LNAS - A PILOT ASSISTANCE SYSTEM FOR LOW-NOISE APPROACHES WITH MINIMAL FUEL CONSUMPTION

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Abstract

Landing is one of the most labor-intensive flight phases. In order to help pilots with the complex handling procedures for a low-noise approach, DLR has developed the LNAS (Low Noise Augmentation System) pilot assistance system. This system shows exactly to the pilot when to perform which pilot action via a display in the cockpit. This display on the Electronic Flight Bag (EFB), which can be intuitively and instantly grasped, thanks to its simple representation, is used as a long-term planning basis for the entire approach. The optimal approach profile is divided into different phases. The optimum times for setting flaps and extending landing gear are each marked in the approach profile. If the pilot follows these instructions, the approach can be implemented with minimum thrust from cruising altitude to the stabilization height of 1000 feet above ground level. Therefore the lowest possible noise development and lowest possible fuel consumption can be achieved. In 2016, the LNAS pilot assistance system successfully completed initial flight tests during everyday peak-time operation at Frankfurt Airport. A total of 74 approaches were implemented on board the DLR A320 ATRA (Advanced Technology Research Aircraft) in five test series. The assistance system was of great help to the pilots, especially in difficult situations, such as strong tailwinds or speed restrictions from air traffic control. For long-term testing, Deutsche Lufthansa is currently equipping up to 86 aircraft of the A320 family with the assistance system LNAS developed by DLR. First, software integration and integration flights were successfully completed. Currently, a group of selected Lufthansa pilots are using the LNAS assistance system for pre-trial testing in regular flight operations during approaches. As soon as all conditions have been met, the test will be extended to all Lufthansa A320 pilots.

1 Introduction

Air traffic is still growing and will double within the next 15 years. The growth will generate new routes and require new airports and more new planes. The expansion of airports, particularly in the vicinity of densely populated regions, is accompanied by an increasing number of aircraft movements. This increases the possibility of conflicts between residents and airport operators. In order to increase the acceptance by local residents and to avoid conflicts, the topics of environmental and noise protection will play an important role in the future among other themes like safety and will continue to be a key driver for the aviation industry as a whole. The challenge is to reduce continuously the environmental impact in the face of continuing expansion in aviation. The Advisory Council for Aviation Research and Innovation in Europe ACARE presents a summary of the objectives for future air transport: In 2050 technologies and procedures available allow a 75% reduction in CO2 emissions per passenger kilometer and a 90% reduction in NOx emissions. The perceived noise emission of flying aircraft is reduced by 65% [1]. These numbers are seen relative to the capabilities of typical new aircraft in 2000. The ambitious aims will drive the need to deliver revolutionary technology solutions at an increasing rate.

The most consistent way to reduce aircraft noise would be the optimization of the noise source itself. However, the development cycles of new aircraft and also the service life of current models are very long. Therefore it is useful to deal with other aeronautical aspects in addition to the technical characteristics of aircraft in order to analyze possibilities for reducing the environmental impact. For example, arrival and departure procedures are particularly interesting. Due to the very high flight safety requirements an optimizing and modifying of standard procedures is only possible within the scope of existing regulations. Such changes can be implemented, at least in the medium term. A further potential to reduce noise is the optimization of the final approach procedure. This is only possible if such an approach procedure is conducted precisely. In most cases pilots are not able to achieve this precision without further support. A promising approach is the concept of an onboard assistance system, which helps the pilots to manage the energy budget, thus enabling a more precise implementation of the approach procedure.

Even under ideal conditions (no wind, no restrictions due to other traffic or flight safety regulations) the interpretation of low-noise flight procedures is a complex process. The main sound sources (engine, airframe, landing gear and hight-lift devices) cannot be influenced independently. For example, aerodynamic noise basically scales to a high degree with the airspeed, but a slow flying aircraft does not automatically result in a lower noise impact. At low airspeeds a higher high-lift device configuration is required, which is accompanied by increased aerodynamic drag and consequently by higher noise levels. Flying higher with otherwise unchanged parameters obviously provides a lower noise immission directly below the flight track, but from a certain lateral distance, the noise level increases due to the lower ground attenuation. In addition, it should be remembered that an approach with a higher approach angle to the same touchdown point must be designed differently and is not necessarily quieter.

2 Problem description and current state of the art

Over several decades the aircraft noise sources could be reduced through newly developed technical solutions. The evolution of aircraft noise technology‐design performance over time against the noise limits is shown in Fig. 1. The figure illustrates the cumulative margin of the certified aircraft noise levels relative to the associated Chapter 3 cumulative limit [3], plotted against the year the aircraft type was certified. In that way different aircraft types across a range of gross weights are comparable as the associated limit values take into account the fact that larger, heavier aircraft make more noise. In Fig. 1 only the heaviest weights of the respective aircraft type are plotted, which represent the highest noise levels. [2]

To gain further reductions of aircraft noise sources, it is important to emphasize that:

- Cooperation’s with industry, research establishments, academia, EASA and Eurocontrol are continuously needed towards achieving a significant and balanced research programme.
- There is a need of improved databases of aircraft noise (e.g. certification values) as well as of noise modelling methods for use in forecasting in the airport environment.
- The research infrastructure (both for numerical simulations and experimental testing) is a key enabler for new technologies.
- Incentives could help in the faster introduction to service of new technology or in the phase out/retro-fit of noisy aircraft/engines.

