the next step both pilots set the LPV minimum from the RNP chart on their side. As LPV minima are not frequently set by airbus pilots, special attention shall be paid to the correct minimum. After that the procedure continues with checking of the landing elevation by the PF and all the following items as shown in Table 2 and explained in chapter 2.1.1.

Table 6 – Proposed descent task list using GLASS technology and RNP operation. The list includes the items to be performed by the flight crew during the descent until the initial approach, that differ from Table 3. Items that are specific for an approach using GLASS technology and RNP operation are shown in bolt and italic (Derived from A320 QRH [36])

DESCENT	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
As shown in Table 3	
Press Landing System Button	Press Landing System Button
	Verify correct Channel Number and identifier
Complete Approach Checklist	Complete Approach Checklist

Table 6 shows the descent task list for the approach using RNP operation. It is the same as for GLS operation. By pressing the landing system button on the FCU, the deviation display on the PFD is enabled and the PM can verify the correct GLS channel number and identifier with the RNP chart. As such an RNP chart contains a SBAS and a GBAS channel number for the same approach it is important to pay special attention to the correct GBAS channel number entered. After the verification of the identifier the flight crew completes the approach checklist.

Table 7 – Proposed aircraft configuration for approach task list using GLASS technology and RNP operation. The list includes the items to be performed by the flight crew between the initial approach and the minimum altitude, that are differing to the items in Table 4. Items that are specific for an approach using GLASS technology and RNP operation are shown in bolt and italic. (Derived from A320 QRH [31])

AIRCRAFT CONFIGURATION FOR APPROACH	
Tasks for Pilot Flying	**Tasks for Pilot Monitoring**
As shown in Table 4	
Press Approach Button on FCU	
Check LOC and GS Armed	
Call out LOC* when Intercepting GLS LOC	
Check Correct Lateral Intercept of Approach	***Check Correct Lateral Intercept of Approach***
Callout GS* when Intercepting GLS GS	
Check Correct Vertical Intercept of Approach	***Check Correct Vertical Intercept of Approach***
Set Go Around Altitude	
As shown in Table 4	
Call Out any Flight Mode Annunciator Change	Monitor Flight Parameters
Continue or Go Around at LPV Minimum	Monitor One Hundred Above and Minimum call

The next phase of the approach using RNP operation is also similar to the same phase when using GLS operation. All items until activation of the approach mode by pressing the approach button on the FCU are unchanged. By pressing the approach button, the LOC and GS shall be armed. This behavior is different to other RNP approaches. Usually, these modes are not available during an RNP approach and the aircraft would arm the "FINAL APP" mode when pressing the approach button. The LOC and GS modes are available because the GLS was tuned using the backup tuning function on the COM/NAV panel. The PF checks that LOC and GS modes are armed and calls out the mode change when entering intercept mode LOC*. Both pilots monitor the correct intercept of the localizer and the PF calls out the mode LOC once engaged. The same procedure applies for the intercept of the vertical path. After that the PF enters the go around altitude. The procedure continues as shown in Table 4 and explained in Chapter 2.2.1. It ends with the decision of the PF to continue or go around at the LPV minimum.

The two described variants of utilizing the GLASS technology are compared in the study. The following subchapter deals with a method to measure the workload during the flight of these approaches. After that, the study design is explained.

2.3. NASA-TLX

To allow an objective assessment of the two kinds of operation, the workload of the pilots shall be measured when flying the respective approaches. A commonly used method is the Task Load Index of the National Aeronautics and Space Administration (NASA). The NASA-TLX was developed over 30 years ago and published 1988 by Hart & Staveland. It is a multi-dimensional scale that is designed to obtain workload estimates [38]. The original NASA-TLX consists of a weighting and a rating procedure. The factors used to determine the workload are given different weights according to each subject's personal definition of workload. This definition is determined in a pretest, during which pairs of workload factors are compared by the subject [39].The paper and pencil version of NASA-TLX was published in 1986 with an explanation on how to use it. After completion of a task the subject is asked to provide a rating on each of the six subscales. After completion of all tasks of one group the subject is asked to provide the source of workload by comparing all sets of two different factors with each other [40]. The described weighting procedure is nowadays not always used and does not necessarily offer higher sensitivity [41]. The reason behind that is that the higher rated subscales are also the ones with a higher weighting result. Subfactors that do not play an important role in the specific task would therefore get a low rating result and a low weighting result. The information gain from the weighting procedure is not relevant. The author of the original publication of NASA-TLX states in the paper from 2006, that the NASA-TLX can also be used without the weighting. In the paper it is referred to as Raw TLX (RTLX) [38].

In this study the weighting procedure was not performed because there is no additional information gained from it. As stated above, even the author of the original NASA-TLX states that the weighting procedure is not required to obtain high quality workload information. Additionally, it simplifies the procedure during the simulator session.

To obtain information about the workload the RTLX requires only the rating on six subscales. The six subscales of the NASA-TLX represent six sources of workload. A short description for each source is given in appendix A of the 1986 article by Hart and shown here [40]:

Mental Demand:	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand:	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand:	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance:	How successful do you think you were in accomplishing the goals of the task set by the experimenter? How satisfied were you with your performance in accomplishing these goals?
Effort:	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level:	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

The mark placed on each subscale can be assigned to a value between 0 and 100. Where 0 on the left means low demand and 100 stands for high demand and is on the right side of the scale. By adding all values and dividing by 6 an average workload can be generated.

In this study the RTLX was performed using iPads and the platform LimeSurvey. The participants were asked to select the demand experienced on the corresponding scale on the iPads. A detailed description of the questionnaire is given in subchapter: 2.4.2.1.

2.4. Study Design

For the study commercial pilots are used as test subjects to evaluate the different options of operation. Additionally, the crews can offer valuable feedback on the operation of the approach. The study is divided in three parts. Prior to the approaches in the simulator the participating flight crews are briefed about the new approach type and the following simulator flights. After briefing the flight crews enter the simulator and fly several approaches using the different chart layouts. After each approach they fill in a questionnaire about their experienced workload. After the simulator session the flight crews are asked for a debriefing. They fill in another questionnaire that offers room to give feedback concerning the approaches and its representation.

2.4.1. Briefing

During the pre-flight briefing, the basics about the GLASS approach are explained. To give all participants a similar knowledge when entering the simulator, GBAS, SBAS and the corresponding approaches are also explained shortly. In addition, the benefits of the GLASS are stated. It is important for the participants to understand, that the approach is technically an RNP approach to a LPV minimum. The approach is designed as an RNP approach with all its associated rules. The only difference is the way the signal required for the final segment is transmitted to the aircraft and processed there.

The two charts are presented to the participants and the required kind of operation is explained. Especially the manual tuning of the GLS during the RNP operation is described since that function is not commonly used by airline pilots. To get familiar with the layout and the specifics of the charts, the crew is shown the charts and given some time to study and discuss the charts.

After seeing the charts, the crew is given some explanation about the study. The NASA-TLX is explained shortly. Possible questions about the NASA-TLX are answered to allow a timely filling in of the NASA-TLX questionnaire and therefore an orderly and on time simulator session.

Last part of the pre-flight-briefing is the explanation of the planned simulator program. Every pilot shall fly both approach variants as Pilot Flying (PF) and Pilot Monitoring (PM). The order in which the approaches are flown is as follows:

1. GLS approach CM1 is PF
2. RNP approach CM2 is PF
3. GLS approach CM2 is PF
4. RNP approach CM1 is PF

Crew Member 1 (CM1) is the pilot in the left-hand seat and Crew Member 2 (CM2) is the pilot in the right-hand seat.

After every approach both participating pilots are asked to fill in a NASA-TLX questionnaire as explained in the previous subchapter. In this questionnaire they are asked to state their role and the approach variant during the last run. More detailed information on the NASA-TLX Questionnaire can be found in the following paragraphs. After the last approach, all pilots shall fill in the post flight questionnaire, described at the end of this chapter. Additionally, all pilots are given a participant ID to link the different questionnaires and the track recordings to each other for data analyzation.

2.4.2. Simulator Flights

The simulator flights take place in the Flight Training Simulator 76 of Lufthansa Aviation Training (LAT) at the facilities of TFC Flugbetrieb und -technik Beratungsgesellschaft mbH in Essen, Germany. This simulator is based on the Airbus A320-214, is one of the most modern A320 simulators and was taken in service in April 2018. It is a Level D full-flight simulator qualified by the Luftfahrt Bundesamt (German Federal Aviation Office) [42]. Usually, this simulator is used for cockpit crew training. The custom designed approaches were implemented by LAT into the database of the simulator prior to the session. This enables the simulated aircraft to fly the RNP and the GLS variant of the approach. After the briefing, the first two pilots begin in the simulator. Both variants of the approach are flown to runway 15 in Salzburg (LOWS).

The operation is kept as close to that of a normal flight as possible. That is done to minimize additional workload for the crew resulting from factors, that are not part of the study. Therefore, the initial departure is a Standard Instrument Departure (SID) as usual for flights with commercial air transport aircraft. The initial take off is performed by CM1 out of runway 15. The SID selected is the INROM 1X departure, which leads to the north east of LOWS. After passing the last point on that departure route the flight is cleared to the waypoint WS814. WS814 is the initial approach fix (IAF) of the approach to runway 15. At a position approximately 5 NM before WS814 the simulator is put in a position freeze to allow the crew enough time to prepare the approach. This position is also be saved, so the position can be reloaded for the next approaches.

Another factor that keeps the operation close to reality is the Air Traffic Controller. The simulator operator working in this study is a trained ATCO, who used to work for Deutsche Flugsicherung (DFS). During the flights in the simulator, he not only operates the simulator but also serves as a simulated ATCO. No distinction is made between the approach controller, the tower controller, and other controllers, since only one person was available to simulate all these positions.

The first approach to be flown is the GLASS approach with GLS operation to runway 15. The corresponding chart is called GLS E RWY 15. Pilot flying on this first approach is CM1. All approaches are flown to the minimum of 1700 ft, followed by a standard go around. The track of the missed approach procedure continues with a left turn towards the intermediate fix (IF) of the approach, the point WS815. When the crew finishes with the go around drill and the aircraft is stable and clean inbound WS815, the simulator is paused, and the aircraft is repositioned to the point saved earlier on its way inbound WS814. Clean in this context means, that the flaps, the gear, and the spoilers are retracted. After the flight is put to freeze, the crew is given the first NASA-TLX questionnaire as described in the following subchapter 2.4.2.1.

When both pilots are finished with their questionnaire, they are asked to prepare the second approach. This time PF is CM2, and it is flown according to RNP operations. As soon as preparations are finished, the repositioned aircraft is unfrozen, and the second approach begins. The chart for this approach is called RNP E RWY 15 (LPV only), which has been modified as shown in Figure 7. The approach ends in a missed approach, which is again flown until stabilized and clean inbound WS815. At this point the flight is frozen again and the crew fills out the NASA-TLX questionnaire a second time.

Subsequently the third approach is flown with CM2 being PF using GLS operations, followed by the missed approach and the questionnaire as described above.

The fourth approach is the last for the crew. PF is CM1 this time and RNP operation is used. This last approach is finished with a landing and the crew is again given the NASA-TLX questionnaire. After finishing that questionnaire, they are asked to fill out the post flight questionnaire as well. This questionnaire is described in subchapter 2.4.3

This program is completed for all crews of two pilots each.

2.4.2.1. NASA-TLX Questionnaire

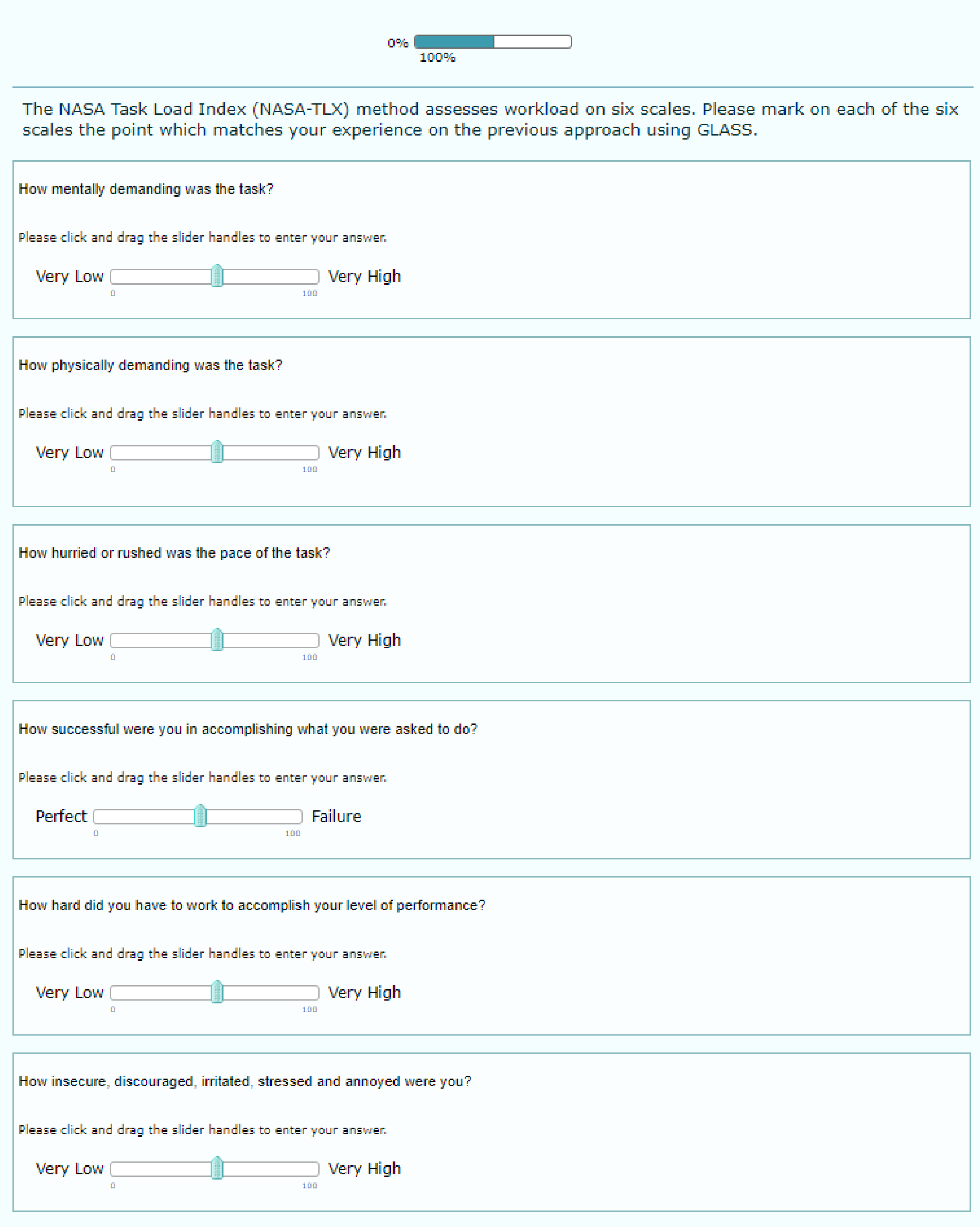
To estimate the workload during the different approaches the flight crew is asked to perform a Raw NASA Task Load Index (RTLX) questionnaire after each approach. A description of the scientific background of RTLX is given in chapter 2.3.

This questionnaire is provided using the platform LimeSurvey. The questionnaire is prepared in advance using the LimeSurvey interface and can be reached online once it is set live using the correct URL given by the program.

The NASA-TLX questionnaire consist of two pages. On the first page at the top the flight crew member is given some explanation about the questionnaire. Below that are three questions for the participant.

- The first question asks for the participant ID. Every participant can choose their own ID, but it is necessary to use the same ID on every questionnaire to allow a comparison of the workload between the different approaches.
- The second and third question is dealing with the approach type flown and the role the crewmember had during the last approach. These questions are also necessary to assign the correct data to the respective approach type and therefore allow an analyzation of the workload for different approach types.

The second page of the NASA-TLX questionnaire contains the rating scales described in chapter: 2.3. Figure 9 shows the second page of the questionnaire as it was used during the study. The participant must move the slider on each of the six scales to the desired position and submit the input at the bottom of the page. If one slider is untouched the system will not allow the submission of the inputs and advise the user to rate every scale.



The NASA Task Load Index (NASA-TLX) method assesses workload on six scales. Please mark on each of the six scales the point which matches your experience on the previous approach using GLASS.

How mentally demanding was the task?

Please click and drag the slider handles to enter your answer.

How physically demanding was the task?

Please click and drag the slider handles to enter your answer.

How hurried or rushed was the pace of the task?

Please click and drag the slider handles to enter your answer.

How successful were you in accomplishing what you were asked to do?

Please click and drag the slider handles to enter your answer.

How hard did you have to work to accomplish your level of performance?

Please click and drag the slider handles to enter your answer.

How insecure, discouraged, irritated, stressed and annoyed were you?

Please click and drag the slider handles to enter your answer.

Figure 9 - NASA-Task Load Index questionnaire page 2 of 2. This questionnaire is to be filled out by participating flight crew members after each approach. The results help to analyze the workload during the two approach variants. (Source: LimeSurvey)

2.4.2.2. Track Recording and Evaluation

During the simulator flights various data is recorded. Information about the aircrafts position in latitude, longitude, and height above sea level is recorded and used for flight path and error calculation. Additionally, its calibrated airspeed, groundspeed, and vertical speed, as well as its roll angle, heading, and gross weight is recorded. This data shall be analyzed and used to show possible differences between an approach flown using the GLS chart with the corresponding procedures and the same approach using RNP chart and procedures.

The recorded data is extracted from the simulator and provided by the simulator operator Lufthansa Aviation Training. The data recording starts with the release of the flight prior to waypoint WS814 and ends after the initial part of the missed approach when established inbound WS815 again.

