Paper 153

Flight Evaluation Of Advanced Sbas Point-In-Space Helicopter Procedures Facilitating Ifr Access In Difficult Terrain And Dense Airspaces

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Abstract

This paper describes the work performed within the framework of the SESAR2020 project "Enhanced Arrival and Departures" (PJ.01 EAD). The Solution PJ.01-06 within Project PJ01 assessed and validated the benefit of advanced Point in Space (PinS) rotorcraft flight procedures. Advanced PinS, which use curved segments and straight segments in the construction of IFR routes, are key enablers for the simultaneous non-interfering concept, noise abatement approaches, and helicopter access in difficult terrain. Three exercises were conducted to demonstrate and analyze the benefits two different enabling technologies. Exercises one and two integrated a synthetic vision system (SVS), a flight management system (FMS) together with a Helmet-Mounted Display (HMD) supporting manual flight that can increase the safety and reliability of rotorcraft operations through dedicated symbology for specific rotorcraft operations, especially during arrival and departure operations including visual segments. The third exercise used an IFR-certified avionics suite (Helionix®), including a flight management system (FMS) and a 4 axis autopilot to automatically fly an advanced PinS approach with different descent profiles. This paper describes the entire validation process, starting with the design of the PinS procedures for Braunschweig and Donauwörth heliport, the hardware integration of both the helmet-mounted display system and flight management system into DLR's Generic Cockpit Simulator (GECO) and research helicopter ACT/FHS (Active Control Technology / Flying Helicopter Simulator), as well as the implementation of real-time simulation and flight tests at Braunschweig and Donauwörth. The results of these validations and a conclusion based on them are also presented.

ABBREVIATIONS

AFCS	Automatic flight control system
ATTAS	Advanced Technologies Testing Aircraft System
DA/DH	Decision altitude/decision height
EP	Evaluation Pilot
FAF	Final approach fix
FATO	Final approach and take-off area
FMS	Flight management system
FTE	Flight Test Engineer
HDD	Head Down display
HMD	Helmet mounted display
IAF	Initial approach fix
IAS	Indicated airspeed
ICAO	International Civil Aviation Organization
IF	Intermediate fix
IFR / VFR	Instrument/visual flight rules
IMC / VMC	Instrument/visual meteorological conditions
LNAV	Lateral navigation performance
LPV	Localizer performance with vertical guidance
MAPt	Missed approach point
PinS	Point in space
RNP	Required navigation performance

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

RTS	Real-time simulation
RF	Radius to fix
SBAS / GBAS	Satellite / ground based augmentation system
SESAR	Single European Sky ATM Research
SNI	Simultaneous non-interfering
SP	Safety Pilot
SVS	Synthetic vision system
TMA	Terminal maneuvering area

1. INTRODUCTION

In general, rotorcraft flight procedures are designed to allow easier access for flights under instrument flight rules (IFR) to FATOs that require visual flight rules (VFR), in particular when weather conditions are adverse. Advanced (e.g. curved) SBAS/GBAS guided Point-in-Space RNP approaches towards landing locations and Point-in-Space departures from landing locations are created with connections to/from a Low Level IFR route network. The curved segment of the advanced PinS can be placed in the initial, intermediate or missed approach segment[1]. The procedures can contribute to a reduced noise footprint and improved access to VFR FATOs. There is also a contribution to safety (fewer VFR approaches in marginal visual meteorological conditions (VMC), IFR approaches with vertical guidance). This also enables the implementation of Simultaneous Non-Interfering (SNI) operations at VFR FATOs located at airports.

This SESAR2020 solution should impact the following Key Performance Areas (KPA):

- Safety under manual flight should be improved thanks to the use of an HMD during PinS operations facilitating the VFR-to-IFR transitions during take-off and IFR-to-VFR transitions during approach, which are usually high-workload phases for the rotorcraft pilot, and through the introduction of GNSS contingency loss procedures (in particular in the final curved approach of a PinS procedure where the pilot shall maintain safe separation during visual segment)
- Safety in auto flight by automatic tracking of the lateral and vertical deviations.
- Human performance should be improved thanks to the use of an HMD during PinS and SNI operations (pilot's eyes-out conformal display of the flight trajectory allows improved performance to follow precisely the allocated trajectory) and full 4-axis autopilot coupling on the entire approach procedure.
- Operational efficiency should also take benefit from the HMD use (optimization of flight efficiency reducing delays)

Access and equity for rotorcraft users to TMA and busy airfields should be improved by facilitating the use of PinS for SNI procedures.

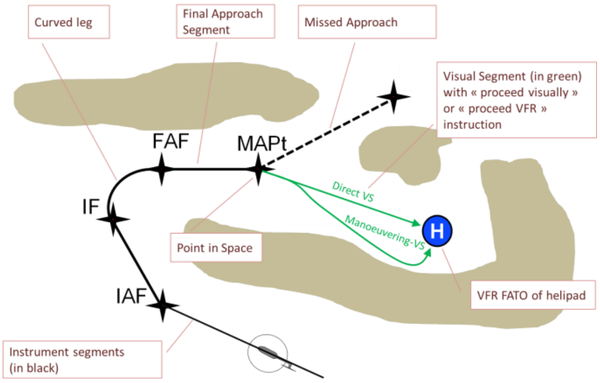

Figure 1: Advanced PinS approach example

A PinS approach (Figure 1) is an instrument procedure based on the RNP navigation specification (ICAO Doc 9613, Ed 4[2]), flown to a PinS (the Missed Approach Point (MAPt)). It may be published with Lateral Navigation (LNAV) minima or Localizer Performance with Vertical Guidance (LPV) minima, as documented in Procedures for Air Navigation Services – Aircraft Operations (PANS OPS) ICAO Doc 8168[1]. The PinS approach procedure includes either a “proceed visually” instruction or a “proceed VFR” instruction from the MAPt to the heliport or landing location. Any visual flight maneuver beyond the MAPt (i.e. in the visual segment) has to be assumed with adequate visual conditions to see and avoid obstacles. PinS IFR approaches are adapted to helicopter operations (i.e. limited airspeed down to 70kts, high descent and climb gradient capabilities). PinS IFR approaches may be developed for heliports that do not support the design standards as defined by ICAO Annex 14[3] for an IFR heliport. These approaches may require some design flexibility, like: a turn before the Final Approach Fix (FAF), a Radius to Fix (RF) leg, a turning missed approach (Figure 1). According to ICAP PANS-OPS 8168 Vol 2[1] the

SBAS approach procedure can contain a RF leg ending at the FAF.

2. VALIDATION EXERCISES

Conducted between June and December 2018, simulations and flight trials at Braunschweig lasted for over 10 hours in total with pilots flying a helicopter equipped with a SVS, an HMD, coupled to the FMS, and further hardware equipment necessary for generating the symbology for both the HMD and the SVS. Separately at Airbus Helicopters facilities in Donauwörth, flight trials with curved and steep approaches were performed with a 4-axis autopilot coupling to achieve a high degree of automation and thereby significant crew workload reduction in approach and departure phases. During these trials, the pilots assessed and validated the benefit of integrating such vision systems and advanced autopilot modes to support the pilots and by this, increase the safety and reliability of rotorcraft operations. The pilots also evaluated the benefit of having SBAS navigation for advanced PinS RNP 0.3/LPV approaches and departures to and from the FATO area.