In the past five decades, a significant reduction in aircraft noise has been achieved (see Fig. 1) next significant economic and social benefits. However, in future it is possible that the positive effects of new technologies are cancelled out by the large continuous growth in air-traffic [2]. Avoiding that, the intensive interaction between new technologies, flight operation/procedures and air traffic control can

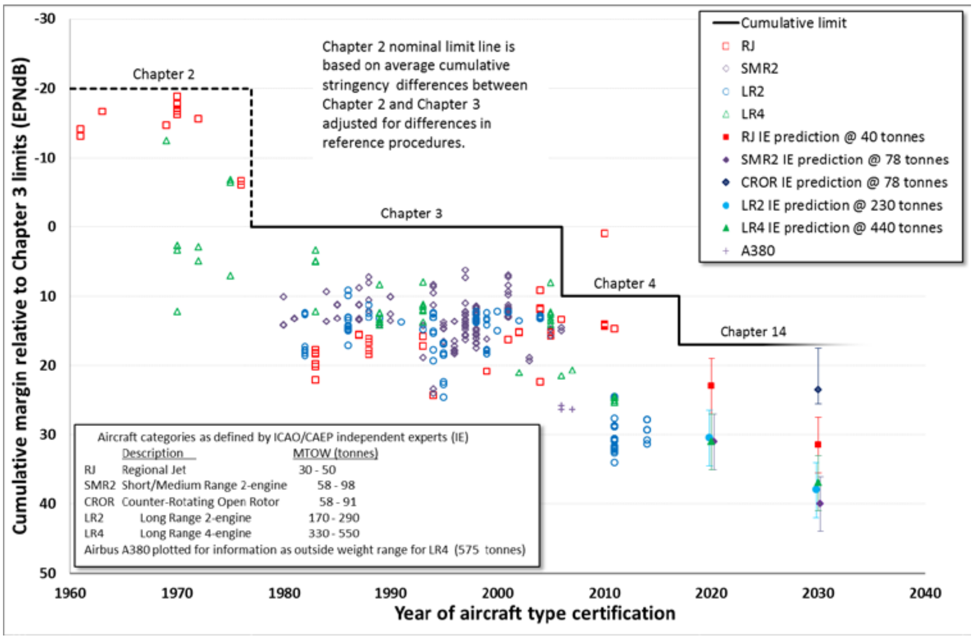

Fig. 1. Continuous improvement in aircraft noise performance has occurred over time across various weight categories [2]

exploit the full potential of reducing environmental emissions like noise and fuel.

Aircraft noise reduction is particularly requested by residents near the airport, which aims at a low-noise implementation of approach and departure procedures. In flight operations, each approach involves different conditions such as aircraft weight, wind and requirements from air traffic control, which make the precise implementation of an approach more difficult. In addition to following controller's requirements, the pilot prepares the aircraft for landing by reducing speed and extending high-lift devices and landing gear.

The DLR Institute of Flight Systems evaluated several tens of thousands flight data from a medium-sized passenger aircraft in order to gain a better understanding of flight conditions and aircraft configuration during approach. Fig. 2 illustrates for 8968 approaches altitude and airspeed related to the distance to the runway threshold at the beginning of the landing gear extension at Frankfurt Airport. In addition, in the lower image of Fig. 2, a distribution curve is shown for the percentage extension of the landing gear related to the distance to the runway. It can be seen that twenty percent of the approaches have already extended the landing gear at about seven nautical miles away from the runway threshold. At the time of extension, the indicated airspeeds and altitudes are in the range of 160 *kts* to 270 *kts* and 2600 *ft* to 11000 *ft*. There is a huge potential avoiding unnecessary aircraft noise impacts on the ground by shifting the landing gear extension closer to the runway with an optimized energy management. This prevents landing gear extensions in low altitudes (e.g. at the 4000 ft intermediate altitude) and high speeds as can be seen in Fig. 2.