The recorded data is provided as an excel file with timestamps. All data is recorded with 2 Hz. For each approach, a separate excel file is received. That allows an easy use and further procession with other programs such as MATLAB.

2.4.3. Post Flight Questionnaire

After completion of the simulator flights each crew member is asked to fill in a post flight questionnaire. This questionnaire consists of three pages and gives the participants the opportunity to give their personal feedback concerning the approach operation. All three pages can be found in the appendix. (Figure 28, Figure 29 and Figure 30)

On the first page the participant is asked to fill in its ID, as done previously on the NASA-TLX questionnaires. He is also asked to rate on a scale 0-100 how comfortable he felt flying when using the respective operation. That allows for an evaluation of the pilots perceived safety during the approach.

On the second page of the post flight questionnaire the crew members are asked another four questions.

- In the first question the participant is asked to state whether the RNP chart and its operation or the GLS chart with the associated operation is more prone to error if used for GLASS approaches. A third option 'No difference' can be chosen, if the participant does not detect any difference.

- The second question on this page deals with the presentation of the information required for the GLASS approach. Again, the participant is asked to choose between the two charts or the option 'No difference' for the clearer presentation.
- In the third question the participant is asked which chart and therefore kind of operation he or she would prefer for an implementation of GLASS. As before it can be chosen between 'RNP', 'GLS' and 'No difference'.
- The fourth and last question on this page asks for changes that the participant would make to the charts and its associated operation. This question has an open field for the participant to enter remarks using own words.

The last page of this questionnaire contains only one question. This question gives room for further feedback and thoughts of the participants. This question also has an open field to write down any feedback. The feedback from this field might cover topics or thoughts that were not considered when designing the study.

3. Results

The study explained in Chapter 2.4 was performed with four participants in the Flight Training Simulator 76 of Lufthansa Aviation Training. All participants hold a valid pilot license and currently fly or previously flew for European airlines. The briefing was conducted as described in chapter 2.4.1. Questions about the GLASS system were answered and the first two participants started in the simulator. They were told to decide who is CM1 and CM2 and stay with those roles during the session. Therefore, one pilot flew on the left seat and the other stayed on the right seat. After the first crew finished the approaches, the second crew entered and performed the same approaches, also staying with the roles they started in as CM1 and CM2.

3.1. Track Recording Evaluation and Results

During the approaches in the simulator several parameters were recorded as explained in chapter 2.4.2. The recorded aircraft position in latitude longitude and height was used together with the timestamps to generate the flown trajectories. To find any obvious differences between the approaches flown using GLS and using RNP operations these trajectories were plotted using the program MATLAB. The plotted trajectories are shown and discussed in the first subchapter. A more precise analyzation of the lateral deviation also called Cross Track Error (XTE) can be found in Chapter 3.1.2 and the results of the questionnaire are presented at the end of this chapter.

3.1.1. Trajectories

Figure 10 shows the plotted trajectories. The approaches using GLS charts and operation are shown in red and the trajectories from approaches using RNP operation are displayed in blue. The minimum altitudes published in the current RNP chart are displayed as a red shaded area from the ground to the respective altitude. This indicates the zone where the aircraft is too low, since flying below that altitude is not allowed on the instrument approach. The upper grey shaded areas show the height above a continues descent using the same gradient as on the final approach segment (3 °). These boundaries are placed in Figure 10 to aid with interpretation of the height on the approaches. Even though being above the 3° continuous descent path is not too high in a legal way, most pilots remain below or close to this path. Under normal circumstances an aircraft can fly a three-degree path without the need to increase the drag with speed brakes. The x-and y-axis represent latitude and longitude in degrees, while the z-Axis displays the height above sea level in meters.

It can be seen, that one GLS approach was significantly higher on profile during the initial approach phase. The flight was on profile during its final approach segment and stayed within operational limits. Nevertheless, it differs from the other approaches. Responsible for this deviation is a miscommunication at the beginning of the simulator session. The flight crew was not aware, that the descent planning was part of their task and expected further instructions to descent from the simulated approach controller or the investigator. When informed about their own responsibility for descent planning, the crew initiated the descent immediately and was established on final approach segment within limits. The flight crew was asked by the simulated approach controller if they preferred a new line up for the approach. The crew said it would be no problem because they were aware of the capabilities of the aircraft. They were correct and routinely descended using speed brakes. The approach was in portions above the 3 ° path that would result from an extension of the final segment descent angle. As the grey shaded area is only touched a little bit after being established on the final course it is determined that the aircraft, while being significantly higher than the other approaches, was not significantly over the 3 ° path.

Another approach that differs from the other in Figure 10 is the lowest one in the initial segment. This was the first approach of the second crew. The participants in the second crew were told about their own responsibility of the descent planning and therefore planned all descents in advance. Nevertheless, the first approach was lower than all other approaches. This might be a result of the crew being careful not to be too high on profile, ending on the lower side during the approach. The flown altitudes were always within limits of the published approach charts. It is by no means wrong to descent to the next lower altitude when passing a waypoint. But to improve efficiency and reduce fuel burn in a real aircraft, it is preferable to remain high longer and descent with idle power to the intercept altitude. The flight crews keeping efficiency in mind might be the reason why the participants decided to remain higher during all other approaches. Often pilots try to maintain a healthy margin to both sides, to be able to react to unexpected changes in clearance such as a shorter approach or a speed reduction. Being low on profile reduces the risk of being too fast or too high on the final segment but it also decreases the efficiency because aircraft operate most efficiently when flying at their optimum flight altitude. The optimum altitude varies with different parameters, such as the mass of the aircraft and the outside temperature but is usually relatively high, for example flight level 340 [43]. The margins can also be seen in Figure 10. The distance between most of the trajectories and the upper 3 ° shaded area is larger than the distance the lower limit, which is a hard limit as derived from the published approach. This indicates that the pilots flying the approaches prefer to stay on the save side in terms of energy management, thereby reducing the efficiency of the flight.

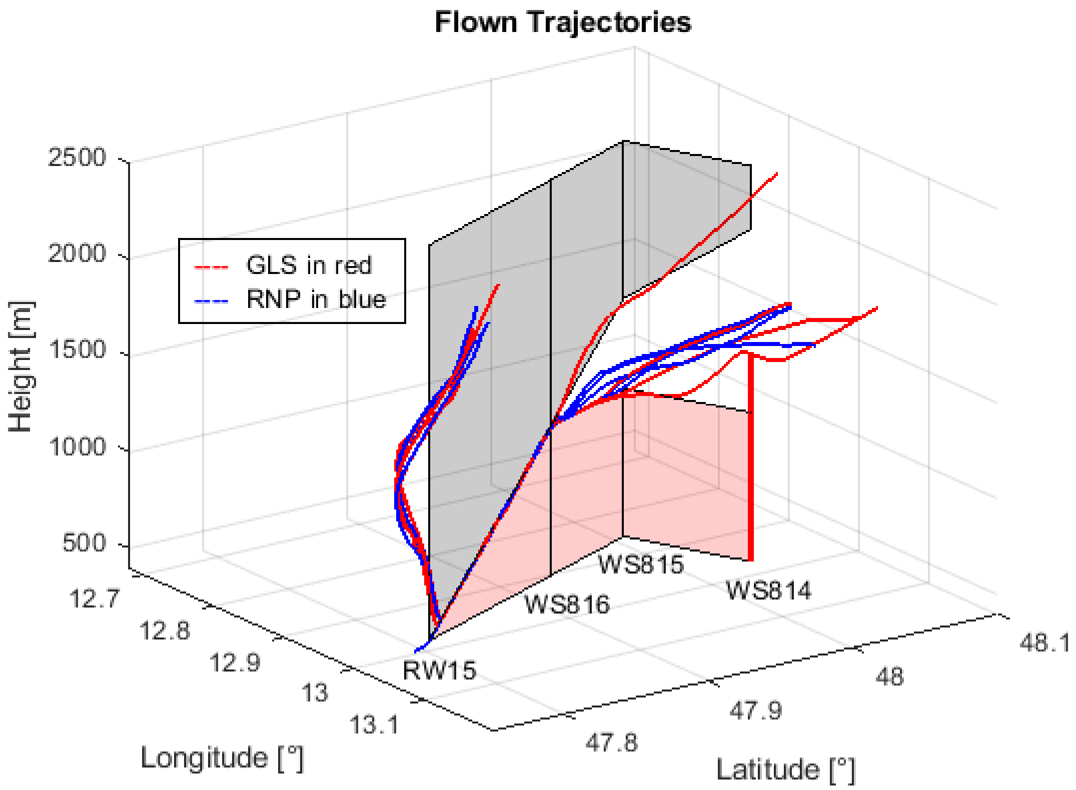


Figure 10 - Flown trajectories of the flights in A320 simulator in latitude, longitude, and height. Additionally showing the minimum height as a red shaded area and the area above the 3 ° path as grey shaded. The minimum height at WS814 is shown with a red line. Most pilots stayed on the conservative side, by being lower than the 3 ° path. The highest and lowest approach are results from communication issues between the simulated approach controller, the flight crew, and the investigator.

3.1.2. Cross Track Error and Vertical Deviation

Displaying the trajectories gave an overview of all approaches. To further analyze the three legs the lateral deviation was calculated and plotted, using MATLAB again. An overview over the cross-track error during the complete approach can be found in the appendix in Figure 31. The first leg in the order in which they are flown is the leg between WS814 and WS815.

3.1.2.1. Leg 1: WS814-WS815

Figure 11 shows the XTE between the first and the second waypoint. The XTE is plotted over the time, therefore the different flights do not end at the exact same value on the x-axis. On the y-axis the cross-track error is displayed in meters. On both ends of each approach the XTE is much larger than in the middle between the waypoints. The reason for these deflections is, that aircraft cannot turn on the spot but have a turn radius. The FMS of the aircraft calculates the turns according to different factors such as speed and type of waypoint. Generally, there are two types of waypoints for the turn calculation. Fly-over waypoints must be crossed before the turn may be initiated. At Fly-by waypoints the turn may already be started prior the passage of the waypoint. This ideally leads to a continuous turn that finishes on the desired track between the past and the next waypoint. As these waypoints are fly-by waypoints, the aircraft deviates from the straight line between the waypoints to intercept the course to the following waypoint, when approaching a waypoint. To allow a more detailed view of the middle part of the leg, deviations larger than 300 m are not plotted in this graphic. It was verified, that deviations of this magnitude were only recorded during turns from one leg to another.

Because the waypoints are not actually overflown it is necessary to define when one leg ends, and another starts. In this thesis the minimum lateral distance between the track and the waypoint is used as the switchover point from one leg to the next.

One approach that differs from the others is the RNP approach in blue that deviates already few seconds in the graph. The reason behind that, is a late start of the track recording. On all other approaches the track recording was started prior to WS814. In one case the start of recording was delayed accidentally resulting in the noticeably short time on the first leg. That approach was flown again at the end of the session of the crew using the same task distribution. Therefore, an additional RNP approach was recorded. Another visible thing is, that multiple approaches ‘overshot’ the desired track. That can be seen as a track deviation to the opposite side as the initial deviation. To find possible reasons for that the speed was also plotted over the time on this leg.

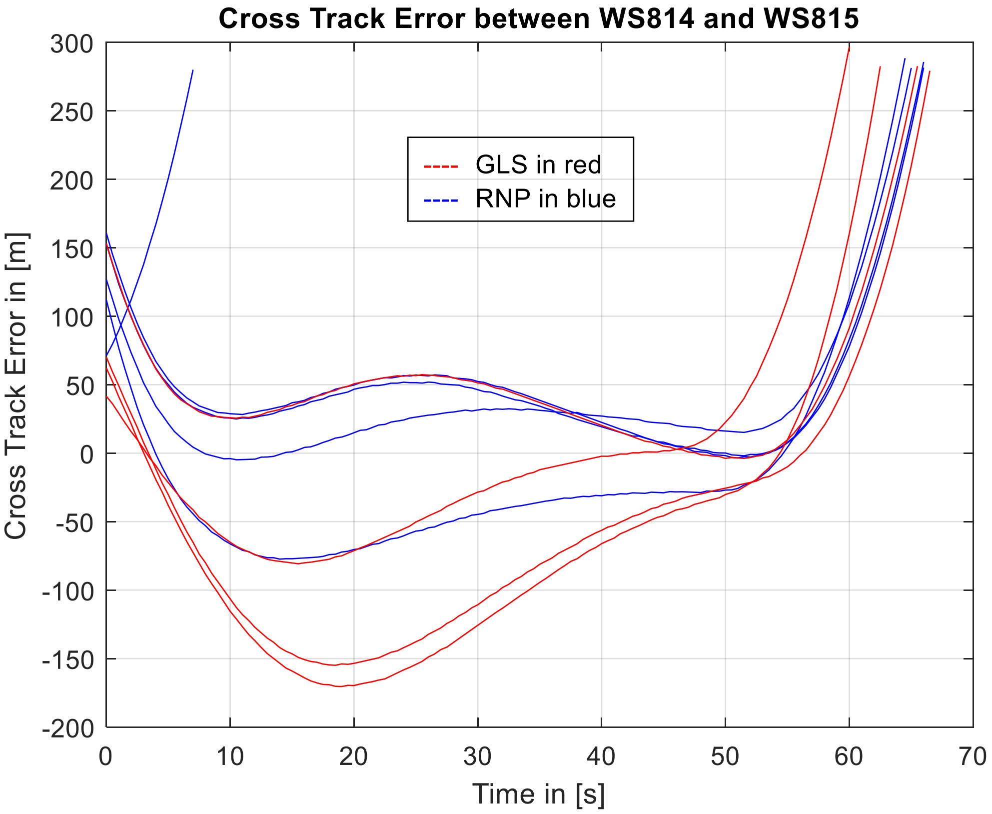


Figure 11 - Cross Track Error during flights in the simulator between waypoints WS814 and WS815. Large deflections on both side due to fly-by waypoints and early turn from FMS. During two GLS approaches the track was overshot significantly, which can be partially explained by the high speed. The shortest line on this figure is a result of late beginning of the recording.

Figure 12 shows the calibrated airspeed (CAS) on the first leg of approach. The relatively high speed on two of the GLS approaches and one of the RNP approaches explain three of the overshooting XTE in Figure 11. But the second largest of the overshoots cannot be explained with the speed, as the speed on that approach is constantly at about 205 kn during this leg. No plausible explanation has been found during the data analysis. A possible explanation is that the FMS calculated an intercept while flying an RNP approach with linear displacement and the intercept during an GLS approach already with the GLS displacement which is angular. It could not be verified if this hypothesis is correct during the study. Another reason could be in the FMS calculation, that changes with parameters that have not been recorded.

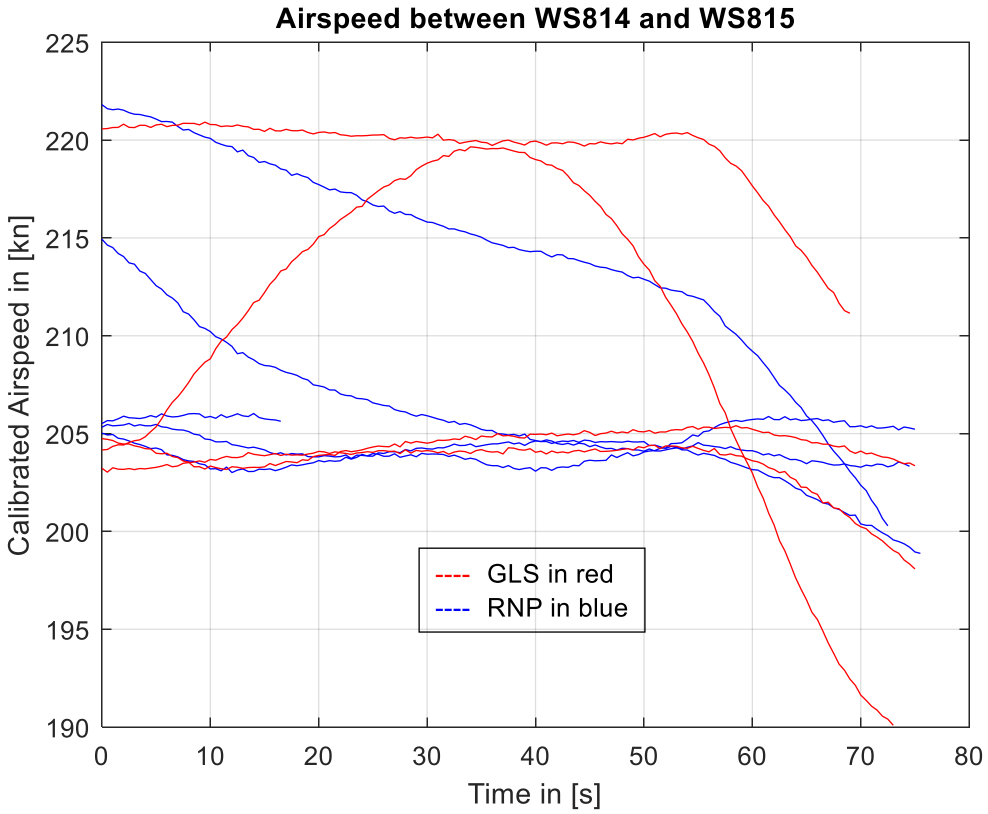


Figure 12 - Calibrated Airspeed of flights in the simulator between waypoints WS814 and WS815. During most approaches, this leg was flown with constant 204 kn, before further configuring and reducing speed towards the end. The two fast GLS recordings were the first approaches of the respective crew. Three of the four faster approaches were flown by the second crew in the simulator. During the first flight of that crew, they let the speed increase during this leg. The first crew stayed slower after being fast on the first approach.