2.1. Real Time Simulation

The first exercise was a real time simulation study in the generic cockpit simulator (GECO) prior to the flight tests. The exercise has to ensure the functional verification of the hardware in use for the flight test and deliver additional objective and subjective results that cannot be covered in the flight test. The structured multivariate testing will use a helmed-mounted device for advanced PinS approaches at Braunschweig (EDVE) under single pilot manual flight. As an outcome the flight technical error and subjective rating will provide evidence of the usability of the concept.

2.1.1 Platform description

The platform that will be used for the Real Time Simulation (RTS) is called GECO (Generic Cockpit Simulator) and is a modular cockpit simulator with flight-mechanical models of the DLR test aircraft ATTAS. The flight-mechanical models are interchangeable, depending on the application required. The GECO can also be converted into a helicopter simulator and will be used in that configuration for the RTS.

The GECO is particularly used to conduct simulations with human test subjects in order to evaluate new display and control concepts. Research also focuses on the development and evaluation of innovative operational procedures that can be applied in the future using new technologies. Examples include systems for the GPS-based determination of position, maneuvering area lighting, air-ground communication, collision detection and avoidance as well as new sensors.

The outside view is simulated using three high-resolution projectors that project an image on a mirror system with a 6-meter diameter (Figure 2). This allows an area of 180° by 40° to be displayed, giving a realistic perception of depth (collimated visual system). To simulate the outside view, the flight simulator X-Plane is used, which enables the detailed 3D modeling of the surrounding area. X-Plane also provides the helicopter flight model of an EC135 for the exercise.

Figure 2: Generic Cockpit Simulator GECO in helicopter configuration at DLR Braunschweig

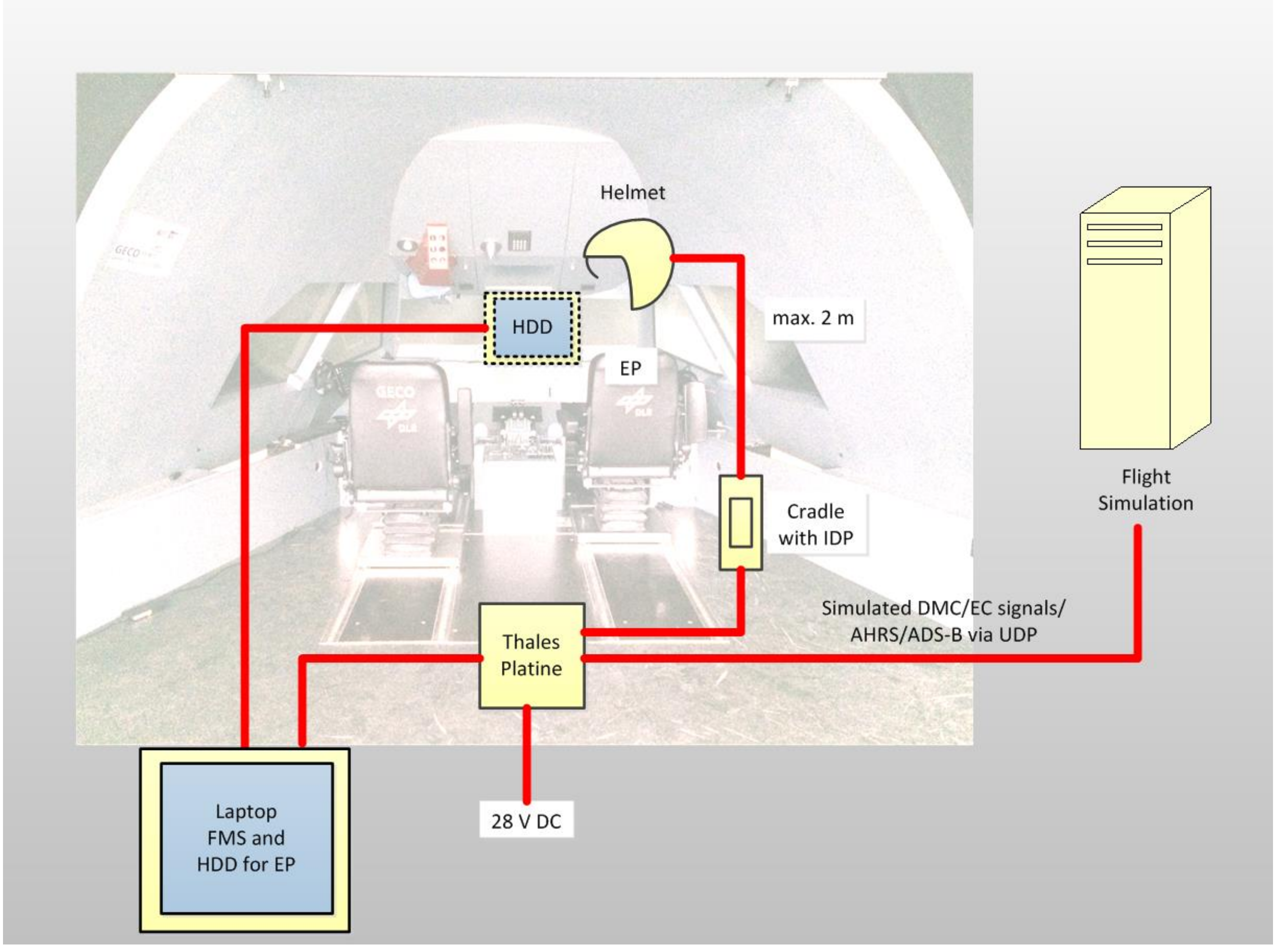

Figure 3: Overview of the different hardware components inside the Generic Cockpit Simulator

The RTS validation used the same approved hardware components as was used in the research helicopter. These are essentially a Flight Management System implemented on a laptop providing the Advanced PinS procedure in ARINC 424 (Type 20) format, an HDD symbology used as a primary and navigation display for the presentation of the entire flight path, as well as the TopEagle HMD including the necessary hardware for data processing (Figure 3). All flight data will be provided by an X-Plane flight simulator in real time. The data are transferred via a UDP interface to the THALES hardware.

2.1.2 Scenario design

The scenario is designed to introduce minimum turn radius as RF-legs to a minimum pattern length. It includes a departure and approach phase at a size close to the standard (noise abatement) VFR traffic circuit at Braunschweig airport (Figure 4).

The Real Time Simulation was a multi pilot multivariate study. Variations planned were wind conditions from nominal to moderate limits, day/night condition, different precipitation levels (overcast altitudes) either leading to DH Minima for visually approach and one abnormal condition leading to a missed approach (go around).