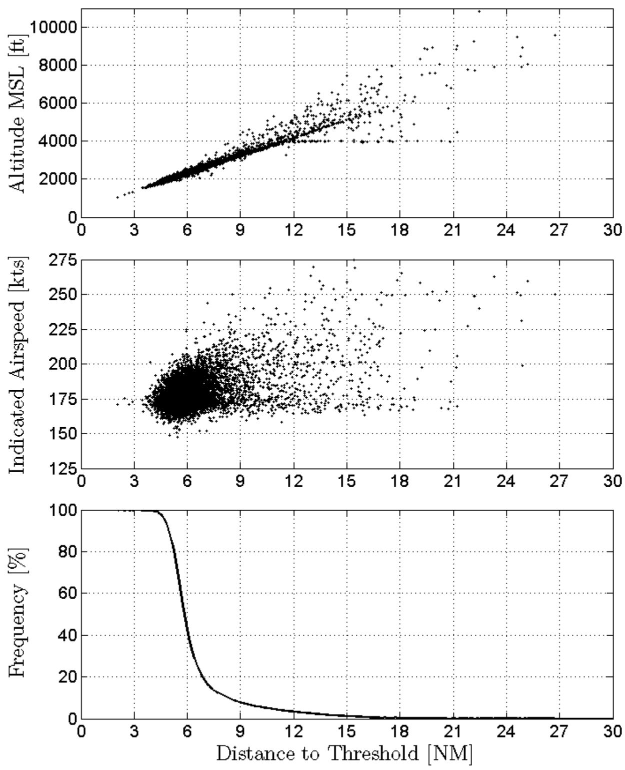

Fig. 2. Position of landing gear extension and related speed

Under certain circumstances, the pilot receives requirements from air traffic control which are only to be realized through the extension of the landing gear. Landing gear is often used to increase aerodynamic drag in order to reduce the excess energy. Unfortunately, the requirements of air traffic control cannot be taken into account due to lack of records of the radio traffic.

The pilot has to decide, in compliance with ATC requirements, when to reduce speed, to set high-lift devices and to extend the landing gear in order to reach the approach speed on time. The earlier the configurations are initiated, the sooner the target approach speed will be achieved, so that additional thrust is needed. If, on the other hand, the configurations are set too late, the aircraft may no longer be able to reduce the excess kinetic energy, which may results in a go-around. It should be noted at this point that this problem is not due to an inadequate qualification of the pilots. Much more is the precise execution of the approach procedures a great challenge. Even years of experience do not lead to optimal results. Therefore, a system-specific pilot assistance is required for energy-efficient approaches, which provides precise information about altitude, speed and configuration management.

Energy-efficient procedures require precise flying of vertical approach profiles also and especially in different boundary conditions (wind and aircraft mass), which is a great challenge in practice. Both the specification of correct speed setpoints and the extension of landing flaps and landing gear at the right times are critical factors for reducing noise and fuel consumption. The use of spoilers, unnecessary engine thrust and premature configuration changes over the optimal profile are the main causes of increased noise impact and fuel consumption. The pilots lack information about the feasibility of the procedure under the current boundary conditions can be identified as major cause of the problem. Furthermore, it depends on experience and estimates, whether the approach can be completed safely and stably.

Navigation displays (ND) have become standard for lateral flight path illustration and navigation in modern commercial aircraft. Here, the entire flight plan is shown in a plan view relative to the aircraft. Information about the vertical profile of the flight plan is not available in this presentation. As an extension, the so-called Vertical Situation Display (VSD) is widespread, which usually depicts the vertical flight plan, e.g. the height above the distance to the touchdown point. Furthermore, in most implementations, the current aircraft altitude is represented by a simplified aircraft symbol along an area with terrain information. This second display is now considered as state of the art and is installed in many newer aircraft designs (Airbus 380, 350; Boeing 787).

The state of the art presents the desired flight plan vertically and laterally relative to the current aircraft position and altitude, but does not provide information about the course of the speeds. Only the current speed together with a short-term forecast (so-called speed-trend arrow) is displayed in the Primary Flight Display (PFD). Especially for the implementation of low-noise approaches, it is essential to have an exact planning for the setting of flaps, landing gear and speed setpoints. A meaningful display including the future speed course to touchdown is not available in current avionics systems.

In summary, it can be said that there is a huge potential for optimization and noise reduction both in conventional approach procedures and in new approaches. To exploit this potential, however, an extended pilot support is necessary. One form of this support was implemented in the assistance system LNAS (see Fig. 3). The aim of LNAS is an energy-efficient descent from cruising altitude to landing. Fuel consumption should also be reduced as a result of the minimum demand for thrust during the approach. Using LNAS, the aircraft is configured as close to the runway as possible (flaps, landing gear), in order to minimize drag for as long as possible. Noise emissions are minimized. Furthermore, the probability of a go-around can be reduced thanks to energetic anticipation. The current status of this system is described in section 4.