3.1.2.2. Leg 2: WS815-WS816

The second leg has been defined the same way as the first. It starts with the closest point to WS815 and ends at the point of smallest distance to the waypoint WS816. This leg is characterized by an initially high cross track error during all approaches. As explained above this large error is a result of the turn from one leg to another. After the flights are stabilized on the track between WS815 and WS816 the XTE remains much smaller. Figure 13 shows the magnitude and direction of XTE over the time on this leg. It took longer during GLS approaches to reach a XTE of less than 50 m, than during RNP approaches. While the initial part of the leg looks similar for all approaches and the small differences can be explained by the different speeds, two GLS approaches look different.

Noticeable are these two GLS approaches, as they do not reach the low cross track error regime as fast and as smoothly as the other approaches. One of these increases its XTE starting at approximately 12 s into the leg until approximately 26 s in the leg. This flight reaches the desired track only about 10 s before passage of the closest point to WS816. Both approaches were flown by the same crew. The larger deviation occurred during the first approach, which was also the approach that was significantly higher than the others. A possible explanation is that the crew, even though they were confident that reaching the correct altitude would be no problem, was paying a little less attention to the cross-track error. But as the crews used the autopilot most of the time it is likely, that the autopilot was still engaged at this stage.

Figure 32 in the appendix shows the flown airspeed between WS815 and WS816. The fastest initial airspeed on this leg was recorded during the first GLS approach. During this approach, the deceleration was in progress when the turn from leg one to leg two was flown. In the experience of the author the FMS of some aircraft calculate the turn with the speed before the turn and does not consider deceleration during the turn. It calculates a bank angle that will lead the aircraft onto the following leg if the speed remains constant. Due to the decreasing speed and the constant bank angle, the turn radius reduces, and a tighter turn is flown. When leveling the wings after the left turn the aircraft has not reached the desired track but remains left of track. The FMS detects the discrepancy and calculates a new turn that brings the aircraft back on track. This is likely what happened with the auto flight system engaged during the first GLS approach, but it could not be verified if it is the like that for A320 aircraft, as the exact way of calculation of the FMS is not available to the public.

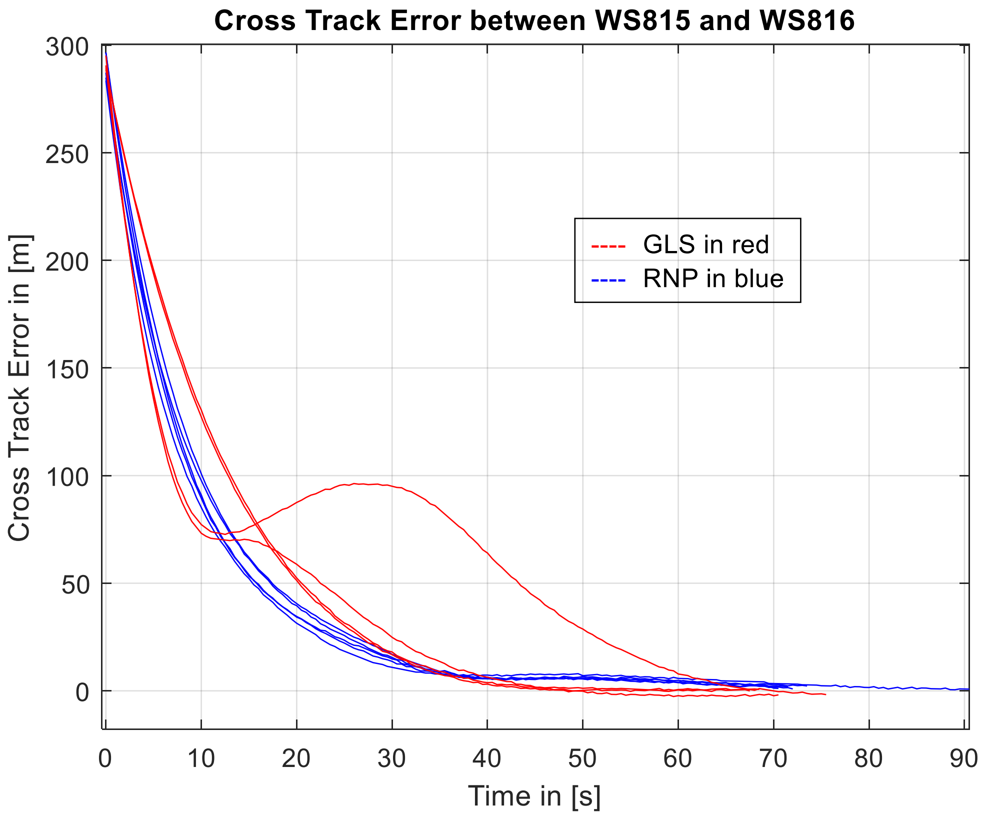


Figure 13 - Cross Track Error during the simulator flights between waypoints WS815 and WS816. Initially high deflection due to fly-by waypoints and early turn through FMS. Most approaches were flown with a very good intercept. During two GLS approaches the distance to the calculated track did not reduce continuously. During one of those approaches the XTE even increased for 13 s before reducing again. The reason behind this could not be determined beyond doubt, but it is assumed, that the FMS calculation of the turn is responsible.

3.1.2.3. Leg 3: WS816-RWY

No turn must be made from the second to the final leg of the approach to runway 15 in Salzburg. Both legs follow the same course and therefore no change in flight direction is required. As a result, the aircraft is already stabilized on course at the beginning of this leg. The initial XTE is much lower than at the other legs and the XTE remains a lot lower during the leg as Figure 14 shows. The figure shows again the lateral deviation from the track on the y-axis and the time on its x-axis. It is important to note the different scale on the y-axis compared to Figure 13 in the previous paragraph. The maximum deviation during the approach on this leg is approximately - 10 m during an approach using RNP operations. It is possible that this error occurred during the transition from autopilot to manual flight, but since the Auto flight Control System (AFCS) status was not recorded this assumption cannot be verified. The large errors at the end of the approach occur during the initiation of the missed approach. At the moment the missed approach is initiated, the FMS mode changes from following the GLS to standard area navigation. The augmentation of the GBAS is not used anymore and the precision might decrease. Additionally, the dynamics of the flight situation changes a lot during that maneuver, as the engines are spooling up the flaps are partially retracted, and the gear is retracted. These factors combined can lead to a larger deviation during the initial part of the missed approach. But as mentioned before the fine scale exaggerates the deviations and the aircraft was well within the 1 NM limits during all missed approaches. This limit is given for missed RNP LPV missed approaches as the Required Navigation Performance value of 1 and includes the different errors previously described [44].

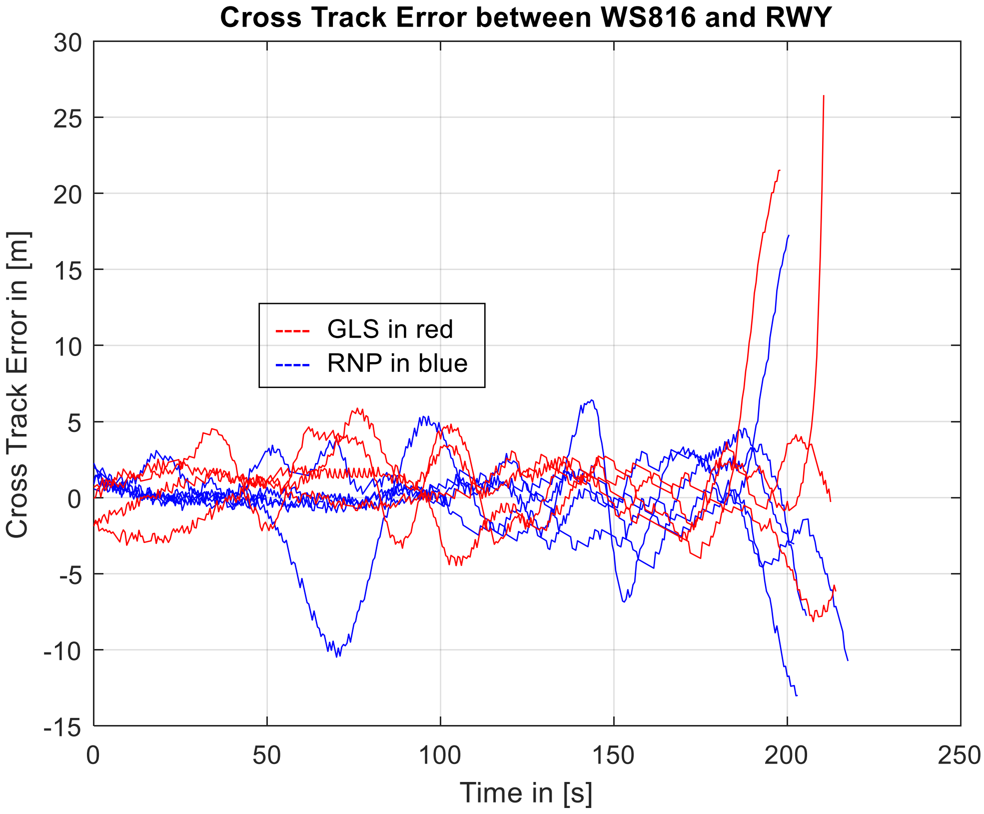


Figure 14 - Cross Track Error of simulator flights on final approach between waypoints WS816 and RWY. Large deflections towards the end due to initiation of missed approach. All errors are small as the scale is different to the previous. The deflections are, likely a result of manual flying skills of the pilots and are well within operational limits.

WS816 marks the start of the final descent. During this part of the approach the vertical path is also precisely defined. Therefore, deviations from the ideal vertical path can be plotted and analyzed. Figure 15 shows the vertical deviation from the 3 ° descent path that is given by the approach design. All deviations remain around plus or minus 15 m of the ideal path. The deviations decrease as the flight progresses on the leg. Just before the missed approach, all vertical deviations are minimal. The figure shows deviations of about -4 ft close to the landing. This is a minimal discrepancy, but no plausible explanation could be found. It is likely, that this error is a result of different heights used for the calculation internally and the exported altitude. The airspeed reduces during the final leg and remains close to the calculated approach speed of 135 k, as seen in Figure 33.

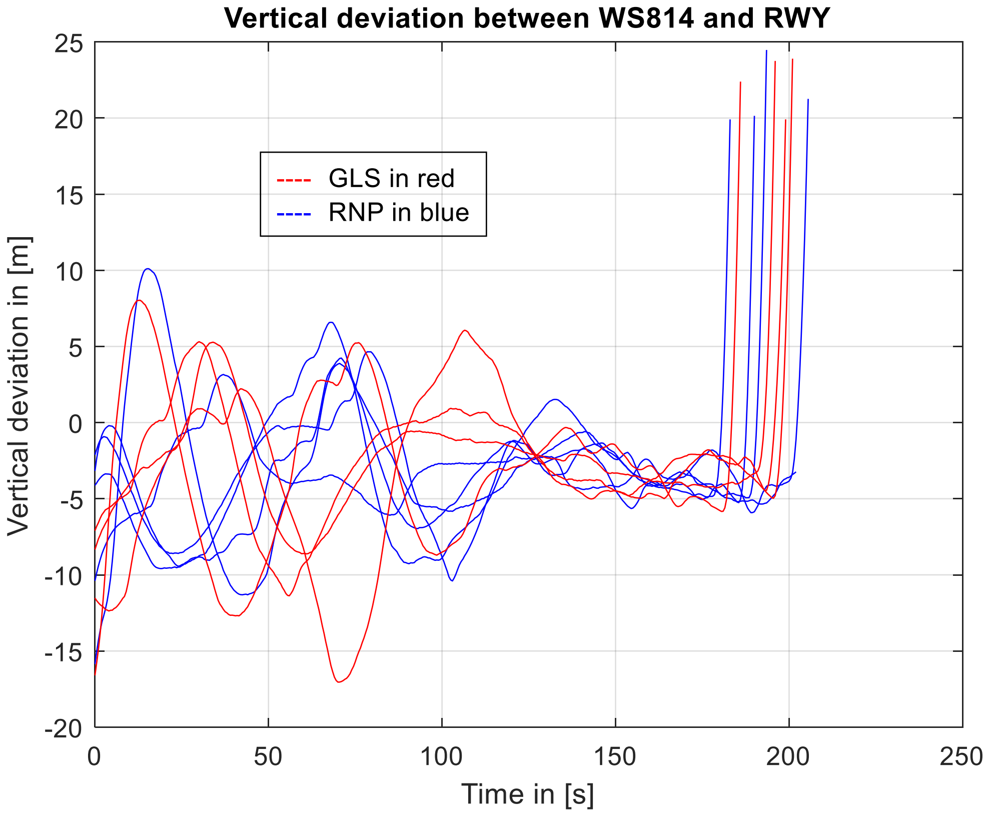


Figure 15 - Vertical deviation on final between waypoints WS814 and RWY. All deviations are within 15m of the ideal path and the deviations decrease on the leg. Just before missed appraoach are only minimal deviations present. The large deviation towards the end are due to initiation of missed approach.

Especially on final no significant difference in XTE or vertical deviation can be found between the approaches using RNP operations and the ones using GLS operations. The recorded data does not seem to support one way of operation over another. The results of the questionnaires are presented in the following subchapters.

3.2. NASA-TLX Results

One of the questionnaires, the NASA-TLX questionnaire, was done by the participants after each approach. The results are presented in this chapter. The results of the Post Flight Questionnaire are shown in subchapter 3.3. One of the participants unfortunately did not fill in a questionnaire for two of the approaches. It is unknown whether that was done intentionally or accidentally. Nevertheless, there is no NASA-TLX data available for these approaches.

Figure 16 and Figure 17 show all subscale results from the different participants. Different participants have quite different perceptions of workload during the approaches. Therefore no comparison between different participants can be made, but only comparisons of the two approach types flown by the same participant. The paragraph below the following two figures deals with these comparisons.

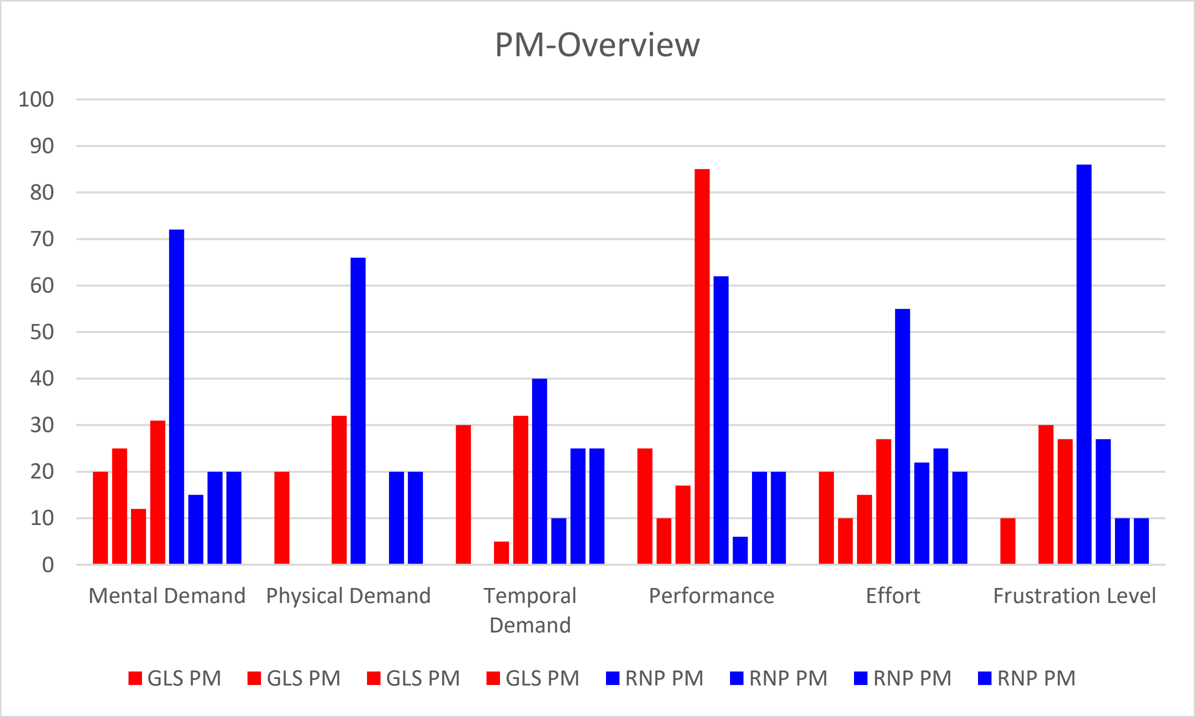


Figure 16 - Overview of all pilot monitoring Task Load subscale results from NASA-TLX questionnaire. Visible is that the individual differences between different participants are large. Therefore, no comparison between different participants is possible.