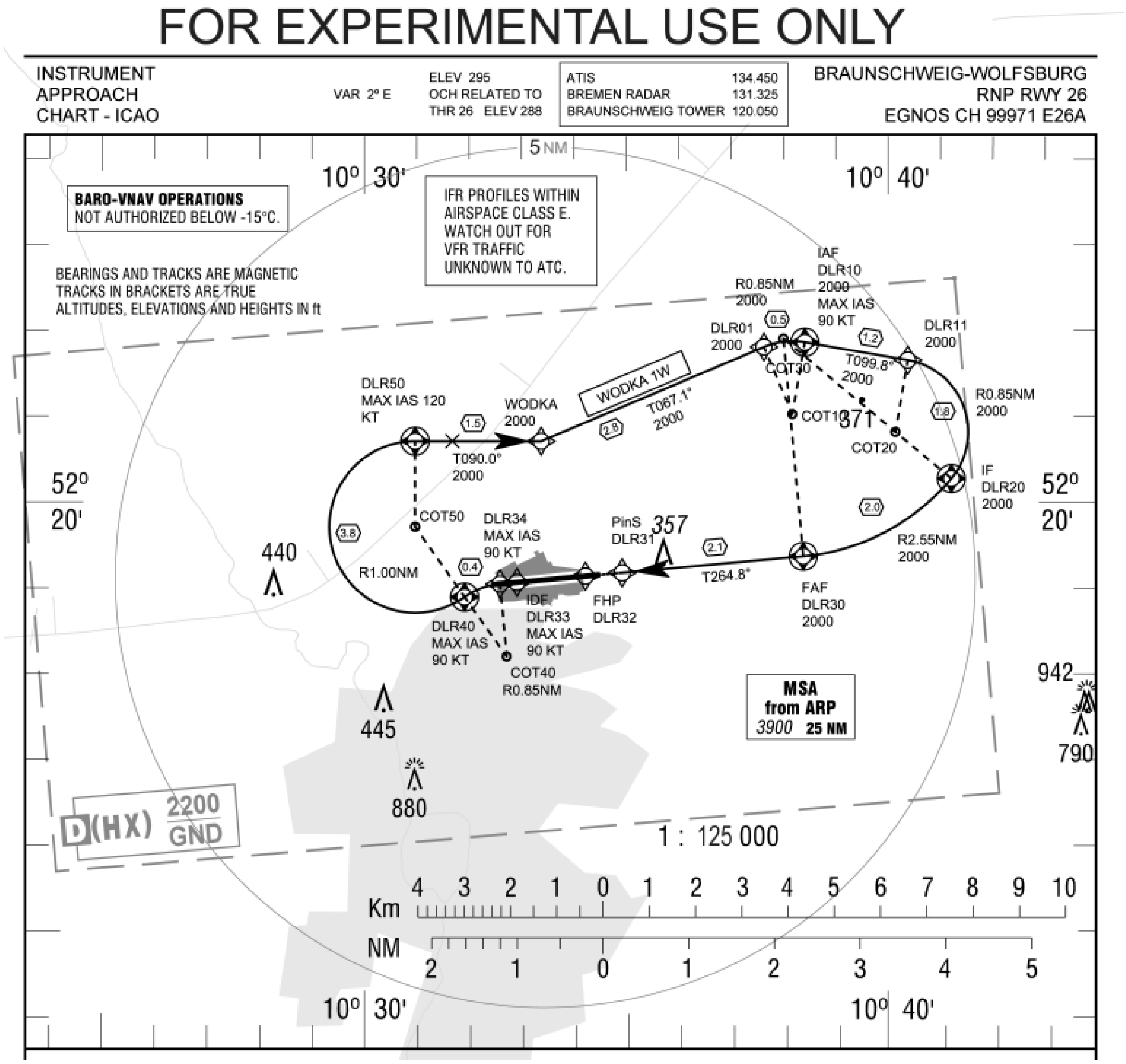

Figure 4: Advanced PinS procedure at EDVE for the RTS exercise

The HMD is particularly interesting in phases of flight including a VFR/IFR transition, i.e. departures and arrivals phases due to its ability to superimpose IFR guidance cues with external visual references. But HMD can also be interesting during cruise phases relatively closed to the ground, especially in mountainous area, for its ability to display simultaneously IFR guidance cues with a Synthetic and/or an Enhanced Vision System on an almost 360° view, thus enhancing considerably the pilot's situational awareness.

3 different solutions have been evaluated during this exercise:

- The CDI solution, based on a Head Down display of the usual Course Deviation Indicators in the shape of a lateral deviation scale as well as a vertical deviation scale, both on the PFD and associating with the flight plan display superimposed with a 2D moving map view.
- The Flight Director solution, based on the display in the HMD of a fully conformal advanced Flight Director 2D symbol, including anticipation features specifically designed for advanced PinS procedures.
- The 3D Pathway solution, based on the display in the HMD of a fully conformal 3D view of the route to fly, including altitude constraints and lateral limits.

Before the experiment each of the four pilots was briefed about his responsibilities and rights that was acknowledged by his signature to the consent form. After this step the pilot filled in a short biographical questionnaire. During the experiment all remarks from the pilot that were relevant for the task were noted in the playbook. The playbook was also used by the experimenter to write down special events with time and impact on the run.

2.2. Flight Trials at EDVE (Braunschweig)

This validation exercise is composed of a set of flight tests performed on the DLR EC135 rotorcraft, flying different IFR Advanced Point-in-Space (PinS) procedures (departures and approaches) designed around Braunschweig airport. The helicopter standard avionics suite will be completed by a set of equipment provided by Thales:

- a Head Mounted Display system, presenting symbology adapted to the intended function (fly on PinS procedures);
- a Flight Management System containing the PinS procedure being flown, managing the RNP0.3 constraint, and generating the flight plan;
- a Navigation Display Application generating the head-down Navigation Display image containing the flight plan, displayed on an existing 10 inches display already installed on-board the rotorcraft.

During these flight tests, the following items were evaluated:

- the capability to fly manually these advanced PinS procedures using a single pilot IFR helicopter equipped with an HMD, under normal conditions,
- the associated navigation performance,
- human factors and crew workload aspects.

2.2.1 Platform description

The ACT/FHS 'Flying Helicopter Simulator' of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) is based on a standard Eurocopter EC 135 type helicopter, which has been extensively modified for use as a research and test aircraft (Figure 5). The mechanical controls, for example, have been replaced by a fly-by-wire/fly-by-light (FBW/FBL) flight control system. Now the control commands are transferred by electric cables and fibre optic cables instead of control rods.

The application portfolio of the FHS covers pilot training, trials of new open and closed-loop control systems, up to simulation of the flight characteristics of other helicopters under real environmental conditions. The FHS is equipped with two engines, a bearingless main rotor and a Fenestron tail rotor as standard; its key features are notably quiet operation and high manoeuvrability and safety.

The fly-by-light control system is a groundbreaking new system where, in contrast with fly-by-wire, the control signals between the controls, the flight management computer and the actuators for rotor blade control are transferred optically via fibre optic cables instead of electrically.

The advantages compared with electrical data transfer are the high transmission bandwidth, high reliability and low weight. The fly-by-light flight control system consists of a quadruple redundant computer and is designed such that the stringent safety criteria of the European aviation authorities are met in full.

The following modifications differentiate FHS from the standard Eurocopter EC 135 helicopter:

- Optical and electronic FBW/FBL flight control system.
- On-board computer system that enables simulation of the flight characteristics of other - real (existing) or virtual - aircraft. In this way, it provides important information for the operational assessment of a helicopter at an early stage of its development. These capabilities are also used in basic research into flight characteristics.

Modular experimental system: The system consists of flight-control computers, data measurement and pre-processing systems, displays and additional equipment and controls in the cockpit. The system also includes a data analysis station and a simulator for test preparation.

Figure 5: DLR's research helicopter ACT/FHS

The Experimental System consists of three computer systems: Data Management Computer (DMC), Experiment Computer (EC), and Graphics Computer (GC). The DMC is responsible for the standard services. It acquires data from all base sensors, all additional non experimental sensors and other systems. It distributes configurable data sets to selected systems such as EC, GC etc. The DMC stores pre-selected data, either continuously or on demand. Analogously pre-selected data is sent to the ground via telemetry. The DMC also handles the user interface via the control and display units of the evaluation pilot (EP) and the flight test engineer (FTE). The DMC operates with a cycle time of 2ms, i.e., the highest data acquisition rate is 500Hz.