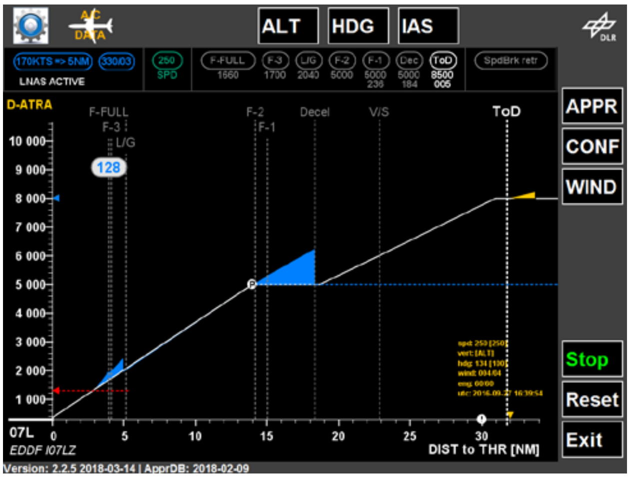

Fig. 3. Display of the assistance system LNAS

3 Methods of resolution

The impact of the growth in air traffic largely compensates for progress in reducing source noise (in particular, the introduction of quieter engines). Demands of airport residents for a ban on night flights and the implementation of noise-reduced procedures, which are possibly more time-consuming and fuel-consuming, collide with the permanent economic pressure on the airlines caused partly by the customer itself.

Due to the long investment cycles - today's commercial aircraft are designed for service periods of up to 30 years - the change of flight procedures appears to be easier to implement than the replacement of loud aircraft. The urgent desire of improved, low-noise approach procedures also results from the high cost of approval of hardware and software components for aerospace applications. For both on-board and ground-based equipment, technical improvements can only take full effect in many years to a few decades.

With regard to the flight speeds that are possible from the point of view of flight mechanics, it should be noted that, without prejudice to restrict the maximum speed by the air traffic control, the design of the flap systems requires a limitation of the dynamic pressure that occurs. Thus, maximum permissible speeds depend on the different flap levels; the tendencies for early configuration of the aircraft and its fast approach to the runway contradict each other. The minimum speeds, however, result from the maximum allowable angles of attack of the respective configuration - here, a safety margin for maximum lift is taken into account - and are additionally dependent on the landing weight: with less mass, the identical aircraft can approach more slowly.

The "Procedures for Air Navigation Services - Aircraft Operations" of the International Civil Aviation Organization ICAO (PANS-OPS, [3]) provide information on the boundary conditions for the design and implementation of noise-reduced approach procedures. These recommendations of the ICAO have been ratified by practically all states and thus are internationally valid [3].

For safety reasons, the implementation of low-noise procedures is only permissible if the requirements are proven! The procedures can then consist of a combination of the following measures:

- preferred use of runways with less noise sensitivity,
- preferred use of approach routes avoiding noise-sensitive areas
- use of low-noise procedures specifically designed to minimize noise exposure to the ground and for which the required level of safety has been demonstrated.

An increased glide path angle from the usual 3.0 to 3.2 degrees results in a higher flight altitude in the final approach segment. Airplanes would fly higher than before over residential areas, which reduces the noise below the flight path on the ground.

Another conceivable measure is to increase the intermediate approach altitudes in independent operation up to 7000 *ft*. This increase was already foreseen in 2012 in the Alliance for Noise Protection at Frankfurt Airport [12]. For this it is necessary that the final approach starts further away from the airport than before. To achieve this, an increase in the range of the instrument landing system (ILS) was originally planned. The examination of this proposed solution, however, showed that this is technically not possible, since the signal of the ILS at this distance from the airport does not possess the quality for approval of the procedure.

To enable the desired extension of the glideslope, GBAS technology shall be used instead of the ILS system - even though only a limited proportion of aircraft landing at Frankfurt Airport are currently equipped with GBAS. In addition, as the coverage of GBAS is also limited by regulatory approval, it is currently examining an extension of the approved GBAS range. Technically, this would be possible in principle. A mandatory condition for the implementation of this measure would also be that GBAS receives an authorization for independent operation [12].

In the so-called segmented approach, airplanes use special approach routes to bypass settlement areas. This reduces the number of affected residents. So far, however, this approach procedure is available only at night - and thus only in the case of delayed flights - and with the help of GPS (RNAV). In any case, there are only a few flights in this time frame, from which less than 50 percent (in Frankfurt, [12]) use the "Segmented Approach GPS (RNAV)" approach procedure. An ILS-based solution based on conventional navigation and thus available to all aircraft should mandate the use of the Segmented Approach and thus increase it to almost 100 %. A non-use is then only in exceptional cases, such as for safety reasons or in special weather conditions. In principle, however, the capacity in the segmented approach is a limiting factor: The use of this procedure is also possible only in dependent mode, even in the segmented approach ILS. With the number of arrivals available today, the Segmented Approach ILS is frequently applicable in the evening hours. A morning expansion, however, is already not possible today, because in this hour there is too much traffic at the airport. However, as the number of flights increases, the segmented approach can no longer be achieved at night without operational or capacity constraints [12].