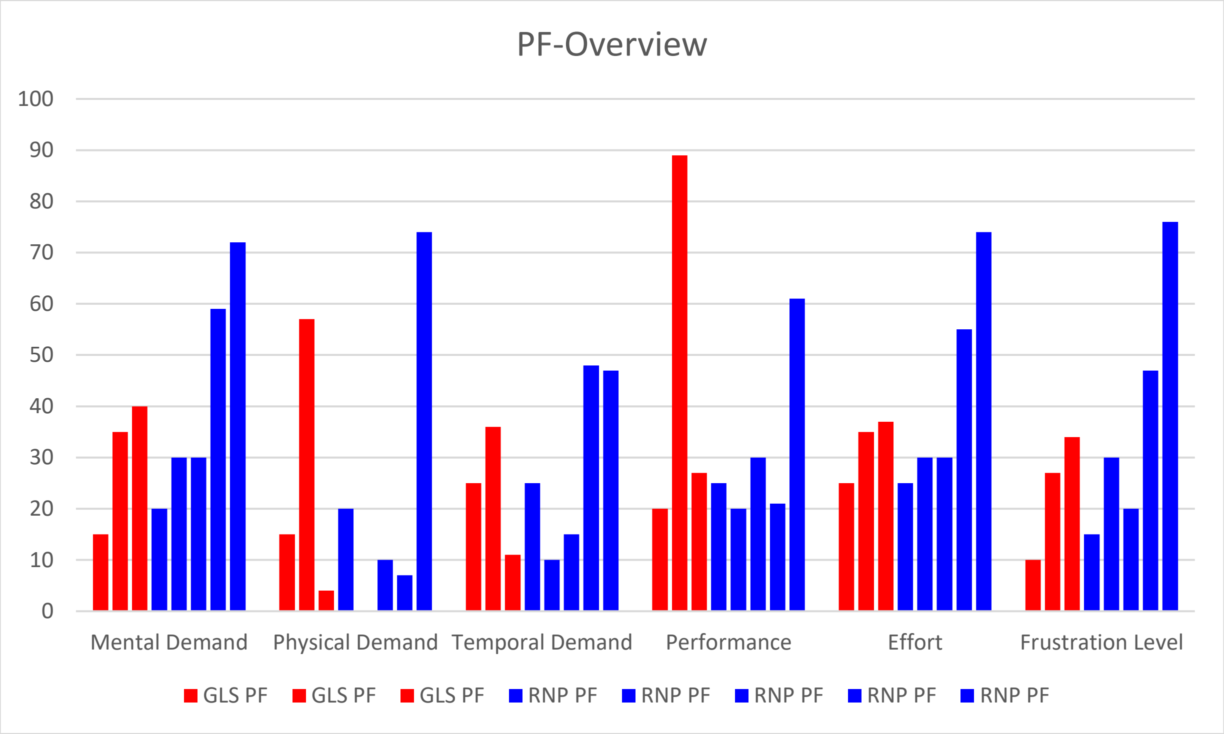


Figure 17 - Overview of all pilot flying Task Load subscale results from NASA-TLX questionnaire. Visible is that the individual differences between different participants are large. Therefore, no comparison between different participants is possible. The results of the RNP variant are slightly higher.

The different subscales of the NASA-TLX were not weighted. The explanation for that is given in Chapter 2.3. The average of all subscales was calculated for each participant. Figure 18 and Table 10 in the appendix show the results of all participants comparing GLS and RNP. CM1 and CM2 of the first crew were given an A prior to the role and the crew members of the second crew received the letter B. This allows a clear distinction between the crew members.

As two questionnaires are missing no interpretation of the data for crew member 1 of the first crew can be done. CM2 of the first crew experienced a slightly higher workload on the GLS approach than on the RNP approach when flying as PM but the other way around when flying as PF. The second crew offered a clearer picture. While CM 1 of this crew experienced a significantly higher workload during the RNP approaches both as PM and PF, CM 2 did not experience different workload as PM, but a higher load during the RNP when being PF. A table showing all answers by the different participants results can be found in the appendix Table 9.

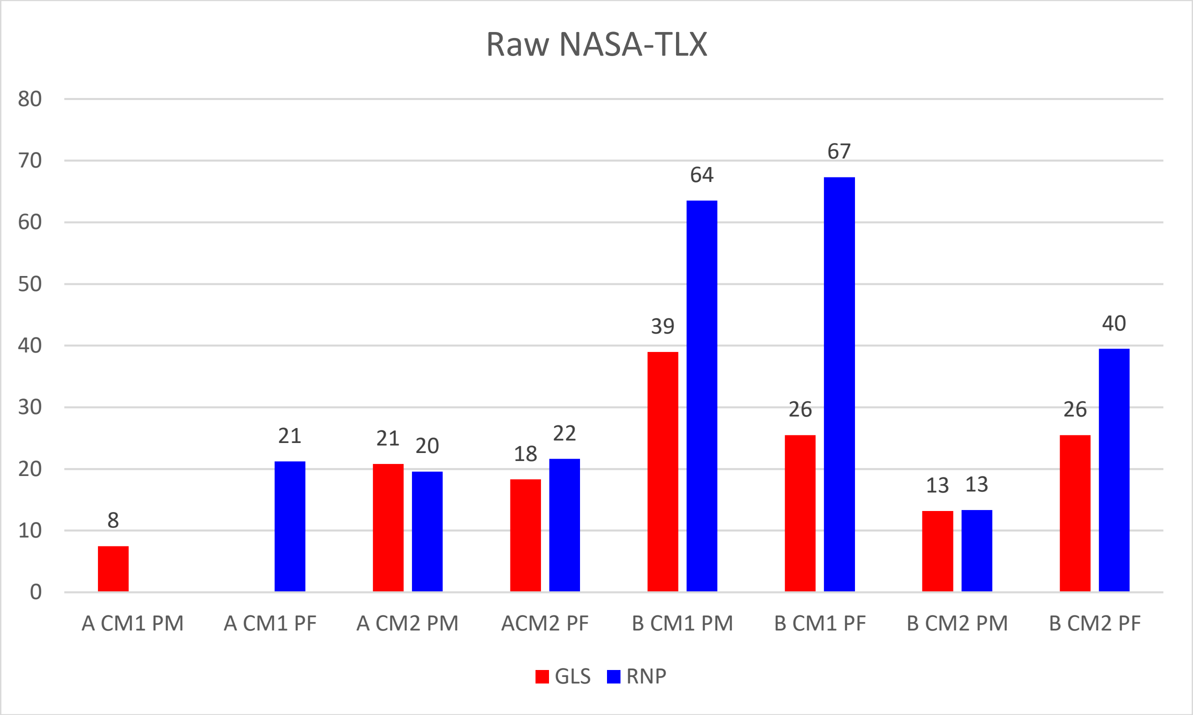


Figure 18 – Averaged Results of Raw NASA-TLX for each crew member in both roles. Results for A CM1 PM RNP and PF GLS are missing. Participant B CM1 reported higher workloads during all approaches. The differences for the other participants are smaller but the RNP variant induced higher RTLX results at five out of six comparisons.

3.3. Post Flight Questionnaire Results

After finishing the last NASA-TLX questionnaire the participants are asked to fill in the post flight questionnaire described and shown in subchapter 2.4.3. Evaluation of the results of the questionnaire is presented in this chapter. Answers were received for all four participants. Visualizations of the results are used for interpretation. The results are presented in the order of the questions in the post flight questionnaire.

3.3.1. Personal Comfort during the Approach

The first question after the participant ID reads:

How comfortable did you feel flying the approach using GLS operation?

The results to this question are presented together with the results of the following question in Figure 19.The mentioned next question reads:

How comfortable did you feel flying the approach using RNP operation?

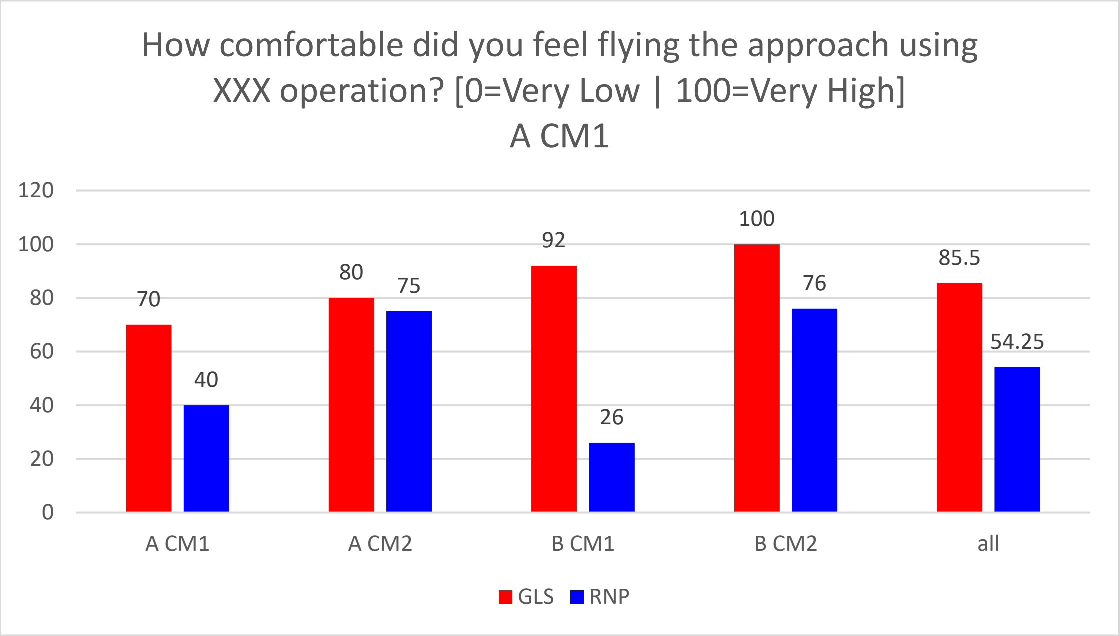


Figure 19 - Personal comfort results from the Post Flight questionnaire. All participants filled in the post flight questionnaire after the simulator session. Even though the difference in scoring varies, higher comfort during GLS operation was reported by all participants.

Even though the difference in scoring varies between the participants, Figure 19 shows that all participating pilots felt more comfortable using GLS operation. When correlating the results from these two questions with the results of the NASA-TLX questionnaire it is noticeable that the large difference in workload for CM1 of crew B is also represented in his own comfort when flying the approaches. Even CM2 of crew A prefers the GLS approach operation although he experienced slightly higher workload when using GLS operation as PM.

3.3.2. Proneness to Error

On the second page the header states, that the participant shall answer the following questions using his own opinion based on the approaches flown during the simulator study. The first question on the second pages reads:

Which chart and associated type of operation would be more prone to error if used for GLASS approaches?

Figure 20 shows the results to this question. Both approach operation procedures were chosen twice giving no clear result. It can therefore be assumed that there is no significant difference in the perceived proneness to error. Nevertheless, no participant chose no difference, therefore it is assumed that both variants are prone to error up to a certain degree.

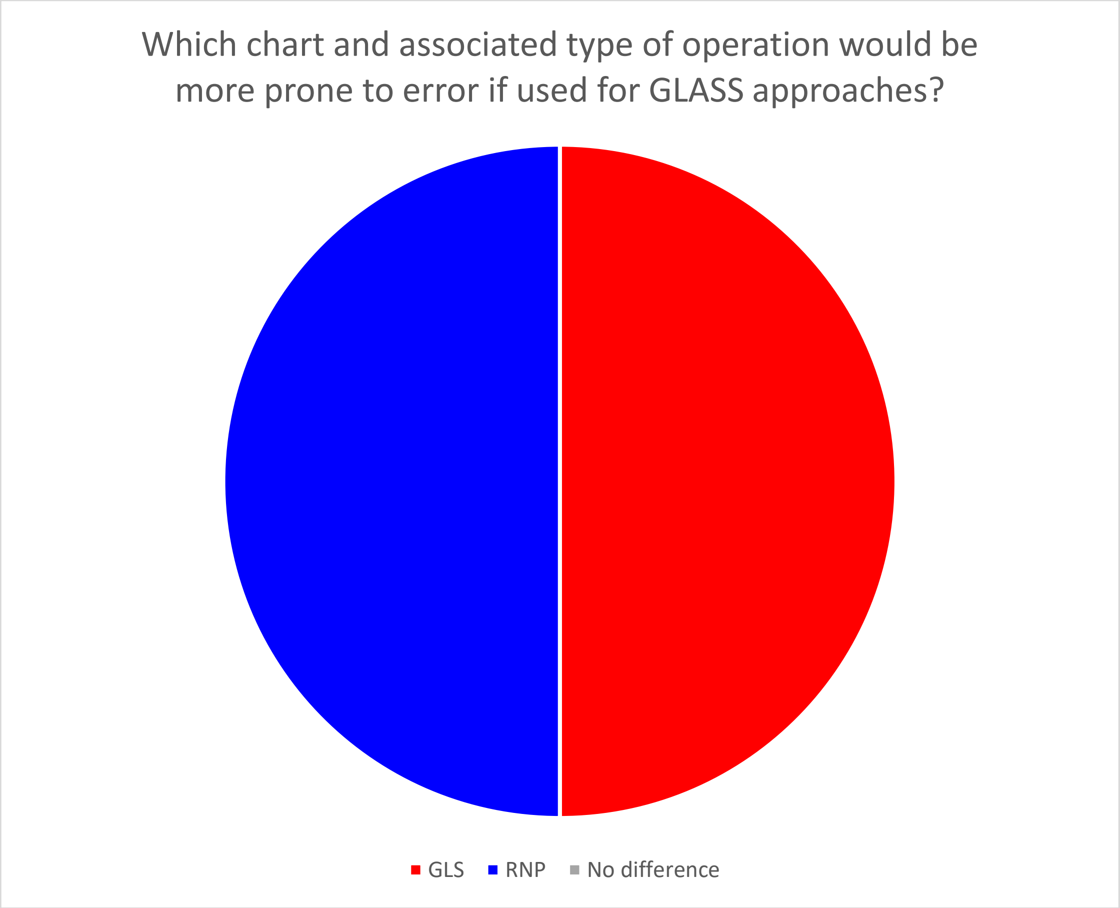


Figure 20 – Result from post flight questionnaire about proneness to error of GLS and RNP chart and operation. Half the participant chose the RNP variant the other half chose the GLS variant. Therefore, no advantage for either option in this question.

3.3.3. Clearer Presentation

The second question on this page deals with the clearness of presentation and reads:

Which chart is clearer in its presentation of the information required for a GLASS approach?

Answers to this question are presented in Figure 21. No participant chose the RNP chart as the clearer presentation. One pilot was indifferent about this question and three crew members voted the GLS chart as the clearer one. The reason for that might be, that the GLS chart contains only the information required for this approach, while the RNP chart also contains information about the normal RNP LPV approach. often RNP approach charts contain even more information. These charts might have various minima for different variants of the RNP approach with and without SBAS augmentation. Therefore, it can be assumed that compared to other RNP charts with added GLASS information the used chart of RNP E (LPV only) in Salzburg is quite clear. Since many other airports have different minima on the RNP approach chart, making it more complex, the difference would most likely be even greater there. This gives the GLS presentation a good advantage at this question.

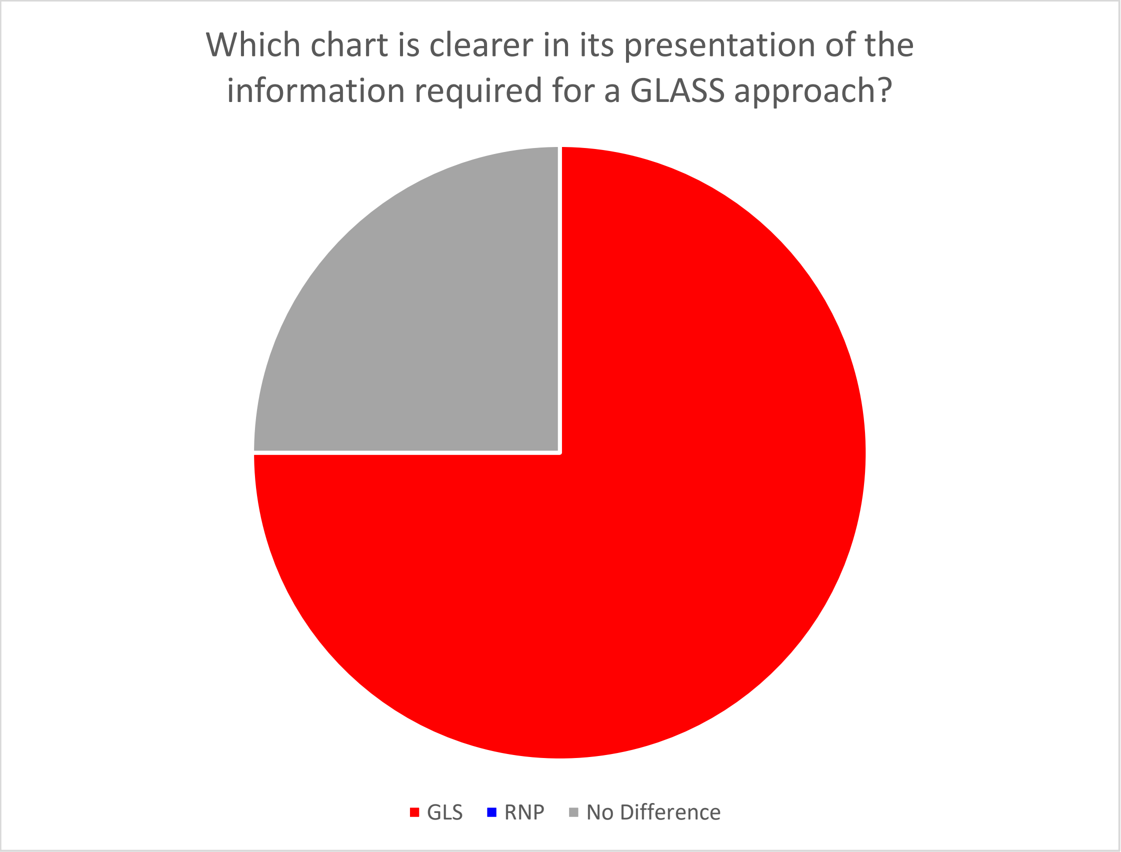


Figure 21 – Results from post flight questionnaire concerning the clearer presentation of GLS or RNP chart. Three out of four participants rated the GLS chart as clearer, and one saw no difference. The difference is expected to be even larger at other aerodromes, where multiple minima (LNAV/VNAV) are presented on the same chart.

3.3.4. Personal Preference of Participants

The third question on this page asks for the personal preference and reads:

Which chart and therefore kind of operation would you prefer for an implementation of GLASS

All participants chose GLS as their preferred chart and operation, as Figure 22 shows. This is the most subjective question but also gives the clearest answer, as all participating pilots chose the same answer. Possible reasons for that are discussed in the following subchapter, where the open questions are evaluated.