The EC operates the interface with the FHS core system. It receives the pilot inputs, actuator positions and status data, and transfers this information to the experimental applications. One of these applications generates the actuator commands, which are sent back to the core system. Additionally, experimental hardware, such as sensors or side sticks, is connected to the EC.

The system software on the EC provides a layer of basic services, e.g., access to signals, transfer of generated data, access to devices connected to the EC, usage of the control and display units, application timing, etc. Above this layer the system is available for the experimental applications, i.e., the customer software. The EC operates with 500Hz; this is the core system transmission frequency. The start of experimental application cycles can be triggered by the arrival of core system data to minimize the latency for controller applications.

The DMC and the EC are VME-bus based systems using the VxWorks operating system. The function of the EC is extended by the Experiment Co-Computer (ECC) which is a Windows based PC, connected to the EC via Ethernet. It is available for non-real-time applications, e.g., long term guidance or map displays.

The cockpit layout (Figure 6) provides seats for a safety pilot (SP), the evaluation pilot (EP) and the flight test engineer (FTE). A comprehensive equipment line-up with sensors and systems for onboard data recording and processing is used to record the data from the flight tests. This data is available to users and engineers for analysis both on board and - via telemetry - on the ground. Due to the fact that the DMC does not know anything about the planned flight path, a second data recording function has been implemented on the laptop computer in order to calculate and record the e.g. cross track error in real time.

During flight, the THALES platine will get the flight status data from DMC and EC, as well as from AHRS-2. For getting information about the aircraft traffic around the helicopter, the ADS-B receiver mounted on the platine is connected to the ADS-B antenna of the helicopter. The SBAS position data will be provided by the DMC as well.

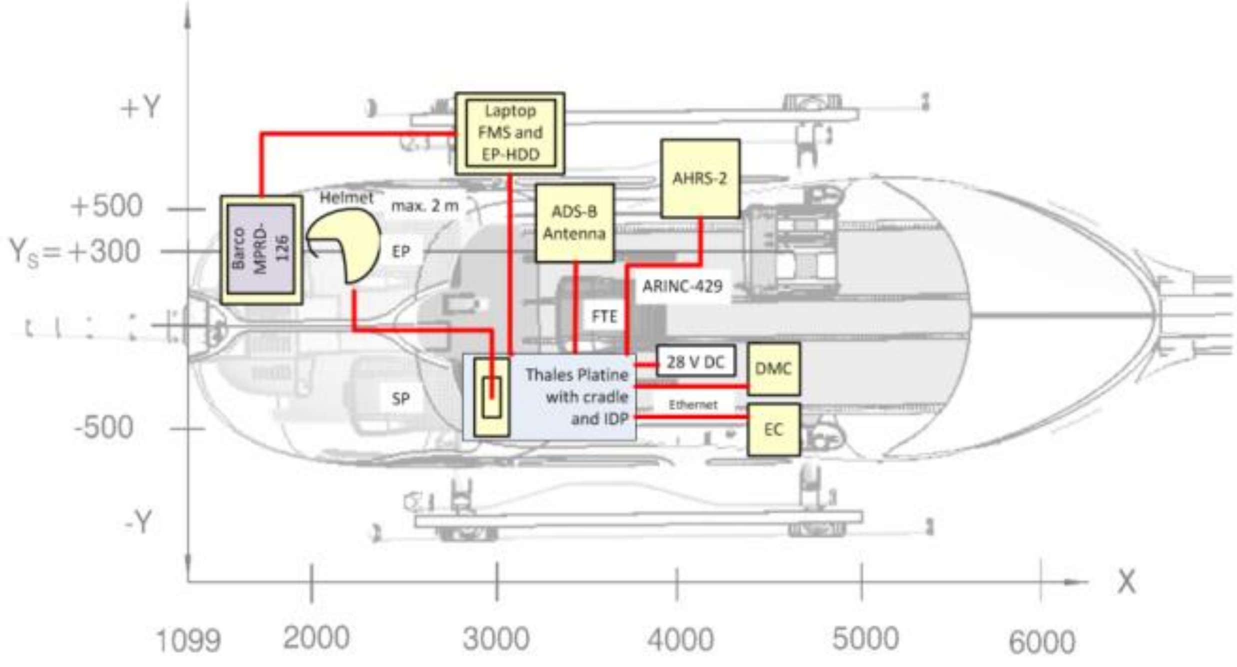

Figure 6: Overview of the different hardware components inside the helicopter

The dashed box in Figure 7 also covers the additional hardware equipment provided by THALES for using during both the real time simulation and flight trials in Braunschweig. The blue boxes represent the sensor systems available on board the research helicopter. Most of the sensor data are acquired by the Data Management Computer (SBAS, ADS-Data) and will be transferred to the Interface Display Processor (IDP) via UDP. To obtain the lowest possible latency for the acquisition of the attitude and heading information of the helicopter, the IDP is directly connected to the AHRS-2 sensor system via ARINC 429 and 705.

The laptop onboard the helicopter will provide both the Flight Management System and the symbology of the Head Down Display. The HDD will also be presented on the console display of the flight test engineer. In contrast to the GECO simulator, only a navigation display will be presented for the evaluation pilot during flight due to a limited size and resolution of the Head Down display. For data analysis especially to investigate the accuracy of flight path performances, high precision flight status data will be recorded during flight using Honeywell IRS/GPS H764.

The Interface Display Processer (IDP) will provide the symbology to the helmet mounted display. In order to give the pilot information about the traffic around the helicopter, an ADS-B receiver is also part of the Thales System. The ADS-B traffic will be presented with dedicated symbols on the HMD.