In terms of perspective, Frankfurt Airport is considering implementing the segmented approach by means of so-called performance-based navigation ("Required Navigation Performance" or RNP-to-xLS). Such a procedure would replace the existing segmented approach. In this new procedure, the aircraft follow a fixed path that leads them with curves ("radius to fix" or RF legs) to the final approach. RF-Legs enable a higher level of directional stability in curved flight. As a result the area affected by aircraft noise would shrink. The basic operational and environmental feasibility of this approach has already been confirmed scientifically: The flight procedure was audited in the framework of the European research initiative SESAR (Single European Sky Air Traffc Management Research). Not all airplanes can use this procedure yet.

For all segmented approaches, the incoming aircraft must comply with a greater safety distances. Therefore, this procedure can only be used in times of very low air traffic. The Segmented Approach Independent Parallel provides exactly this usage in independent parallel runway operation. Then a straight and a segmented approach could be performed at the same time. With this method, an application would be possible even at high traffic loads [12]. The application could be extended in perspective beyond periods of low traffic.

Using the precision flight procedure RNP1 in conjunction with an RF-leg, i.e. a well-defined curve radius, it is possible to achieve higher directional stability and greater bundling in curved flights. This allows aircraft to more accurately comply with the intended routes. In most cases, an attempt is made to map the conventional route exactly with an RNP1 procedure. This would not cause any noise shifts but would improve the directional stability of the flights. Especially the optimization of routes for reasons of noise protection can contribute to the fact that fewer people are affected by aircraft noise.

4 LNAS System description

The assistance system LNAS (Low Noise Augmentation System) has been developed to improve the above described situation. It is based on the so-called Vertical Situation Display (VSD), which maps the vertical flight plan in addition to the Navigation Display (ND). This display is now regarded as state of the art and shows the total energy level, summing potential and kinetic energy over the vertical profile of the flight path. LNAS includes three parts: pre-planning, correction at runtime and an energy-based display. The pre-planning implements a simplified simulation model of an ideal vertical approach profile and is currently based on data of the Airbus A320 family, which is applicable to any type of aircraft with existing data base. This pre-planning should ideally take place before the start of the actual approach. In doing so, optimal points in time for setting speed, high-lift devices and landing gear are determined in such a way that the approach can be carried out with minimum engine thrust and if possible without using the noise-intensive speed brakes. The optimization algorithm is designed for the approach phase until the stabilization altitude at 1000 *ft* above ground level. The optimal profile terminates with fulfilled stabilization criteria at the 1000 *ft* gate so that the landing can be safely carried out. The optimal points in time depend on the wind conditions at current altitude and at the airport, which are already known at this time. In order to optimize the vertical approach profile, the current situation (aircraft mass, wind conditions, flight safety regulations and possible imprecise pilot actions) needs to be taken into account. Finally LNAS shows all pilot actions at the optimal point in time with aim of stabilized approach. Additionally the current speed error and its expected progression are graphically represented. This essential information can be obtained via a suitable simplified simulation model. For a low-noise approach, it is a prerequisite that the required speed reduction can be carried out to the next configuration point under the current boundary conditions without using speed brakes. In the course of the approach, the current wind situation on the aircraft are recorded, as well as possible time delays are taken into account by the necessary actions of the pilot, so that the best possible approach is displayed at any time. A delayed action may be, for example, setting the flap configuration too early or too late. In addition, speed constraints required by air traffic control can be entered by the pilot in order to optimize the approach under the new boundary conditions. The pilots are always informed about the energy balance during the entire approach as well as the necessary speed and height reductions. Impacts due to changes in wind conditions or new air traffic control instructions are immediately visualized. This basic concept and the functional structure in order to ensure the always up-to-date approach optimization are shown in Fig. 4.

The display of the assistance system LNAS can be seen in Fig. 3. Its intuitive structure forms a basis for planning the entire approach. The LNAS is available to both pilots. The pilot monitoring uses the graphical interface to set the values to be configured so that all relevant information for implementing the optimized approach is provided in an intuitive manner. In addition to the aircraft symbolized by the yellow triangle, the display consists of soft keys for configuration, symbols for current states and requirements as well as a schematic representation of the vertical approach profile. The display is located on the EFB of the captain and the first officer. The presentation is always aligned in the direction of flight.

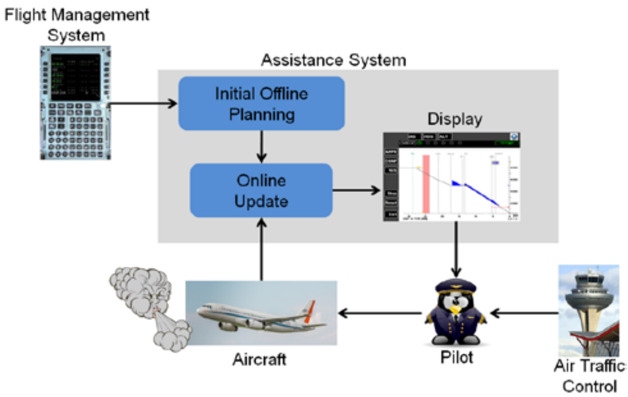

Fig. 4. Basic principle of LNAS

In order to be able to calculate an approach optimized with regard to noise and pollutant emissions, LNAS needs certain input values at runtime. These are subdivided into information that must be configured by the pilot, which are provided directly by the on-board systems of the aircraft and information that is read from a database stored in the software (Fig. 5).