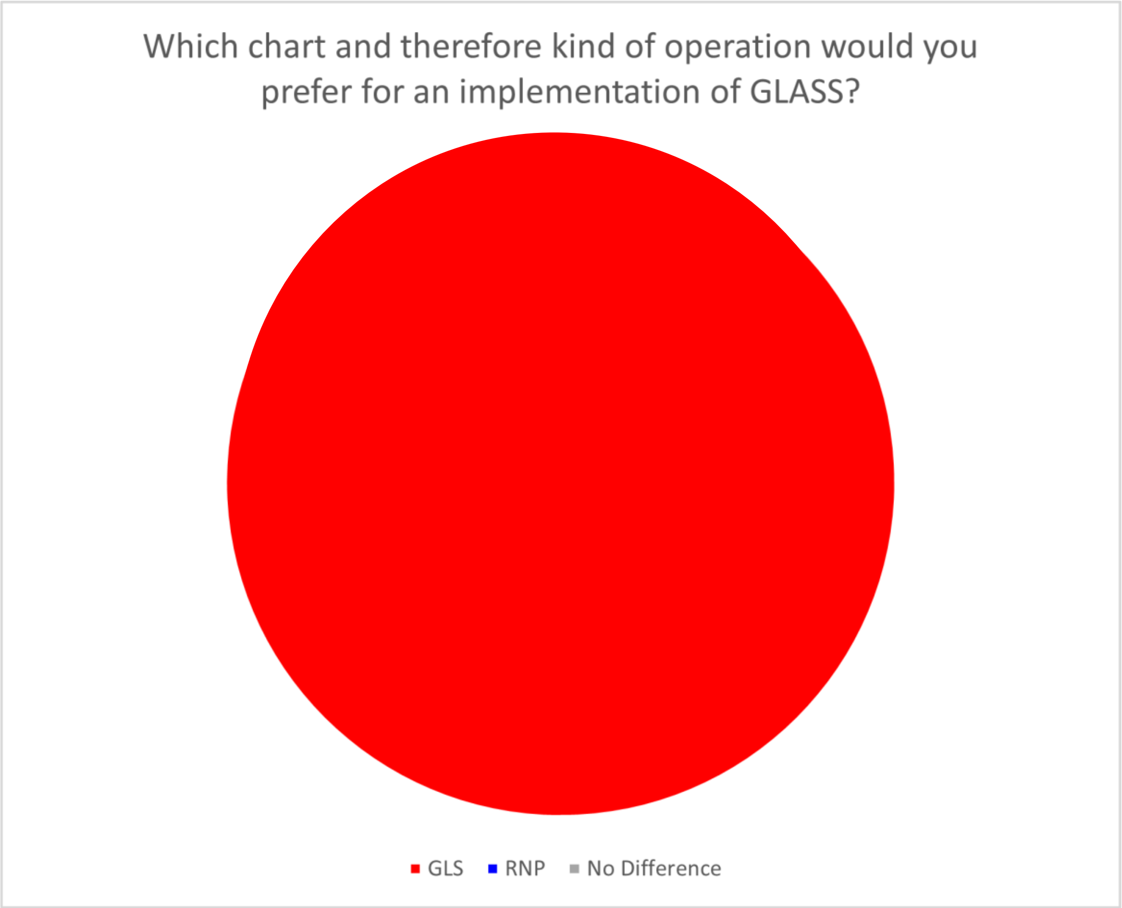


Figure 22 - Personal preference of operation by participants according to post flight questionnaire results. The last question of this type was also in favor of the GLS approach. All participants prefer the GLS operation for an implementation of GLASS.

3.3.5. Changes proposed by the Participants

The last question on this page asks the participants for changes that shall be made to the approach. It reads:

If you had the choice, which changes would you make to the chart and operations associated?

The answers to this question were typed into an open field, giving the participants room for their thoughts on this. Three participants gave feedback to this question. All three answers are listed below.

1. *"Do not use the NAV Backup tuning function of the A320 as it gives the approach the feeling of a non standard operation."*
2. *"RNP Approach on Airbus should not be flown Nav override"*
3. *"Show Glas identifier on rnp chart"*

Two of the three answers refer to the tuning of the GLS channel and course during the RNP approach. As stated in Chapter 2.2.2 Airbus A320 do not follow the GLS during an RNP approach if it is only tuned using the RADNAV page in the FMS. Therefore, the backup tuning must be used to force the aircraft into following the GLS. This procedure is criticized by two pilots. One states it feels like nonstandard operation. The reason for that is most likely that this tuning device is usually not used. During other approaches it is only used if the standard way to tune channels and frequencies via the FMS is inoperative.

The third answer to the question stated above deals with a missing identifier. The chart used during the simulator session did not have the identifier for the GLS displayed for comparison with the received identifier. The only identifier on the chart was the EGNOS identifier for the SBAS LPV approach. Possible charts used for real approaches in the future would have both identifiers displayed if the usage of GLASS is intended as shown in Figure 7. The fact that the identifier is missing was noticed at the beginning of the session and communicated to the second crew. Since only one crew member even mentions it, it is assumed, that the missing identifier had no effect on the recorded tracks and the workloads measured during the flights. The chart in Chapter 2.1 was updated after the simulator session to show both identifiers.

3.3.6. Further Feedback by Participants

The last question on the post flight questionnaire asks the participants for further feedback not covered by previous questions. It reads:

Do you have any further feedback? Please let us know your thoughts:

Two crew members gave feedback in the response field. Both answers are shown below:

1. *Except the Buttons no differences in Approaches*
2. *Using backup nav in normal ops nicht recommended check with airbus if allowed*

One of the answers deals with the same topic discussed in the previous subchapter. The discussion about feedback concerning the tuning with backup NAV can be found in chapter 3.3.5.

The other feedback to the last question states that the approaches are the same except for the buttons pressed. What is probably meant is, that the two kinds of operation do not differ by much. Basically, it is only one approach with minor differences in the approach operation. The "Buttons" probably refers to the way the aircraft is told to follow the GLS. Either by selecting the GLS approach from the FMS database or by manually tuning the correct channel number using the backup NAV panel on the center console. This similarity is natural since both charts represent the same approach to the same runway. The aim of the study is to find a good way to present this approach to the pilots, therefore different presentations were tested.

4. Interpretation, Discussion, and further Research

In this final chapter the generated data shown in previous chapters is brought together and interpreted. The aims of the thesis shown in chapter 1.2 are compared with the results generated and questions that could not be answered in the study are discussed. After that, an outlook to further research is given. The last part of this chapter deals with possible improvements to the study.

4.1. Discussion and Interpretation of Data

In this subchapter the data is analyzed and interpreted. Additionally, the different parameters the thesis was aiming for are compared to the results. The aim of the thesis is presented in chapter 1.2, the performed study is described in chapter 2.4 and the results are shown in chapter 3. The first point that is mentioned in chapter 1.2, safety, is also the most important and is discussed in the following paragraphs, followed by the other mentioned points.

4.1.1. Safety

This chapter deals with the different elements of safety consideration. For every element mentioned in chapter 1.2.1 it is determined whether the GLS variant or the RNP variant is the better option for a future implementation of the GLASS Sbas to GLS converter.

4.1.1.1. Trajectories and Track Deviation

While chapter 3.1 deals with the recorded trajectories, the calculated cross track errors (XTE), and vertical deviations, this subchapter deals with the interpretation of the results presented in that chapter.

Analysis of the trajectories showed one approach that looks different than the others, as it was significantly higher during the initial leg. Even though it is an GLS approach a more detailed analyzation in Chapter 3.1.1 showed that the reason for that is not the different approach operation, but a miscommunication and a delayed descent. The other obviously differing approach is the approach with a lower trajectory than the others. The reason for the different descent was identified to be communication and a very conservative approach by the crew. As shown in Figure 10 the different approach procedures and the corresponding operation did not have an influence on the trajectories.

A more detailed view on the different parts of the flight revealed that the approaches flown using GLS operation perform slightly worse concerning the XTE. In multiple occurrences the autopilot flew the intercept of the next leg better when using RNP operation. The differences were small. A possible explanation is that the turns were calculated using angular displacement during the GLS approaches and linear displacement during RNP approaches by the FMS. This behavior could not be verified during the study and should be part of future analysis. Once on the final approach segment and flying in LOC and GS modes no significant differences could be found. Nevertheless, all approaches remained well within the legal limits. No recorded deviation was safety relevant and therefore both variants to fly the approach are considered safe in this regard. The aircraft would probably have flown a current GLS or RNP approach at another airport the same way, and these are authorized today.

The vertical deviation on the final segment of the approach was also calculated, but no significant difference between the two variants was found. With no difference regarding the vertical error and minimal differences in the XTE, that cannot be correlated to the approach variants with great confidence, no clear advantage for either variant of operation could be determined. Therefore, other parameters such as pilot's assessment of the safety and workload should be kept in focus of the safety analysis.

4.1.1.2. Crew Workload

The crew workload was recorded using the NASA-TLX, which is explained in chapter 2.3. As explained in that chapter the weighting procedure was not performed and the results are therefore the raw NASA-TLX (RTLX). The results of the RTLX questionnaires are presented in chapter 3.2 and shall be discussed here.

Four participants took part in the simulator study. It is important to consider that comparisons between different participants can only be done very carefully, as the number of participants is not enough to counter in-between-rater variability. Other studies conducting experiments in flight simulators about approach plates [45] or display of other information [46] used minimum 13 to 26 participants to generate data. Therefore, the focus in this thesis lies on ratings the same person gave to the two different approach types. Figure 16 and Figure 17 in the results chapter show the ratings each participant gave to the two approach variants as both pilot monitoring (PM) and pilot flying (PF).

One participant did not send results for all approaches. Since he received the iPad with the appropriate questionnaire after each approach and used it for approximately the same time as the other participants, three possible reasons for the missing questionnaires were found. The first possible explanation for the missing results is, that there has been a technical malfunction that was not discovered. This malfunction may have led to the loss of data. The DLR uses the tool regularly and the LimeSurvey tool is found to be reliable. Therefore, this explanation is unlikely. Another possible explanation is that the crew member deliberately did not answer the questionnaire but closed the browser window and waited for the other participant to finish. As the participants were participating voluntarily it is unlikely that one of them would later try to sabotage the results. The last and most likely explanation is, that one crew member had trouble handling the iPad and the questionnaire form. For example, accidentally did not press the submit button in the end or avoided submitting the form in another way unintentionally. For that participant only feedback for pilot monitoring during the GLS and for PF when flying the RNP was received and used for evaluation. Therefore, it is not possible to compare the values of the different approaches for every participant. Nevertheless, the comparisons of the remaining three participants gave the following result:

- As PM: One participant experienced higher workload during the GLS variant of the approach, and two participants reported higher workload during the RNP approach variant. The difference for one of those is exceedingly small. That participant reported only a little higher load on the RNP than on the GLS.
- As PF: All three participants showed a higher workload index on the RNP version of the approach.

A higher workload of the RNP approach can be explained with the required setting of the approach aids using the backup tuning on the NAV/COM panel. It is unusual for flight crews to use this panel in an Airbus aircraft. Typically, the tuning is done by the system or by the pilots in the FMS on the RADNAV page. Therefore, the tuning felt like a non-normal procedure to the crews. In the comments of the post-flight questionnaire three participants stated not to use the backup tuning function. One of those stated as a reason, that it feels like non-standard operation, one did not give a reason, and one questioned whether airbus would allow such a procedure. The feeling of a non-normal might lead to an increase in perceived workload. This can be verified by taking a closer look at the subscales of the RTLX. As mental demand and especially frustration level are expected to indicate the stress resulting from the perception of the non-normal situation, a closer look to those two subscales is taken.

The overview over all subscales is shown in Figure 16 and Figure 17 in chapter 3.2. The following figures show the frustration level comparisons between the two approach variants. Figure 23 shows the mental demand for PM and Figure 24 the mental demand for PF. One participant reported the same mental demand for both approach variants as PM. Two participants experienced larger workload as PM during the RNP variant while all three participants, whose feedback is available, have larger values for the RNP when acting as PF.

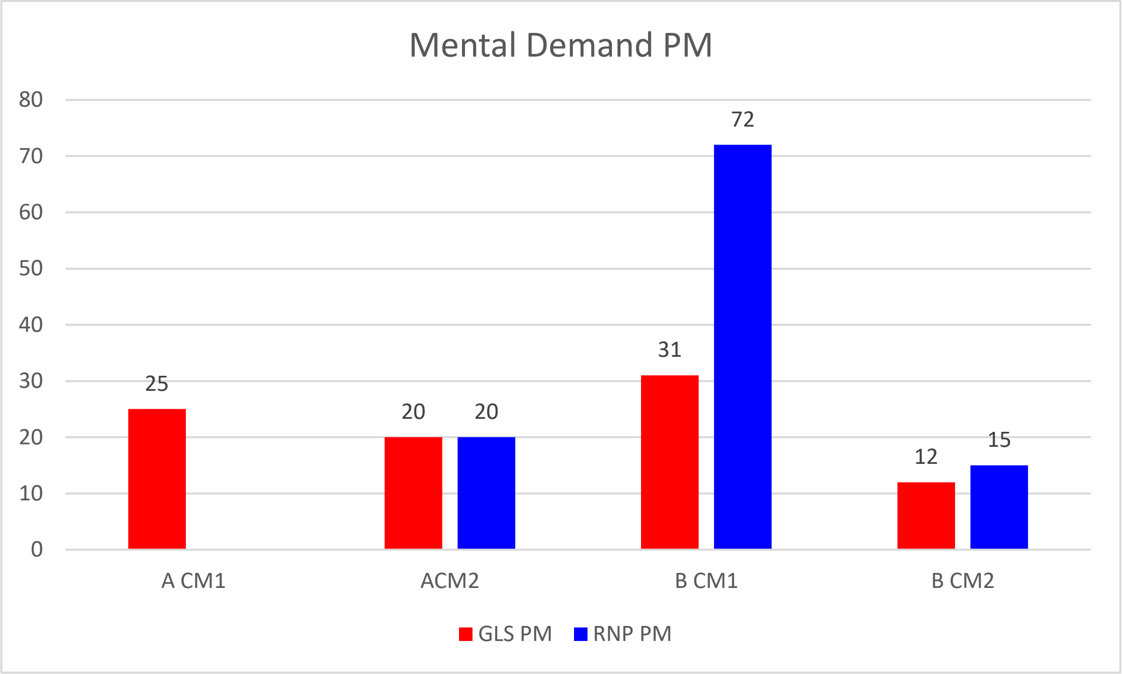


Figure 23 – Mental Demand scale from NASA-TLX questionnaire for pilot monitoring. No data for A CM1 RNP. Two out of three participants reported higher mental demand for the RNP variant when flying as PM.

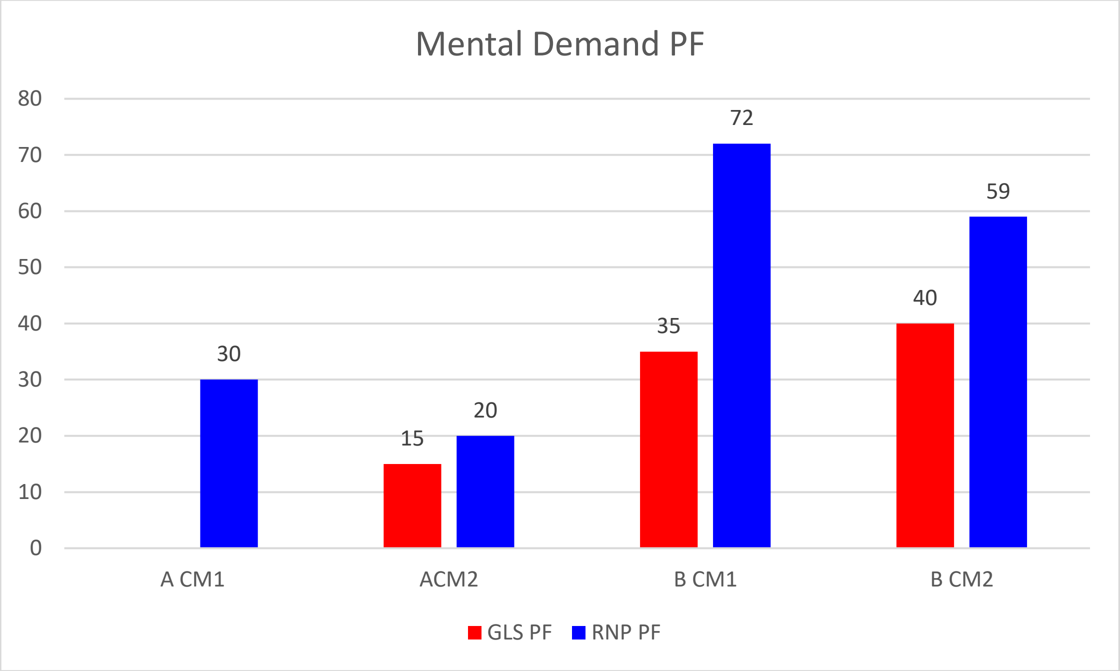


Figure 24 – Mental Demand scale from NASA-TLX questionnaire for pilot flying. No data for GLS A CM1 GLS. All participants for whom a comparison is possible showed higher mental demand during RNP operation. This supports the thesis, that the higher workload is a result of the backup tuning utilization.

The frustration level comparisons are shown in Figure 25 and Figure 26. As PM one pilot reported much higher frustration level rating when flying the RNP variant, one reported the same, and the last participant reported slightly higher values for the GLS approach. The participant, whose results are incomplete reported a frustration level of zero for the GLS variant. As PF all three participants for whom the data is available show a higher rating on the RNP variant of the approach, but to a varying extend.