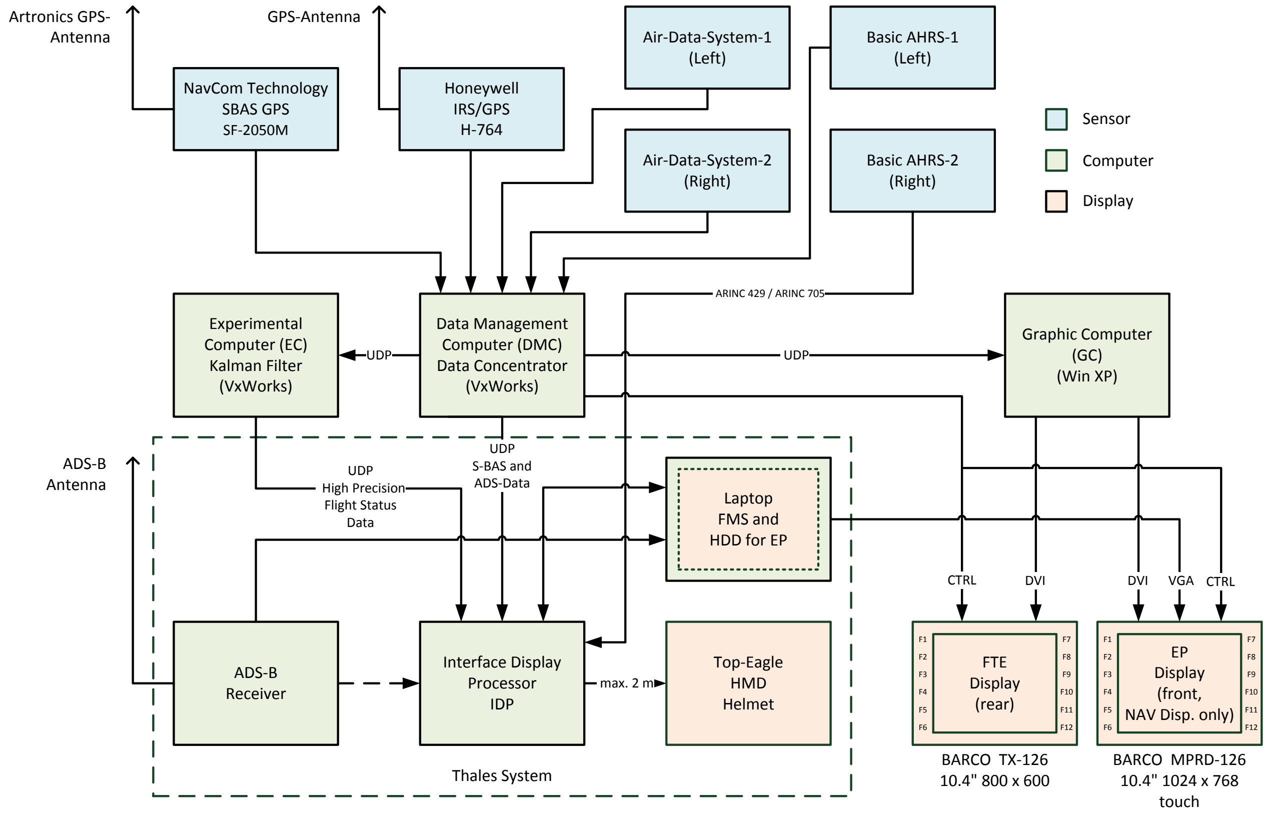

Figure 7: Hardware architecture of the different components inside the research helicopter

These are essentially a Flight Management System implemented on a laptop providing the Advanced PinS procedure in ARINC 424 (Type 20) format, an HDD symbology used as a navigation display for the presentation of the entire flight path, as well as the TopEagle HMD including the necessary hardware (cradle with IDP) for data processing. All flight data will be provided by the data management computer (DMC). The data are transferred via a UDP interface to the THALES hardware (platine).

2.2.2 Scenario design

The flight tests are performed with multiple approaches and departures along an IFR Advanced Point-in-Space (PinS) procedure around Braunschweig airport, and supported by Thales equipment including head mounted display system, flight management system and a navigation display application. The approach procedure and intended use of HMD is exactly as described in chapter 2.1 and therefore not repeated here for brevity.

The presented display conditions were limited to Flight Director and the 3D Pathway because the CDI only condition already proved to not allow flying the pattern.

The subjective questionnaires used were identical with the ones used in the real-time simulation, as well as the flight data recording process.

The pilots were formally briefed before flight. A video of the display content and the pattern to fly was presented and all elements of the display were explained. Since most of the pilots participated in the real-time simulation this part was rather short. They were given in-between standardized workload and situation awareness ratings after each pattern. The pilots filled-in a de-briefing questionnaire and were formally de-briefed. Additionally there was a round-table discussion after each block.

2.3. Flight Trials at EDPR (Donauwörth)

The third validation exercise was a flight trial performed by Airbus Helicopters using a serial helicopter equipped with Helionix® avionics suite in Donauwörth. The scope of this exercise was to design a proprietary advanced PinS approach, insert the experimental procedure in the on-board flight management system and demonstrate the feasibility to fly this approach in a real operational scenario. The objectives were to assess navigation performance and pilot workload during such PinS approaches, using HDD in nominal and abnormal conditions, with and without AFCS coupling.

2.3.1 Platform description

An experimental BK117 D-2 prototype and an experimental EC-135 prototype, both owned by Airbus Helicopters and holding EASA civil type certificates, have been used in the flight trials. A representative image is shown in Figure 8. Both helicopters are certified for VFR day and night operations, as well as IFR CAT A operation. Both helicopters are used worldwide in a variety of missions, including emergency medical services, police and parapublic missions, and passenger transport. The Helionix® avionics suite, shown in Figure 9, is installed in the latest generation of both aircraft. Helionix® comprises of an integrated module avionics (IMA) architecture with a dual duplex four-axis autopilot, intelligent flight monitoring functions and enhanced external situation awareness features including digital moving map (DMAP), Helicopter Terrain Avoidance and Warning System (HTAWS) and a Synthetic Vision System (SVS). It is also equipped with a dual-FMS configuration and a Traffic Advisory System. All functions are integrated in a unique cockpit display concept, which contributes to ease of piloting in both IFR and VFR. Further descriptions of these avionics functions are found in Ref. [4].

Figure 8: EC-135 Helicopter

The cockpit layout provides seats for the test pilot, safety pilot, and the flight test engineer. The pilot side MFD displays flight and navigation information as shown in Figure 10. It includes a synthetic vision display including obstacles, terrain, ground vector indication, heliport identifier and helipad display behind the primary information as a pilot assistance function.

Figure 9: Helionix Cockpit in BK117 D-2 and EC-135

The FMS stores the navigation database, including the PinS approach used for experimental purposes. When a procedure is loaded and coupled to the AFCS, the FMS transmits the flight plan and appropriate steering commands based on the lateral path deviations. In a 3D final approach, the final approach segment datablock is also transmitted by the FMS. FMS commands are executed by the AFCS and constantly monitored by the pilot on the primary flight display format (see Figure 10) and the navigation display format (see Figure 11). At or before the MAPt, the pilot takes over controls and proceeds VFR to land on the heliport. For data recording purposes, the experimental platform consists of a standard flight test instrumentation (FTI) which acquires data from the onboard systems and equipment for post-flight analysis. All data required for assessing navigation performance, namely lateral and vertical deviations, present position (latitude, longitude, altitude), speeds, are recorded. Additionally, the data recording also includes video streams of the HDD multi-function displays to study pilot actions in the cockpit.

Figure 10: Primary flight display during final approach

2.3.2 Scenario design

The scenario for flight trials is an experimental approach procedure including multiple RF legs in the initial and intermediate approach segments. The consecutive RF legs also result in a turn direction reversal at the connecting waypoints. The final RF leg terminates directly to the final approach segment at the final approach fix. The final approach is flown down to the LPV minima at 6.30° glidepath. The approach procedure is depicted in Figure 12.

Within this scenario, different approach profiles, in terms of altitude, airspeed, and autopilot coupling were defined for the flight trials. The maximum airspeed is restricted to 100 knots IAS in the initial and intermediate segments, and 70 knots IAS in the final approach segment. The pilot flies in simulated IMC conditions, in which out of cockpit visibility is restricted by a dark film on the pilot's visor.