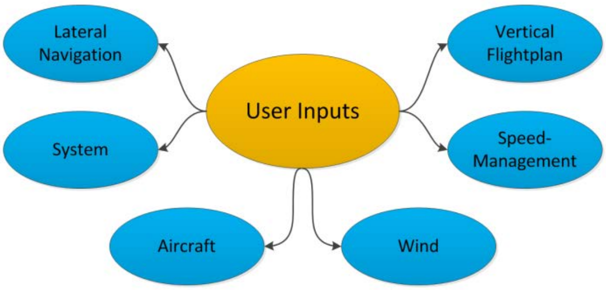

Fig. 5. System interfaces and signal inputs

Among the data provided by the on-board systems are i.e. Autopilot modes, navigation data, aircraft configuration, airspeeds and lever / switch positions. Through these different interfaces, the software has all the information needed to calculate the optimal profile in every approach situation. By known values, such as the intermediate approach altitude and the glideslope angle, the vertical approach profile is optimized and displayed schematically to the pilot.

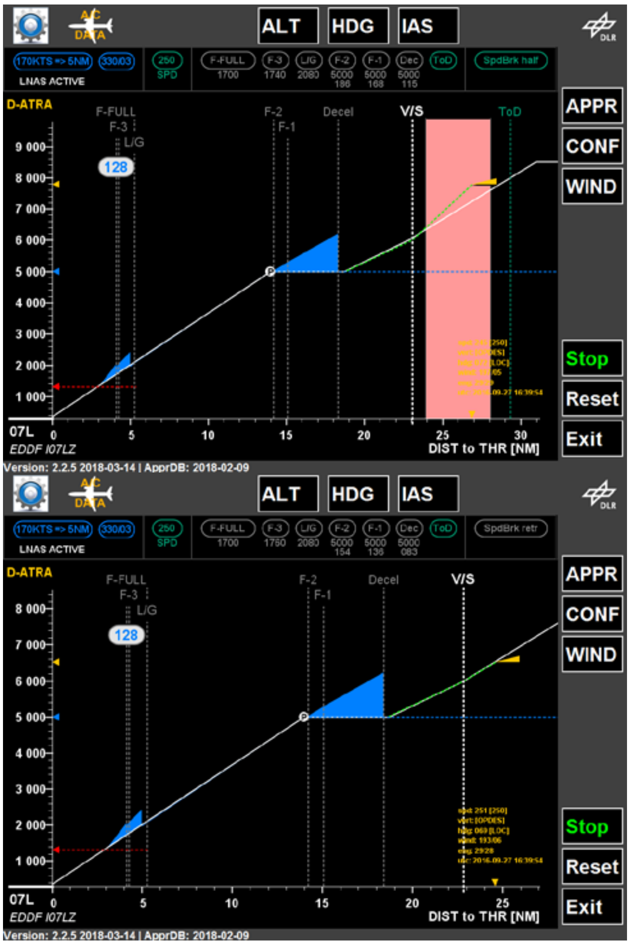

Fig. 6. Use of speed brakes after late approach clearance

In the upper part of the display, icons show the configured values for a speed restriction and the wind situation on the ground. The information comes from air traffic control or the Automatic Terminal Information Service (ATIS). In addition, the typical actions during an approach are shown in symbolic form, which includes setting the flap configuration, setting the speed brakes and the associated position, the top of decent and landing gear setting. The symbols are arranged in the typical order for an approach. Initially the symbols are displayed in grey, but the color of the next action, which has to be executed by the pilot, changes to white. For this purpose, in addition to the altitude the distance or a countdown for each action is displayed under the symbol. If the action was executed by the pilot, the color of the corresponding symbol changes to green (see Fig. 6 and Fig. 7). If the pilot misses the action or cannot do it for other reasons, the symbol color changes to yellow.

In the remaining area of the display, the vertical approach profile is shown schematically as altitude over the distance to the runway threshold. The optimal times of the different actions, which are shown above as icons, are displayed in the approach profile as vertical dashed lines with designation at the top. In addition, for each current action, the speed is displayed, which should be taken over from this point in the autopilot. The speed setpoints will appear 10 seconds before the next action has to be executed, so that the pilot has enough time to turn in the new setpoint. As already mentioned, it is attempted to avoid the use of the airbrakes in an optimal approach. However, if this is not possible, the best possible period of use is displayed next to the above symbolic representation as a red area (see Fig. 6 and Fig. 7). The green dashed line describes the further optimal vertical approach path and may deviate from the previously calculated approach profile, depending on whether the previous vertical approach path was correctly flown, as proposed by the system, or not.