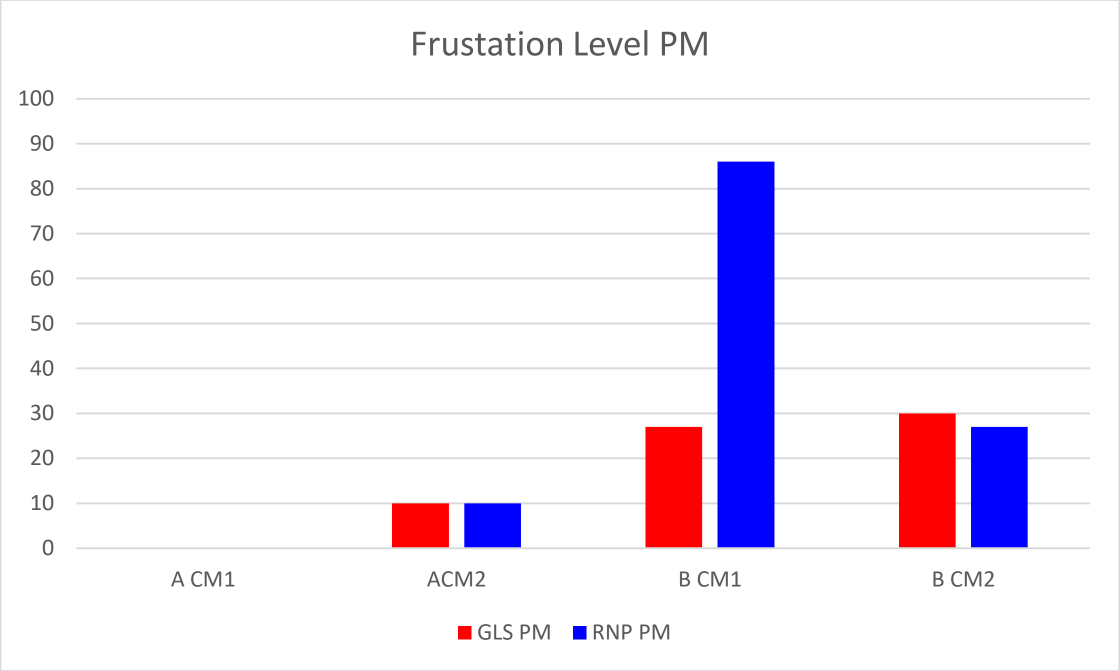


Figure 25 –Frustration Level scale from NASA-TLX questionnaire for pilot monitoring. No data for A CM1 RNP.

The frustration level results for the pilot monitoring are inconsistent. One participant reported higher values during the RNP variant one during the GLS variant and one reported the same.

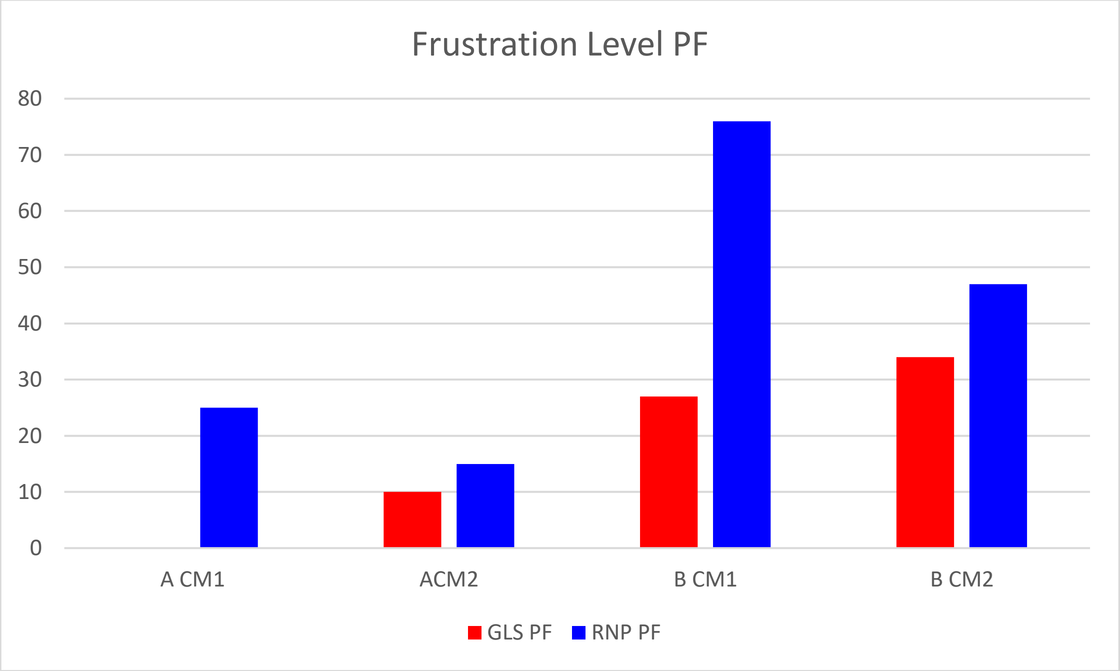


Figure 26 - Frustration Level scale from NASA-TLX questionnaire for pilot flying. No data for GLS A CM1 GLS.

The results of the RTLX for the frustration level of PF show larger workload during the RNP approaches. This supports the thesis, that the higher workload is a result of the backup tuning utilization.

The data from these subscales substantiate the hypothesis that the higher workload in the RNP variants of the approach is a result of the non-normal feeling the participants had. One comment in the post flight questionnaire stated that the only difference between the variants in his opinion are the buttons he uses.

By comparison of the crew workload the GLS variant, using a separate GLS chart and the corresponding procedures shall be preferred. Other safety relevant comparisons are shown in the following subchapters.

4.1.1.1. Chance of Flight Crew Error

Chapter 3.3.2 deals with the results from the post flight questionnaire concerning the proneness to error in the opinion of the participants. As shown in Figure 20 no variant is superior in this category. Even though the navigation aids had to be set manually the crews did not think the RNP variant to be more prone to error.

As explained in chapter 3.3.3 RNP charts for other aerodromes are often more complex. This complexity can increase the chance of error. This would make the GLS chart the better option. But that could not be proven in this simulator study.

Overall, no clear advantage for either variant can be determined concerning the chance of flight crew error.

4.1.1.1. Ease of Understanding

During the simulator flight no questions were asked by the participants about the flyability of the approach. The crews received the introductory explanation in the briefing prior to the session. The flight crews understood the way both variants had to be flown and had no difficulties interpreting the associated charts.

Nevertheless, the participants asked multiple questions about the GLASS system, its working principle, and other background information. It is therefore important to provide training materials for the pilots prior to the usage of GLASS. These materials should include a system overview for the crews to understand the principle. In addition, a more detailed system description shall be included, for the pilots to look specifics up, if questions arise during the operation.

A difference of the ease of understanding could not be determined during the simulator but it must be considered when establishing the GLASS system.

4.1.1. Clearness of Chart

The clearness of the charts was inquired in the post flight questionnaire. The results to that are presented in chapter 3.3.3. As described in that chapter the GLS is superior to the RNP variant in terms of clearness of chart.

4.1.2. Satisfaction of Pilots

Pilots' satisfaction was measured with different questions of the post flight questionnaire. In the first question asking for the comfort during the approaches all participants stated, to be more comfortable during the GLS variant of the approach. The values ranging from 70 % to 100 % indicate, that the crews are accepting this kind of approach and do not have serious doubts. The RNP variant with values ranging from 26 % to 76 % were significantly lower.

Additionally, the remarks by the participants given in the last two questions of the questionnaire shall be considered. The major topic commented on as explained previously, is the usage of backup tuning function. Multiple crew members stated their skepticism about this procedure.

The question about the personal preference was also answered in favor of the GLS approach by all participants.

Overall, the satisfaction of pilots is larger with the GLS variant. The values from the questionnaires and feedback from the study do not show serious doubts of the GLASS system and a high acceptance of pilots when the approach is implemented is expected.

4.1.3. Additional Coding and speed of Implementation

This subchapter discusses the additional effort to implement the two variants of GLASS.

For the GLS variant a new chart would have to be produced for every approach that shall be flown with the GLASS technology. The approach would be published in the AIP of the state in which the approach lies. The charts published by LIDO and Jeppesen are based on the AIP of the respective country. Every country would therefore need to implement the approach in some way, making the process of implementation potentially time consuming and bureaucratic.

Additionally, all approaches published this way would need to be coded for the FMS of the aircraft intended to fly the approach. The new approaches would be available in the aircraft after the following Aeronautical Information Regulation and Control (AIRAC) cycle. Even though these approaches are based on the current RNP approaches, a lot of effort, money, and time would need to be spent to have charts and FMS coding of the approaches.

The other option of using the GLASS technology that is considered in this thesis is the modification of the RNP chart. Beneficial for this option is, that no new chart must be produced and published, but the required information to utilize the GLASS technology is added to current RNP charts. This addition could be done by Lido or Jeppesen for the customers in consultation with the authorities. No change in the FMS databases would be required, as the RNP approaches are already included. This option would potentially ease the implementation of the technology.

4.2. Conclusion

Two different ways of chart representation and operation are compared in this thesis. Both have advantages and disadvantages. During the simulator study the focus was laid on safety relevant items such as the crew workload and the trajectory analysis. Other aspects of the implementation of the GLASS technology such as the satisfaction of pilots and possible speed of implementation were also discussed.

Safety wise the collected trajectory data during the simulator session does not suggest a strong advantage of one variant over the other. While the autopilot performed slightly better during the RNP variant the crew workload was lower during the GLS variant. The crew workload is considered the mor important factor because the differences in the autopilot performance were marginal. No difference in chance of flight crew error could be determined during the study and the ease of understanding was not measured. But as RNP charts contain more information than required for the approach, the GLS variant is expected to perform better concerning those factors, as it is clearer. Therefore, the GLS has a small advantage over the RNP in this category.

The participating pilots gave feedback to the two variants. The feedback was in favor of the GLS variant of the approach. Even though the satisfaction of the pilots with the RNP variant was lower it was not very low. Two of the four participants gave a rating of about 75% when asked about their personal comfort during the approach. The low result of the satisfaction of the other two participants can be explained with the usage of the backup NAV tuning.

The Airbus A320 that was used in this study does not follow the GBAS-signal unless a GLS approach is selected in the FMS or it is overridden using the backup NAV tuning via the COM/NAV panel. During the approaches using RNP operation it was necessary to use the override function. This usage was criticized by the participants as they felt like during a non-normal situation. Consequently, the RNP variant should not be used during normal operation of the GLASS technology with aircraft of the Airbus A320 family or other aircraft, that must utilize a backup system to follow the GLASS generated GLS signal.

The implementation of the glass technology is possibly simpler and faster when using RNP charts. This contradicts the workload ratings and the feedback of the participating flight crew members. A possible solution for the implementation is explained in the following paragraph.

4.2.1. Proposed implementation procedure

As the implementation is quicker and less bureaucratic the initial usage of modified RNP charts and RNP operation is recommended. Since some aircraft such as the Airbus A320 family can only use the GLASS technology on an RNP approach with a manual override, the pilots flying these approaches shall be specially trained. During this training they shall be familiarized with the technology and the usage of the backup NAV tuning. A regular usage of this technology and its procedures ensures the crews are not stressed or experiencing high workload, when already familiar with the special approach operation. Consequently, it is recommended that the crews using this procedure are required to use it regularly.

If the operation using GLASS technology shall not be limited to a certain group of specially trained pilots, but expanded to all pilots within an airline, the GLS chart and operation is the better option because the workload is lower, and the backup tuning does not have to be performed. Especially when pilots do not use the backup tuning often it leads to a higher workload as discussed in Chapter 4.1.1.2. This step-by-step implementation gives time for the more complex way of generating new GLS charts for every aerodrome utilizing GLASS technology.

Theoretically a completely new chart would be another option, but since the GLASS technology transmits a GLS signal, it is faster and cheaper to implement it with current GLS or RNP procedures. A completely new chart is unnecessary because it can be flown and is received by the aircraft exactly like a standard GLS approach.

This study dealt primarily with the operation in A320 aircraft. Other aircraft types have different cockpits layout and philosophies. The tuning of navigation aids differs, and it is not necessarily required to use backup tuning to permit the auto flight control system to follow a GBAS signal during an RNP approach.

4.3. Possible Improvements and Further Research

During the simulator session and its evaluation a few things were discovered, that can be optimized in the future. The first thing that became obvious is, that during the first approach of each crew the largest deviations appeared. To reduce the effect this has on the evaluation of the approach variants, each crew member shall fly an ILS approach at the beginning of the session. The ILS is chosen, since it is the approach type pilots are normally most comfortable with. Additionally, the ILS approach can be used as a benchmark for the different variants using GLASS technology. During these approaches, the crew can settle in and become familiar with the aerodrome the approaches are flown to. Besides that, the usage of the iPad or other device for the questionnaires can be tested and each crew member can practice the NASA-TLX form, while giving the benchmark for other approaches. The investigator shall verify that the data send from these forms is received by the server to ensure correct handling of the iPads and questionnaires. If necessary, the investigator can assist with the iPad or questionnaire without interfering with the results.

Since the number of participants was only four, more meaningful results could be generated with more participants. As stated previously other studies to similar topic used 13 to 26 pilots as subjects for evaluation [45–47]. It is therefore advised to do the study with the suggested improvements again with at least 12 participants to complement the generated data. The differences between individuals play a smaller role when more pilots participate and a more objective view on the workload values can be obtained. When using that many participants the average results of the TLX can also be used to compare them versus a meta-analysis of workload ratings [48].

Additionally, a similar study shall be done with a different type of aircraft. The other type of aircraft shall preferably be able to follow a GBAS signal even when an RNP approach is loaded in the FMS. This would allow a better analysis of the differences in operation of the two variants without the crew feeling like in a non-normal situation. It is possible, that the differences in workload are neglectable between the variants when not using the backup tuning.

Exemplary the study could take place in a Boeing 737 simulator, as it is the Boeing counterpart to the Airbus A320 used in this thesis. It is also one of the most produced aircraft [49]. The GLS functionality is available for B737 and the tuning can be accomplished manually [50]. This additional study should also consider the lessons learned mentioned above. Every crew member shall fly an ILS prior to the GLASS variants and 16 or more crew members should participate to allow a good comparison of the variants.

5. Appendix

This appendix includes the used references, the List of Tables, the List of Illustrations, List of Abbreviations and additional Plots and Figures.

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List of Tables

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List of Abbreviations

Acronym/ Abbreviation	**Description**
AFCS	Auto Flight Control System
AGL	Above Ground Level
AIP	Aeronautical Information Publication
AIRAC	Aeronautical Information Regulation and Control
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
CAS	Calibrated Airspeed
CM1	Crew Member 1 (left-hand seat)
CM2	Crew Member 2 (right-hand seat)
CPF	Central Processing Facilities (EGNOS)
CRC	Cycle Redundancy Check
CRM	Crew Resource Management
DFS	Deutsche Flugsicherung
DLR	German Aerospace Center
ECAM	Electronic Centralized Aircraft Monitoring

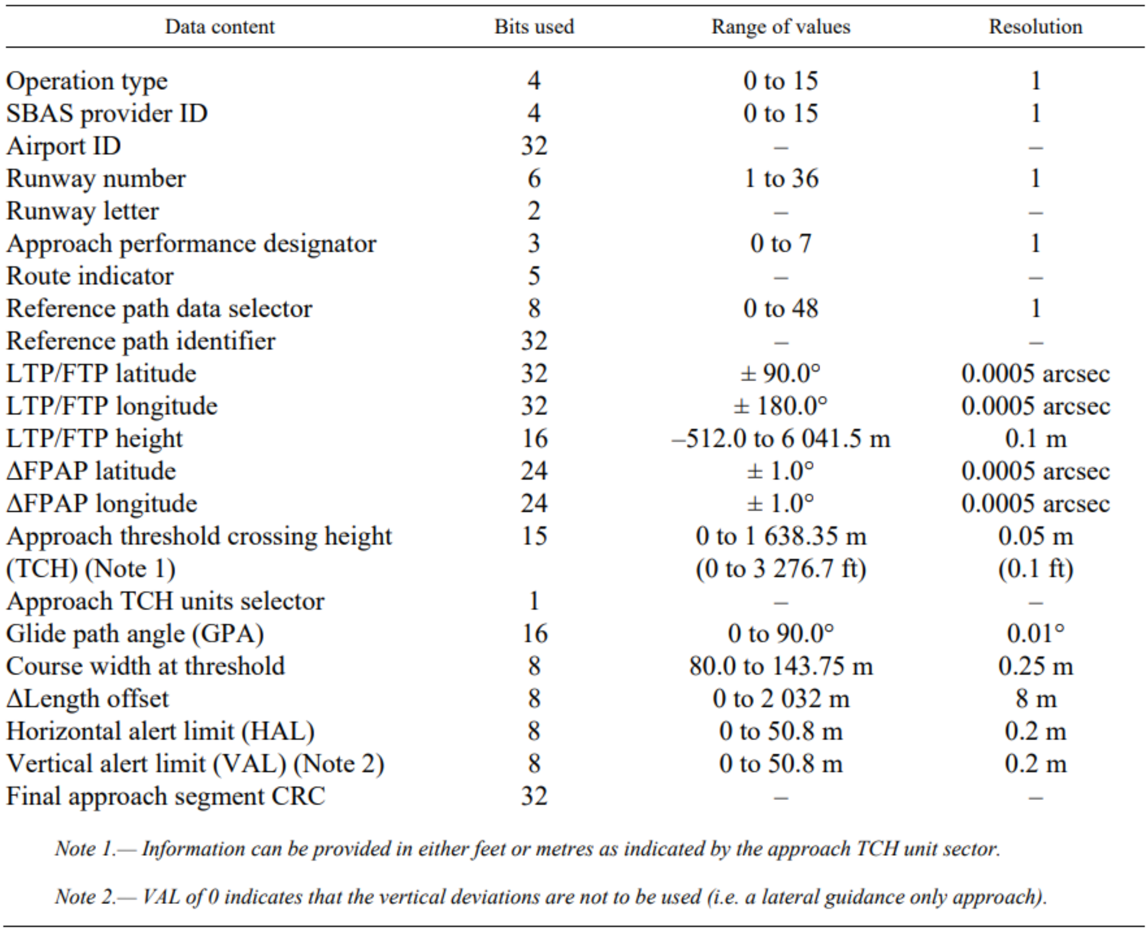
EFIS	Electronic Flight Instrument System
EGNOS	European Geostationary Navigation Overlay Service
FAP	Final Approach Point
FAS	Final Approach Segment
FAS DB	Final Approach Data Block
FCU	Flight Control Unit
FMS	Flight Management System
FPAP	Flight Path Alignment Point
FTE	Flight Technical Error
GBAS	Ground Based Augmentation System
GLASS	GLS Approach based on SBAS
GLS	GBAS Landing System
GPA	Glide Path Angle
HAL	Horizontal Alert Limit
IAF	Initial Approach Fix
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IF	Intermediate Approach Fix
ILS	Instrument Landing System