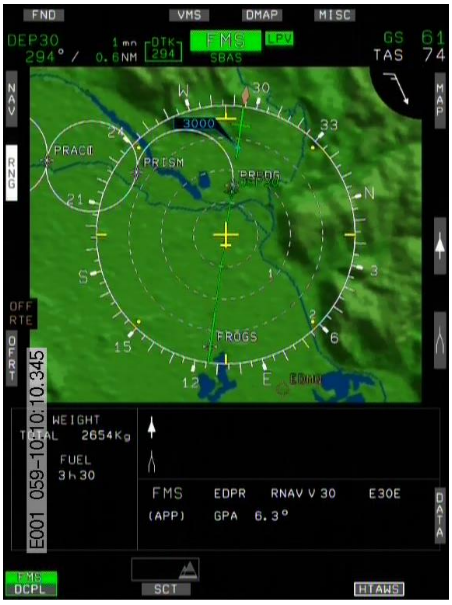

Figure 11: Navigation display during final approach

Nominal Scenario (N1) "Level-off approach": In N1, the lateral flight plan is coupled and executed by the AFCS during the complete approach. All flight legs between IF (PRULI) and FAF (FROGS) are flown at a constant altitude of 3000ft. by engaging altitude hold mode. Airspeed is adapted by the pilot using rotary knobs on the control panel to decelerate from 100 knots to 70 knots IAS at FROGS. The glidepath is captured at FAF resulting in a 3D final approach guidance (lateral and vertical flight path coupling) until the LPV minima are reached.

Nominal Scenario (N2) "Continuous descent in flight path angle mode": N2 is similar to N1, except that the altitude at IF (PRULI) is 6400 ft, which corresponds to a 6,3° slope from FAF (FROGS) using the along track distance. Using the flight path angle knob, the pilot attempts to remain in the vicinity of 6,3° between PRULI and FROGS, with the objective of reaching FROGS at 3000 ft. for successful glidepath capture. Airspeed is adapted by the pilot using rotary knobs on the control panel to decelerate from 100 knots to 70 knots IAS at FROGS.

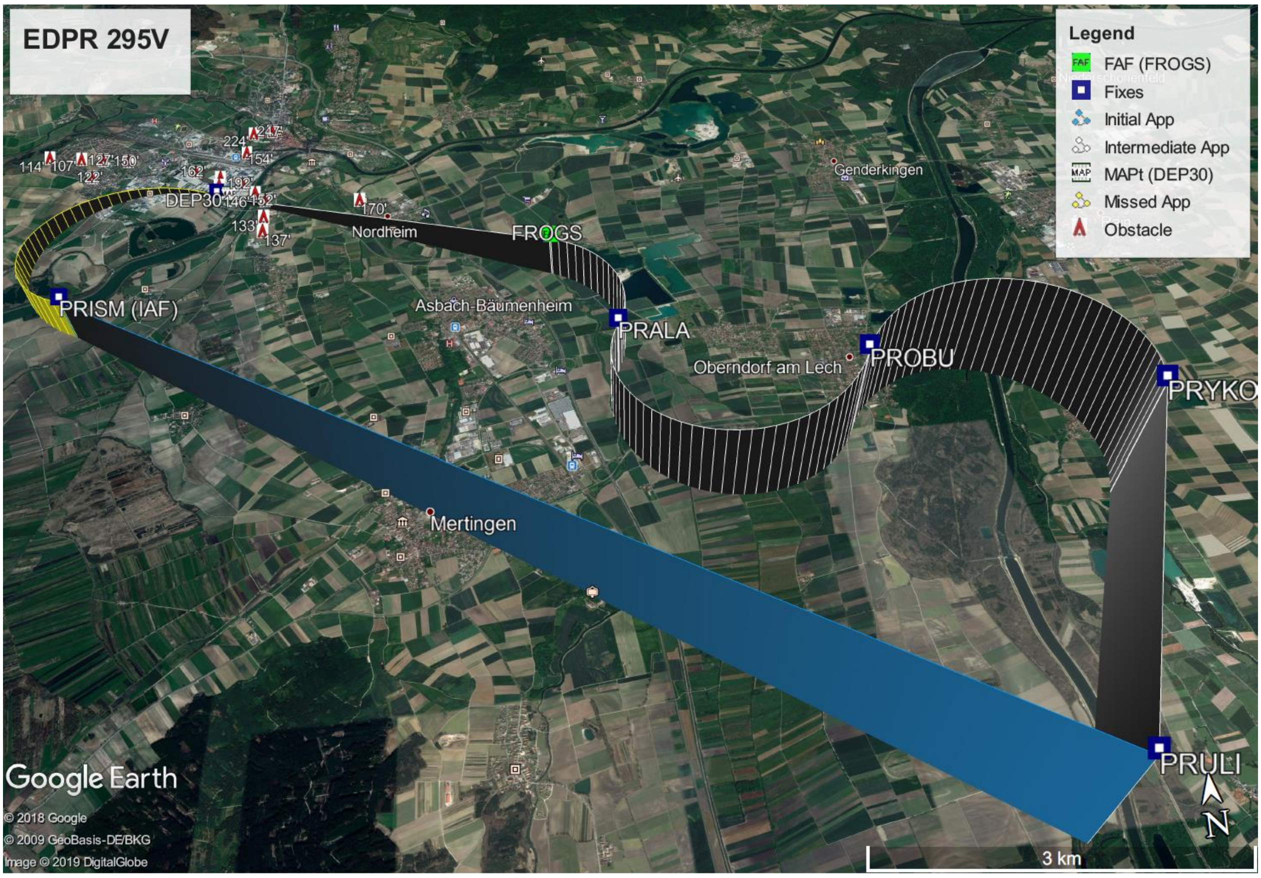

Figure 12: Advanced PinS procedure at EDPR (Donauwörth) for the flight trial exercise

Nominal Scenario (N3) "Continuous descent in vertical speed mode": N3 is similar to N2, the key difference lying in the vertical mode. The altitude at IF (PRULI) is 5700 ft., which corresponds to 800 fpm climb from FAF (FROGS) using the along track distance, at reference speed and in calm air. Using the vertical speed knob, the pilot attempts to adapt vertical speed between PRULI and FROGS depending on wind conditions, with the objective of reaching FROGS at 3000 ft. for successful glidepath capture. Airspeed is controlled as in N2.

Failure Scenario (F1) "3-axis autopilot": F1 investigates the ability to execute continuous descent RF legs with manual control of the vertical axis. It represents a vertical axis failure, or installation of 3-axis autopilots which is true of many helicopters. The reference descent profile is similar to N2, i.e. 6.3° descent from IF (PRULI) 6400 ft. While flight path angle mode is engaged, the pilot is hands-on on the collective stick and uses it to decelerate from 100 knots to 70 knots IAS at FROGS.

Failure Scenario (F2) "No autopilot or loss of autopilot modes during level-off approach": in F2, the approach procedure is flown hands-on on all axes with only a backup SAS operating on standby instruments (IESI). It represents either all-axes autopilot failure, or the absence of autopilot coupling modes on a helicopter. The lateral and vertical path profiles are similar to N1. The task of the pilot is to remain close to the reference lateral and vertical paths, and attempt to capture the glidepath at FROGS.

Failure Scenario (F3) "No autopilot or loss of autopilot modes during continuous descent approach": F3 is similar to F2, except that all flight legs, including RF legs before FAF are flown at a reference 6,3° flight path angle, starting from 6400ft. at PRULI. Only backup SAS is operational as in F2. The task is to maintain lateral paths and to reach 3000 ft. at FROGS followed by a capture of the glidepath at FROGS.

Failure Scenario (F4) "SBAS downgrade to GPS": This case simulates a downgrade of SBAS to GPS during RF legs, just before the FAF. The downgrade does not permit approach to LPV minima, and the pilot has to revert to either LNAV or LNAV/VNAV minima.