The goal of each approach is to reach a certain flight condition at the stabilization height, which is shown in the display as a red dashed line. In this case, both potential and kinetic energy must be reduced to this threshold. The reduction of the excess kinetic energy is visualized in each section of the approach as a blue triangle. On the other hand, it can also be possible that unexpected headwinds caused more energy to be dissipated than expected and the thrust has to be increased.

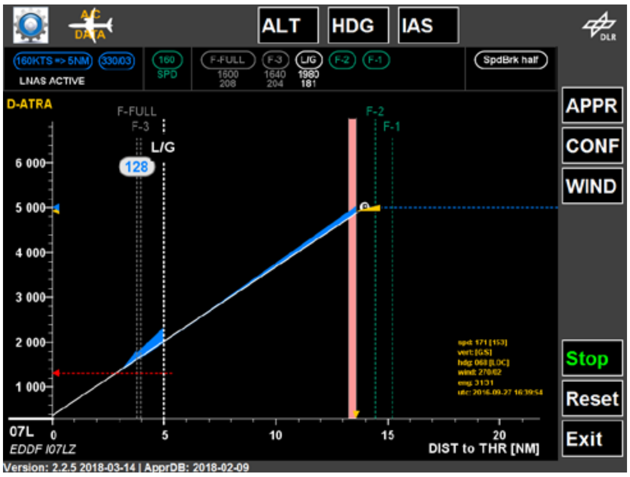

Fig. 7. Use of speed brakes due to speed restrictions

If, in the current situation, the achievement of the required flight condition at the stabilization height is not possible, e.g. by applicable speed restrictions, the expected speed difference is displayed at the stabilization height in different colors (see Fig. 8). In addition, the information is provided to the pilot in which area the speed brakes must be extended in order to reduce the expected speed difference to a permissible level. With this functionality it is already known in advance whether the aircraft will meet the speed requirements in the stabilization height under the prevailing boundary conditions or whether the approach will have to be ended with a go-around maneuver.

LNAS is a software-based solution and requires a suitable platform in operational operation. DLR's research aircraft A320 ATRA (Advanced Technology Research Aircraft) has two installed Class 2 EFB systems from Rockwell Collins, which are very well suited for the LNAS application and provides a legal connection to the hardware on board the aircraft for providing the necessary aircraft data (see Fig. 9).

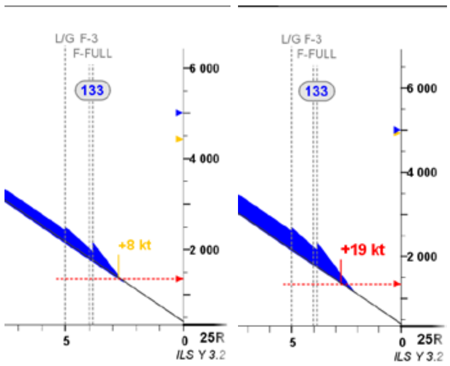

Fig. 8. Excess speed at 1000ft

5 Results of testing

5.1 LNAS in simulator

In preparation for the flight trials at Frankfurt Airport, the pilot assistance system LNAS was set up and extensively tested in the simulator center AVES (Air Vehicle Simulator) at the DLR Braunschweig. Several professional pilots from four different airlines took part in the tests in the cockpit of the A320 simulator. The aim of the four to five-hour training sessions was to familiarize the pilots with the functionalities and operation of the LNAS display. During the tests, the crew simulated various approaches to Frankfurt Airport. To test the assistance system to the full extent, the conditions of each approach varied: weather conditions, visibility conditions, the weight of the aircraft or the requirements of air traffic control influenced each approach differently. After each training session an extensive debriefing with the participating pilots took place, in order to eliminate possible ambiguities with the use of the system and also to include suggestions for improvement by the pilots and to let into the further development of LNAS. It could be shown that the optimization algorithm for the vertical approach profile proved to be successful and the pilots rated the intuitive display of the LNAS positively.

5.2 LNAS in real flight

After LNAS had been successfully tested in the simulator and in subsequent first research flights conducted by DLR test pilots, it had to pass the test in regular operation at Frankfurt Airport. For three days, the DLR's research aircraft A320 ATRA flew various approaches to Germany's largest commercial airport. The LNAS flight trials took place from 26 to 28 September 2016 and included a total of 25 test flight hours. In addition to the DLR crew 17 professional pilots from four different airlines were available for the test flight program, so that the acceptance of LNAS could be evaluated by a group of possibly later users. For each flight, 4 professional pilots took part in the trial, so that it was intended to deploy several pilots several times in compliance with the rest periods.

Fig. 9. Flight trials, LNAS onboard DLR's ATRA A320

The aim of the LNAS experiments was to test the system under real boundary conditions of a busy traffic airport. During the flight trials at Frankfurt Airport, the test approaches were carried out without special treatment by the air traffic control. During the entire period, ATRA was treated like any other aircraft and directed for the approach to the North-West runway.