IRU	Inertial Reference Unit
ISA	International Standard Atmosphere
LAT	Lufthansa Aviation Training
LPV	Localizer Performance with Vertical Guidance
LS	Landing System
LTP	Landing Threshold Point
MCC	Mission Control Centre (EGNOS)
MSL	Mean Sea Level
MTOW	Maximum take-off weight
NASA	National Aeronautics and Space Administration (U.S. federal agency)
NASA-TLX	NASA Taskload Index
NSE	Navigation System Error
PDE	Path Definition Error
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
RIMS	Ranging Integrity Monitoring Station (EGNOS)
RNAV	Area Navigation
RNP	Required Navigation Performance

RTLX	Raw TLX
SBAS	Satellite Based Augmentation System
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TSE	Total System Error
VAL	Vertical Alert Limit
VDB	VHF Data Broadcast
VHF	Very High Frequency
XTE	Cross Track Error

Additional Plots and Figures

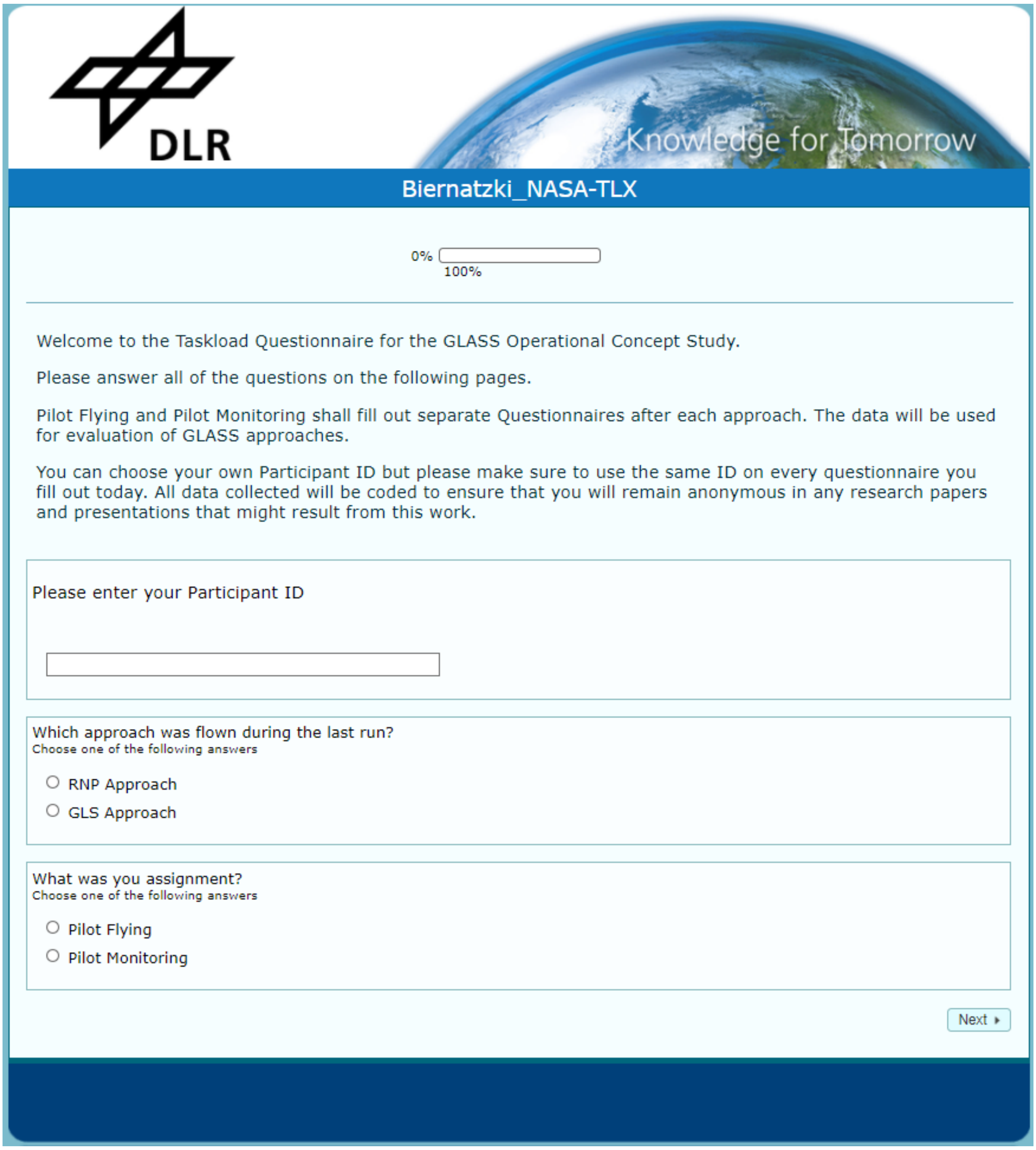
Table 8 - SBAS FAS data block including range of values. In addition to the values of the GLS FAS DB the SBAS FAS DB contains information about the Horizontal alert limit and the Vertical alert limit and a cycle redundancy check (CRC) value to assure the database is current (Source: ICAO Annex 10 [11])



Data content	Bits used	Range of values	Resolution
Operation type	4	0 to 15	1
SBAS provider ID	4	0 to 15	1
Airport ID	32	–	–
Runway number	6	1 to 36	1
Runway letter	2	–	–
Approach performance designator	3	0 to 7	1
Route indicator	5	–	–
Reference path data selector	8	0 to 48	1
Reference path identifier	32	–	–
LTP/FTP latitude	32	± 90.0°	0.0005 arcsec
LTP/FTP longitude	32	± 180.0°	0.0005 arcsec
LTP/FTP height	16	–512.0 to 6 041.5 m	0.1 m
ΔFPAP latitude	24	± 1.0°	0.0005 arcsec
ΔFPAP longitude	24	± 1.0°	0.0005 arcsec
Approach threshold crossing height (TCH) (Note 1)	15	0 to 1 638.35 m (0 to 3 276.7 ft)	0.05 m (0.1 ft)
Approach TCH units selector	1	–	–
Glide path angle (GPA)	16	0 to 90.0°	0.01°
Course width at threshold	8	80.0 to 143.75 m	0.25 m
ΔLength offset	8	0 to 2 032 m	8 m
Horizontal alert limit (HAL)	8	0 to 50.8 m	0.2 m
Vertical alert limit (VAL) (Note 2)	8	0 to 50.8 m	0.2 m
Final approach segment CRC	32	–	–

Note 1.— Information can be provided in either feet or metres as indicated by the approach TCH unit sector.

Note 2.— VAL of 0 indicates that the vertical deviations are not to be used (i.e. a lateral guidance only approach).



Biernatzki_NASA-TLX

Welcome to the Taskload Questionnaire for the GLASS Operational Concept Study.

Please answer all of the questions on the following pages.

Pilot Flying and Pilot Monitoring shall fill out separate Questionnaires after each approach. The data will be used for evaluation of GLASS approaches.

You can choose your own Participant ID but please make sure to use the same ID on every questionnaire you fill out today. All data collected will be coded to ensure that you will remain anonymous in any research papers and presentations that might result from this work.

Please enter your Participant ID

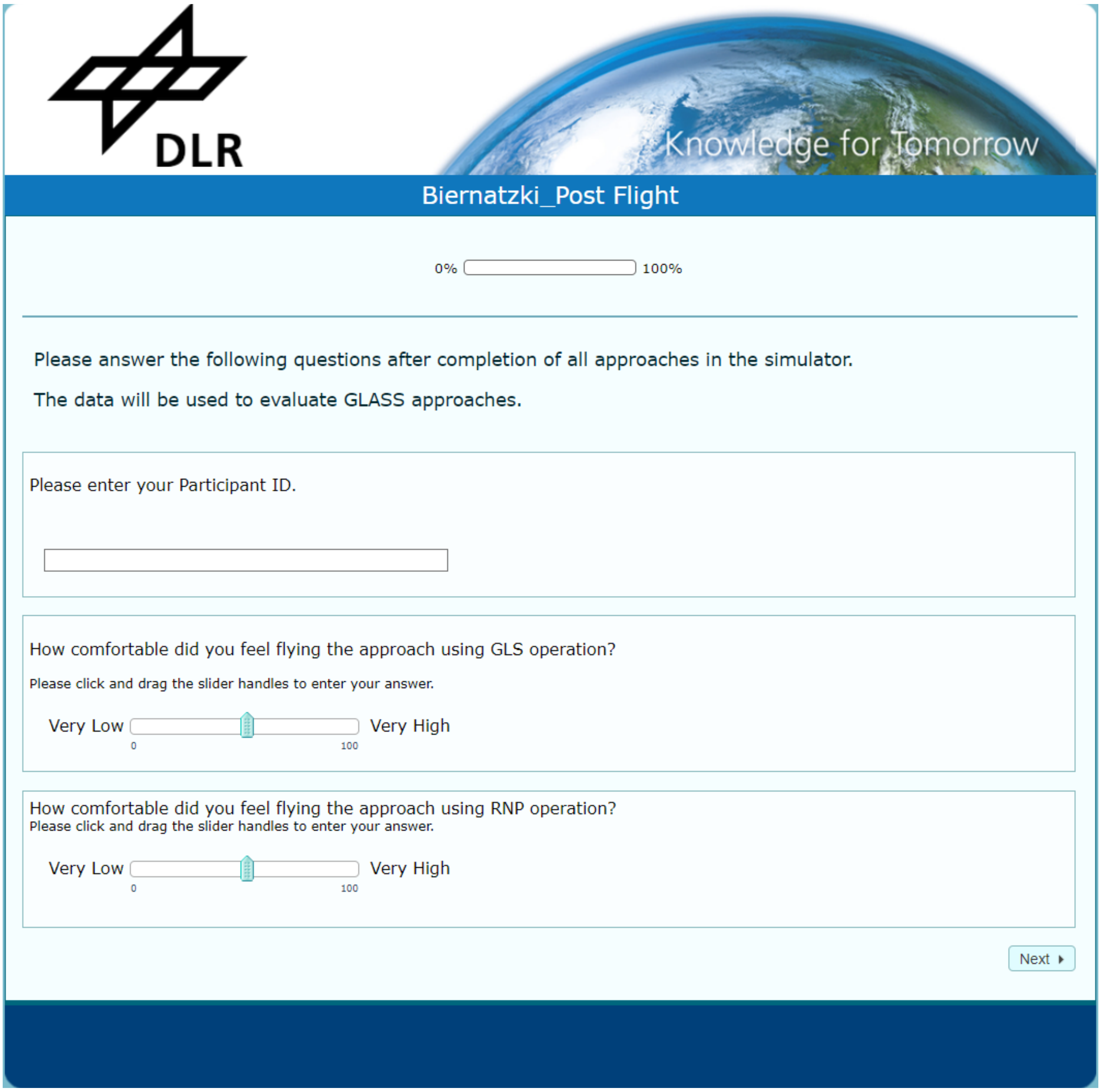
Which approach was flown during the last run?
Choose one of the following answers

○ RNP Approach
○ GLS Approach

What was you assignment?
Choose one of the following answers

○ Pilot Flying
○ Pilot Monitoring

Figure 27 - NASA-TLX questionnaire page 1 of 2. The first page of the NASA-TLX questionnaire shows questions that are required to assign the generated data to the approach type and a participant.



Biernatzki_Post Flight

Please answer the following questions after completion of all approaches in the simulator.

The data will be used to evaluate GLASS approaches.

Please enter your Participant ID.

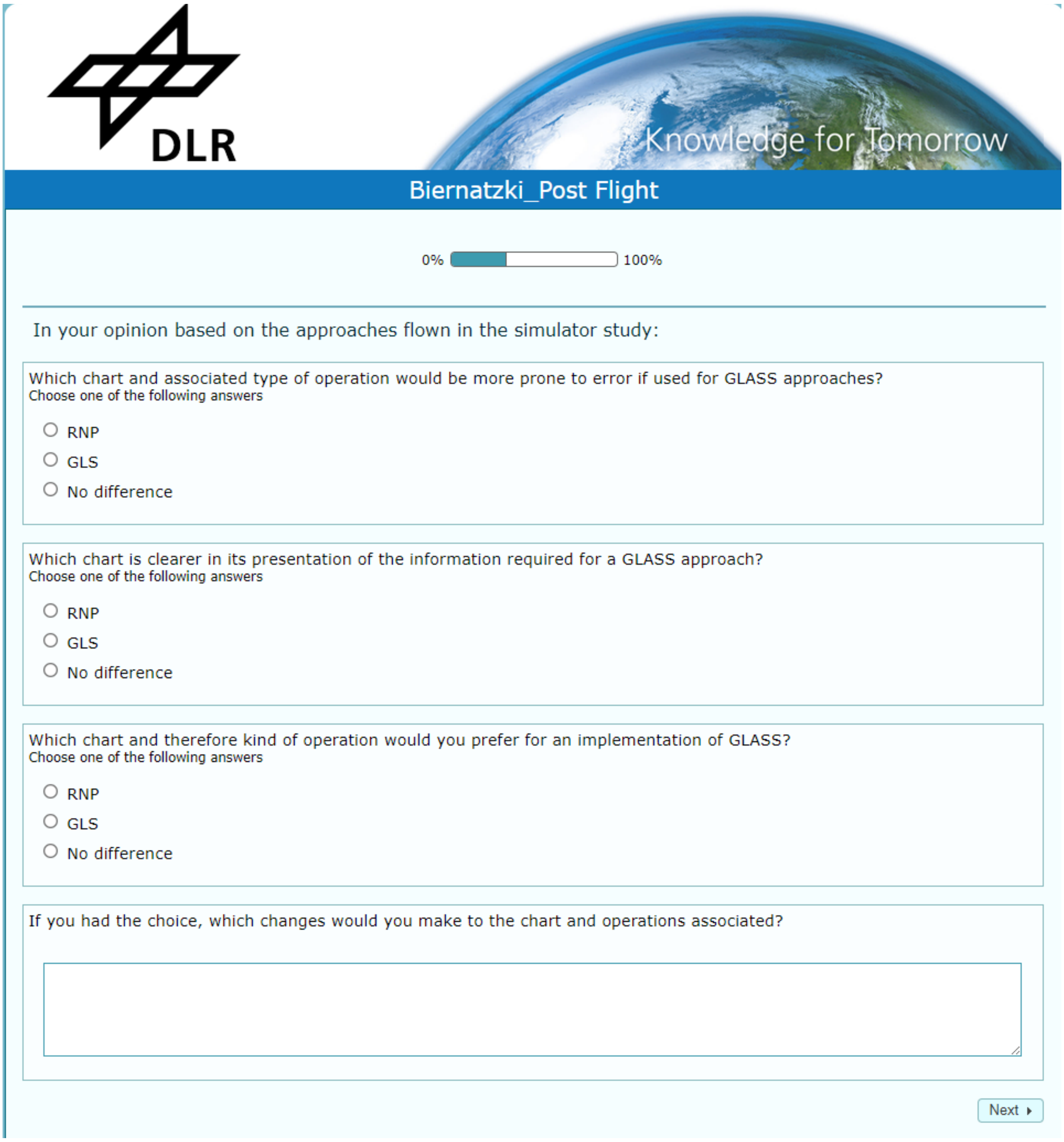
How comfortable did you feel flying the approach using GLS operation?

Please click and drag the slider handles to enter your answer.

How comfortable did you feel flying the approach using RNP operation?

Please click and drag the slider handles to enter your answer.

Figure 28 - Post flight questionnaire page 1 of 3. The first page of the post flight questionnaire asks for the participant ID, that allows assignment of the data to the values of the other questionnaires. Additionally, the participants are asked to slide bars to represent their comfort flying the different variants.