For subjective workload analyses in each scenario, the test pilots had to fill out questionnaires after each run.

3. RESULTS OF VALIDATION EXERCISES

3.1. Results of Real Time Simulation

All results gathered during this exercise, recorded flight data, NASA TLX data and pilot's questionnaires, show that the advanced PinS procedure designed for this exercise is manually flyable and reliable with both solutions proposed: advanced flight director display in the HMD; and 3D route display in the HMD. Both solutions have a positive impact on the pilot's workload compared to the reference Head Down solution. No safety issues have been identified. Both solutions show more or less an equivalent level of performance in this exercise.

It was also shown with SART data and pilot questionnaires that the SVS system designed for this exercise increased the situation awareness with both solutions

The following bullet items summarize the main results:

- Lateral flight path performance varies between pilots and display variants
- Lateral flight performance with Flight Director and 3D Pathway guidance is always within RNP0.1
- However it is still possible to fly the Advanced PinS procedure with lateral CDI only guidance within the prescribed RNP0.3 limits
- Lateral deviations of CDI only are similar between different pilots and are related to the dynamic of displayed deviation and the resulting (over-) correction of the pilot
- CDI only guidance should only be used for straight route segments
- Pilots are not used to fly climbs with vertical guidance
- Flight Director and 3D Pathway provide sufficient support to fly procedures with advanced lateral and vertical profile
- Straight descent segments with lateral guidance are common procedures for helicopter pilots

3.2. Results of EDVE (Braunschweig) flight trials

5 test pilots participated to the flight trials. Due to missing weather minima during one day, the flight records of one pilot could not be used in the analysis but its subjective questionnaires did. A mix of VMC and simulated IMC (enabled by an opaque visor) conditions were experimented with alternatively both symbology guidance solutions, the 3D pathway and the advanced Flight Director.

The results gathered during this exercise, recorded flight data, NASA TLX data and pilot's questionnaires, show that the advanced PinS procedure designed for this exercise is manually flyable and reliable with both solutions proposed, the advanced flight director display in the HMD and the 3D route display in the HMD. Even if an integration issue on the pilot's head tracking system has decreased the system's performances, no safety issues have been identified. The advanced flight director solution has shown a slight advantage on the trajectory flight precision and a slight decrease of the workload compared to the 3D route display solution.

The following bullet items summarize the main results:

- Lateral flight performance with Flight Director is always within RNP0.1 for 4 pilots. The off-track situation can be attributed to the head tracker issue;
- Vertical guidance should be improved to allow a departure phase that fits with the R/C best climb rate performance.
- Pilot's workload is higher with the 3D pathway solution, especially under IMC conditions.
- The HMD allows pilots to remain eyes-out during both VMC and IMC conditions.
- No strong discomforts induced by the HMD have been notified even if some improvement needs have been identified.
- The operability of the advanced PinS could be demonstrated
- It proved to be technically feasible
- The pilots were able to fly the pattern in a reliable manner

Full results aren't disclosed in this article because of the head tracker integration issue that induces degraded results not representative of our system performances. We also don't wish to share some data for confidentiality reasons.

3.3. Results of EDPR (Donauwörth) flight trials

Of all scenarios described in Sec. 2.3.2, only the key results from the flight trials are plotted for conciseness. Figure 13 to Figure 15 plot the navigation performance during continuous descent approach in flight path angle mode (Scenario N2). This approach was flown by three different pilots on different days. Two flights, shown in cyan and magenta in Figure 13 to Figure 15, were flown in wind speeds exceeding 30 knots.

Figure 13 shows the lateral flight path was accurately tracked. The corresponding cross-track error in Figure 14 is found to be less than 0.1NM during all RF legs.

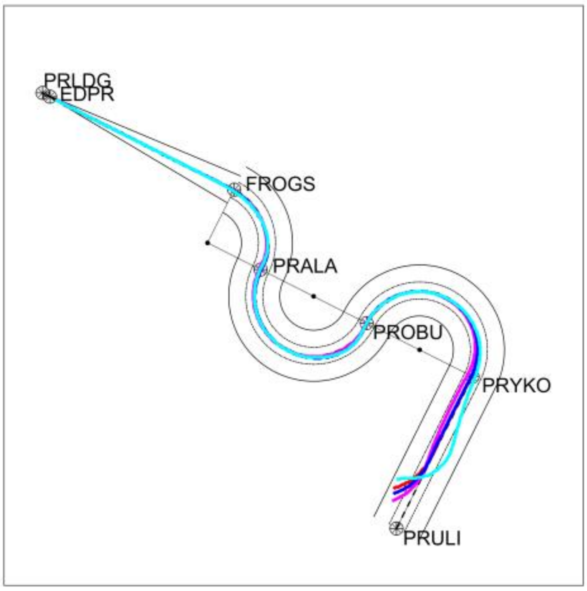

Figure 13: Horizontal path performance with autopilot coupling at constant flight path angle descent

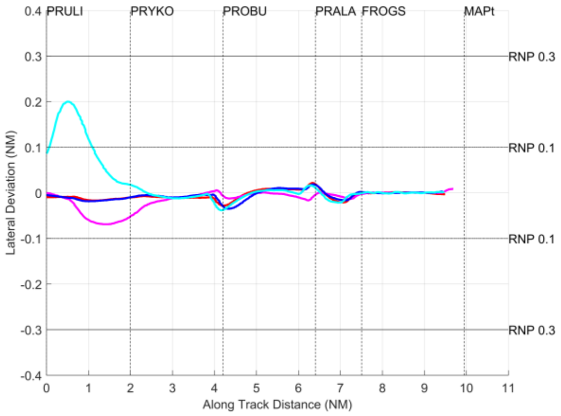

Figure 14: Cross-track error with autopilot coupling at constant flight path angle descent

Despite strong winds, all altitude profiles in Figure 15 show a smooth descent until the MAPt. One pilot chose a step-wise descent by attempting target altitude at each waypoint. This can be seen from the plot in blue, whereas other pilots chose to set the target altitude at the FAF. Overall, navigation performance in all scenarios with autopilot coupling was found to be satisfactory.

Figure 16 to Figure 18 plot the navigation performance during continuous descent approach for hands-on flight with backup SAS (Scenario F3). It was also flown by three pilots. Figure 16 and Figure 17 show that the lateral navigation performance along the path remained within RNP 0.3 containment limits. The vertical flight path in Figure 18 was close to the desired descent profile and the glidepath was successfully captured at FROGS in all flights.

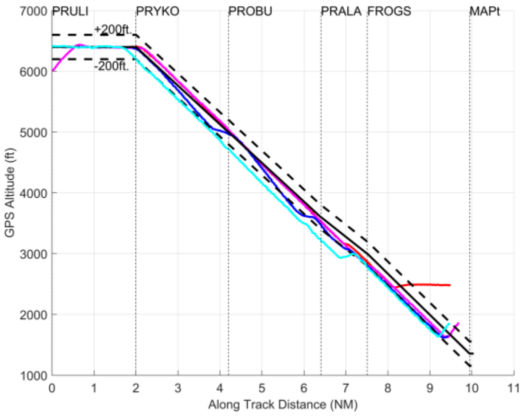

Figure 15: Vertical path performance with autopilot coupling at constant flight path angle descent

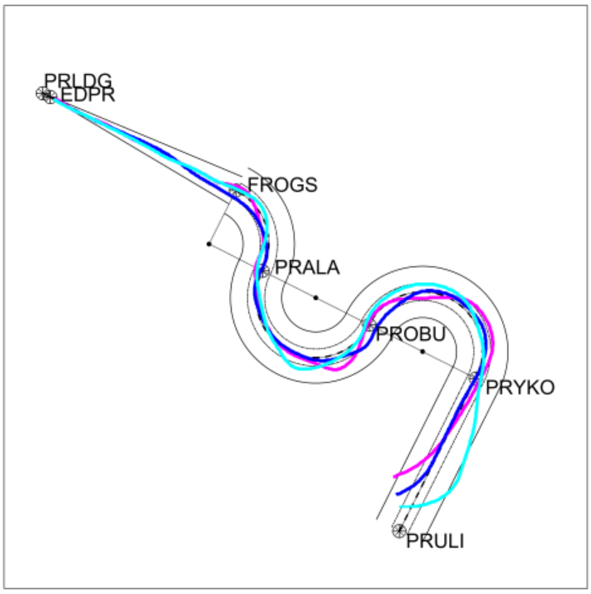

Figure 16: Horizontal path performance without autopilot coupling during continuous descent approach

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

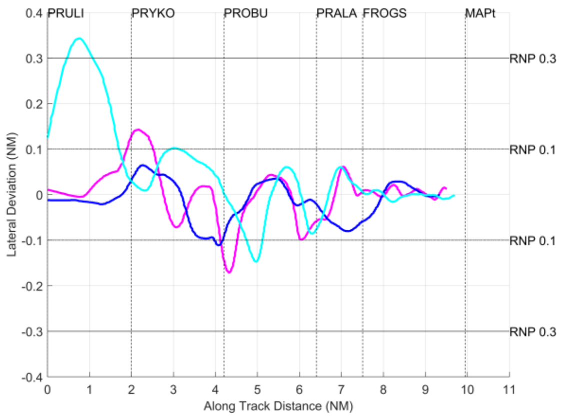

Figure 17: Cross-track error *without* *autopilot coupling during continuous descent approach*

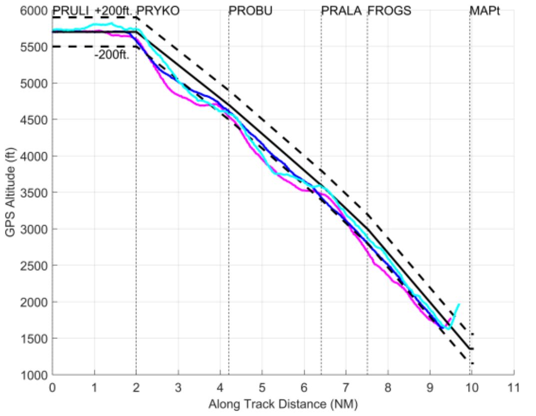

Figure 18: Vertical path performance *without* *autopilot coupling during continuous descent approach*

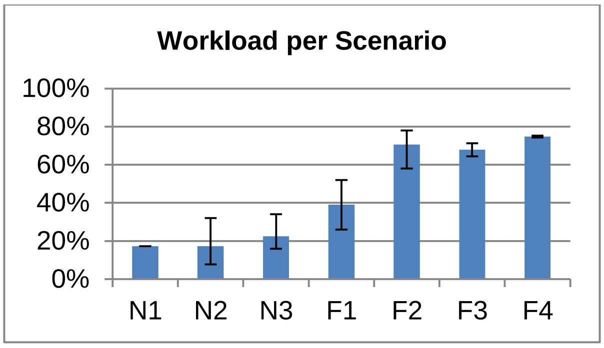

Figure 19: NASA TLX Workload per scenario for EDPR flight trials

Figure 19 plots the mean workload for all pilots per scenario. It can be seen that workload in all nominal scenarios (N1 to N3) is in the range 17% to 22%. It is interesting to observe that N3 has a slightly higher workload of than N2, which reflects pilot's opinion that descent during curves using a flight path angle mode is more intuitive as it is unaffected by wind. F1 has an acceptable workload of 39%, indicating that 3-axis autopilot is an acceptable mode to fly advanced PinS. However, F2 through F4 show a high workload in the range of 65%-75% which indicates that these scenarios need additional workload mitigation means in order to be feasible to be flown in realistic scenarios

4. SUMMARY AND DISCUSSION OF RESULTS

Regarding concept clarification, rotorcraft tend to fly with nonzero slip angles. Slip angles are particularly high in side winds, which make it difficult to fly turns in this situation. Both the RTS and flight trials in Braunschweig with HMD assistance but no autopilot showed that pilots need to turn their heads like in visual flight to allow a smooth transition from IMC to VMC. The Donauwörth flight trials showed that the autopilot is effective in following the desired path despite strong winds.

RF legs ending at the FAF/FAP and RF legs connected the IDF do not impose a safety issue, either with HMD assisted manual flight, or autopilot coupled flight. The technology and guidance in all exercises allowed a precise and reliable intercept of the glide path. Pilots reported time pressure during this transition, and therefore a short straight level-off segment between RF leg and final glidepath is recommended.

Concerning the HMD only, there is a limitation on guidance quality. The HMD should guide the pilot to a higher altitude than the minimum at the IDF and beyond. The concept of 3D pathway does not work optimal during the departure if it is designed to go along the lowest allowed altitude. If there is only an upper limit constraint to fulfil, the system should provoke the pilot to climb at best rate to meet the level-off constraint as early as possible.

Concerning autopilot-coupled Head Down display, pilots reported carefree handling and large spare capacity to devote to other mission tasks. Thus, actively seeing and avoiding other aircraft and radio communications could be were easily handled by the pilots. Descents during the RF legs were also flown to a good level of accuracy. Lateral containment was always within the required containment limit of 0.3NM. If descent is required, then the flight path angle mode was rated easier and more intuitive than vertical speed mode. However, autopilot or GPS failures were found to significantly increase pilot workload.

Regarding technical feasibility, two different designs have been tested, an advanced flight director concept allowing an anticipation of the next change in the flight trajectory, and a conformal 3D display of the route to fly. A slight advantage has been shown in favour of the advanced flight director concept regarding the trajectory flight precision and the workload level. The qualitative results concerning the achieved RNP show that the limits can be met even in a high wind scenario, despite the fact that the HMD system installation was not optimal. An integration issue regarding the head tracker had an impact on the system usability and still all RNP limits were met besides some (one major) off track situation that can solely be attributed to this issue.

5. CONCLUSIONS

The technical feasibility of automating the flying of RF legs can be assured by means of a reliable autopilot and avionics installation. Both the FMS and autopilot which are capable of reading and executing the RF type of navigation fix from the navigation database, greatly contributed to complying to the RNP containment limits, reducing pilot workload, and increasing pilot's situational awareness. In terms of the onboard monitoring function, a similar level of monitoring and alerting as for standard PinS is considered sufficient.

It can be stated with confidence that a combination of HMD system and an autopilot coupling will further reduce pilot workload and greatly enhance situational awareness in advanced PinS.

ACKNOWLEDGEMENT

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement number 731864.

The project members extend many thanks to the experimental test pilots who participated in the simulator and flight trials: Lionel Arlen (Airbus), Didier Delsalle (Airbus), Daniel Maulet (Thales), Uwe Göhmann (DLR), Miles Barnett (DLR), and Sebastian Soffner (DLR).

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