Biernatzki_Post Flight

In your opinion based on the approaches flown in the simulator study:

Which chart and associated type of operation would be more prone to error if used for GLASS approaches?
Choose one of the following answers

○ RNP
○ GLS
○ No difference

Which chart is clearer in its presentation of the information required for a GLASS approach?
Choose one of the following answers

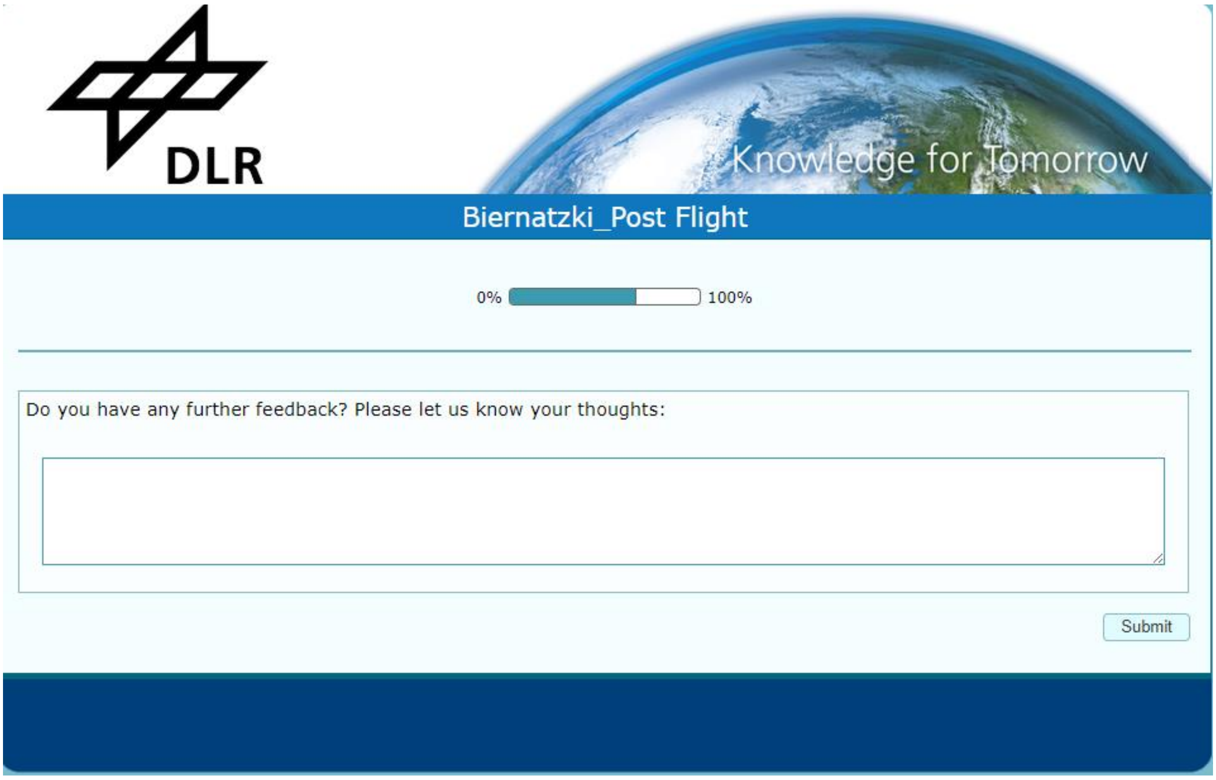
○ RNP
○ GLS
○ No difference

Which chart and therefore kind of operation would you prefer for an implementation of GLASS?
Choose one of the following answers

○ RNP
○ GLS
○ No difference

If you had the choice, which changes would you make to the chart and operations associated?

Figure 29 - Post flight questionnaire page 2 of 3 shows the questions comparing the two variants and offers a field for proposed changes.



Biernatzki_Post Flight

Do you have any further feedback? Please let us know your thoughts:

Figure 30 - Post flight questionnaire page 3 of 3 asks for further feedback in case it was not covered by previous questions.

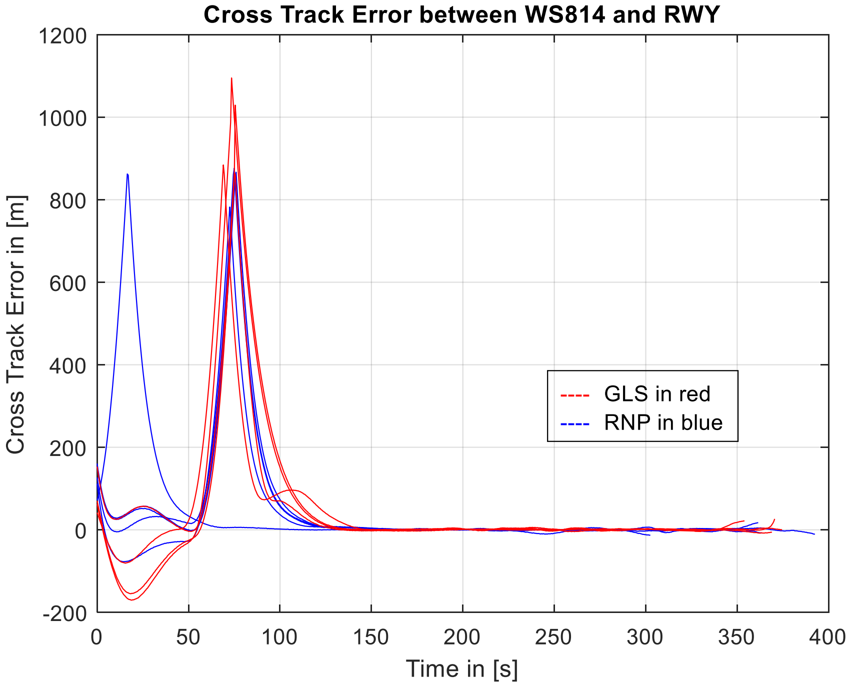


Figure 31 - Cross Track Error for the complete Approach. This overview gives a first impression on the XTE during the approaches. The large deflections are a result of the fly-by waypoint and the early turn.

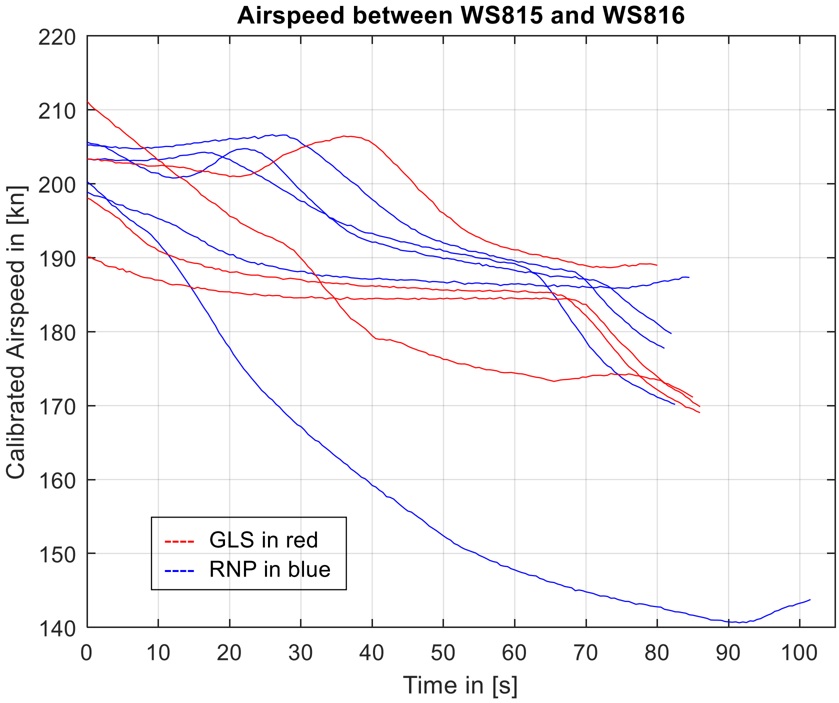


Figure 32 - Airspeed between waypoints WS815 and WS816. While most pilots continued the deceleration towards the end of this segment one pilot decided to configure and slow down early.

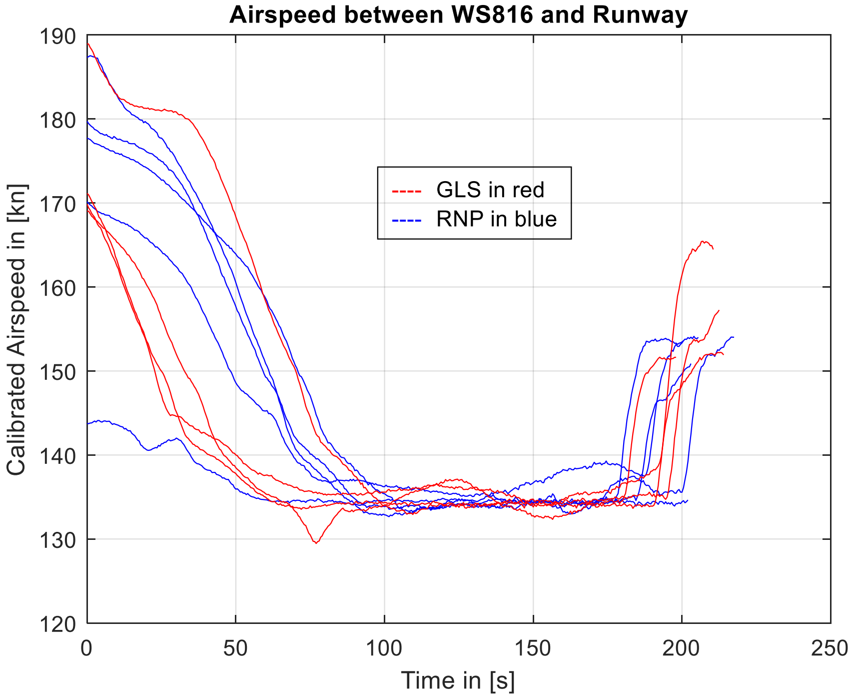


Figure 33 - Airspeed between waypoint WS816 and Runway. During all approaches, the airspeed was reduced during the last leg and kept for about 1 minute at the final approach speed before initiation of the missed approach.

Table 9 - Raw NASA-TLX Questionnaire Results. This table contains all the values the participants submitted with the NASA-TLX questionnaire.

ID	Approach type	Assignment	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration Level
CM2	GLS Approach	Pilot Monitoring	20	20	30	25	20	10
CM2	RNP Approach	Pilot Flying	20	20	25	25	25	15
Cm1	GLS Approach	Pilot Monitoring	25	0	0	10	10	0
CM2	GLS Approach	Pilot Flying	15	15	25	20	25	10
Cm1	RNP Approach	Pilot Flying	30	0	10	20	30	30
CM2	RNP Approach	Pilot Monitoring	20	20	25	20	25	10
CM2	RNP Approach	Pilot Monitoring	20	20	25	20	20	10
Cm1	RNP Approach	Pilot Flying	30	10	15	30	30	20
BCM1	GLS Approach	Pilot Flying	35	57	36	89	35	27
Bcm2	GLS Approach	Pilot Monitoring	12	0	5	17	15	30
CM1B	RNP Approach	Pilot Monitoring	72	66	40	62	55	86
Bcm2	RNP Approach	Pilot Flying	59	7	48	21	55	47
Bcm2	GLS Approach	Pilot Flying	40	4	11	27	37	34
Cm1b	GLS Approach	Pilot Monitoring	31	32	32	85	27	27
Bcm2	RNP Approach	Pilot Monitoring	15	0	10	6	22	27
Cm1b	RNP Approach	Pilot Flying	72	74	47	61	74	76

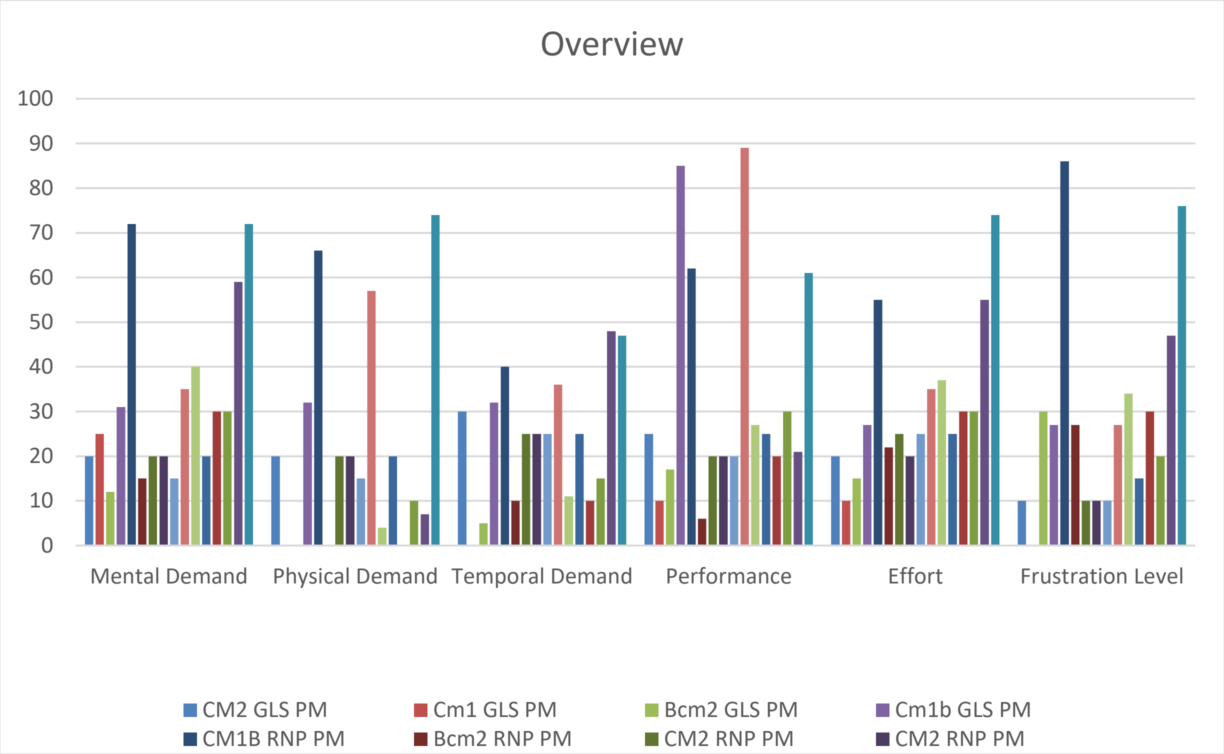


Figure 34 - Overview of all subscales in NASA-TLX questionnaire. Large differences between different participants are visible in this figure.

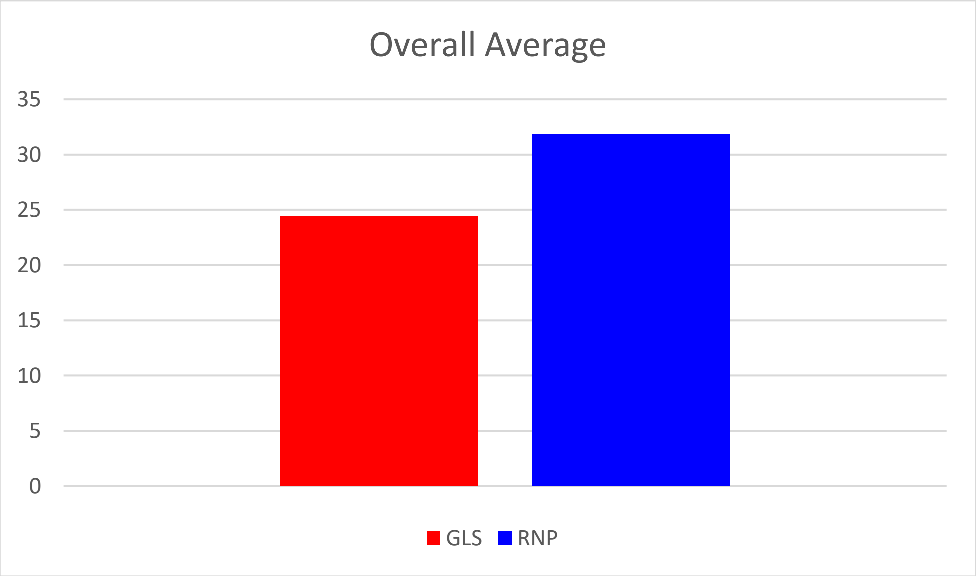


Figure 35 - Overall average of task load comparing GLS and RNP operation. These values only give a first impression of the data. Further analysis has been done by comparing the results of the different variants for the same participant.

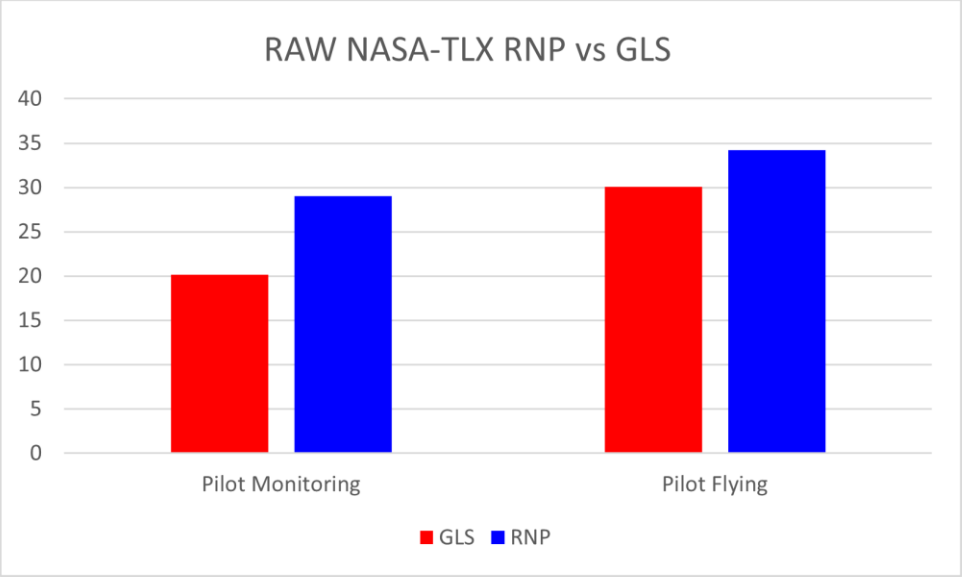


Figure 36 - Average task load retrieved with NASA-TLX for GLS and RNP operation in different functions. Pilot flying as well as pilot monitoring results show a larger workload during RNP operation. Nevertheless, a comparison of the two variants for the same participant gives more detailed results.

Table 10 – Raw NASA-TLX results. Average of all subscales given. Letter A marks the first crew and B the second. Not all results from A CM1 were received.

	GLS	**RNP**
A CM1 PM	8	
A CM1 PF		21
A CM2 PM	21	20
ACM2 PF	18	22
B CM1 PM	39	64
B CM1 PF	26	67
B CM2 PM	13	13
B CM2 PF	26	40