After each approach a go-around followed in 800 *ft* above ground level, a pilot change took place in the cockpit, in order to avoid a learning process as much as possible. Another reason for this was that the pilots only make one landing in general flight operations before the next flight begins. Furthermore, this allowed the greatest possible time interval to the next approach for one pilot, in order to obtain possibly varying weather conditions or new requirements of air traffic control for the pilots. Afterwards, the pilot received the information whether the following approach should be flown with or without LNAS display.

The approaches always took place on the north-west runway of Frankfurt Airport. During the flight trials the runways 07L and 25R were operated, both with a glide path angle of 3.0° (RWY 07LZ / 25RZ) and with 3.2° (RWY 07LY / 25RY). Fig. 10 shows the flight tracks on the runway 25R.

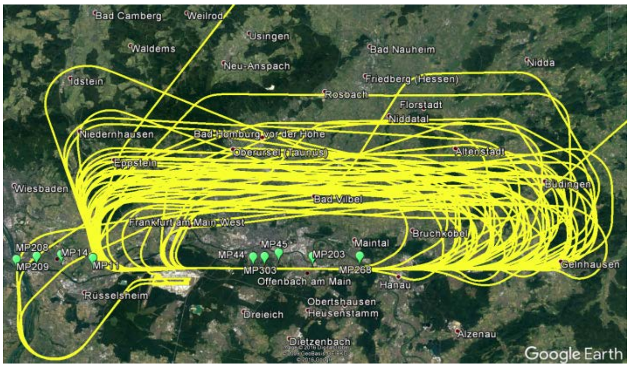

Fig. 10. Flight tracks EDDF 25R

After each go-around maneuver, the aircraft climbed to flight level 70 or 80 and stood ready for the next approach until air traffic control requested the next vectors for entry into the approach baseline. The final approach course was achieved at different distances, so that each approach had to be carried out under different boundary conditions. With regard to the vertical profile, it should be noted that not all tests could be carried out using the planned LDLP (Low Drag Low Power) approach procedure.

As mentioned before, during the trials air traffic control treated ATRA the same as all other approaching aircraft. Of course, this leads to restrictions during the approaches with respect to climb and descent clearance as well as to speed restrictions. In total, 36 *%* of all approaches were made without air traffic control speed requirements. The percentage distribution of approaches without speed restrictions for approaches with and without LNAS is almost identical (35% / 36%). It was found out that the "reduce and maintain 170 *kts* until 5 *NM*" and

"170 at GP" speed settings were most frequently used during the flight trials.

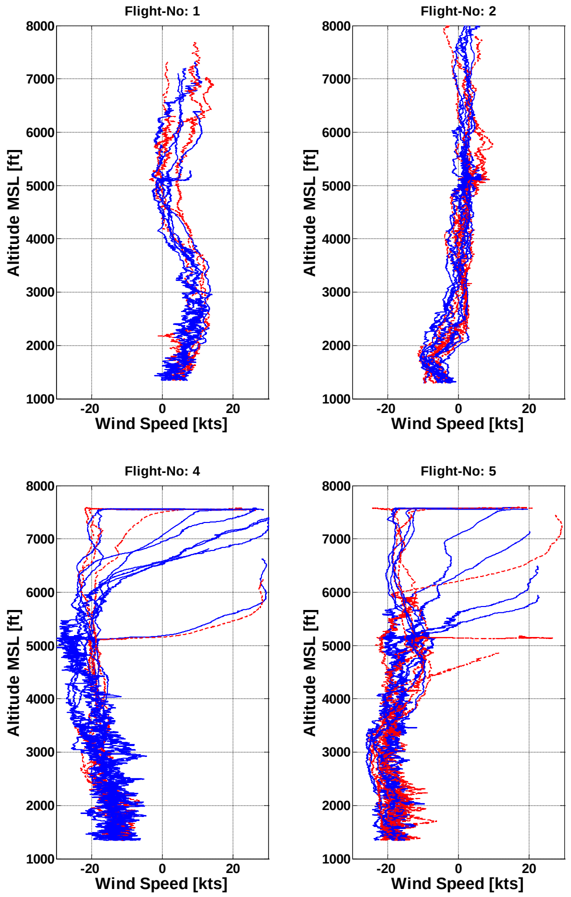

Fig. 11. Wind profiles in flight direction; pos./neg. values: tail-/headwind

In addition to the restrictions of air traffic control, the influence of environmental conditions is of course very important in real flight. The wind profiles of four test flights are illustrated in Fig. 11. It should be noted that the wind speeds are plotted in the direction of the aircraft's longitudinal axis and the blue-colored lines represent the approaches with LNAS and the red-colored without LNAS. The approaches with and without LNAS of the respective test flight have the same wind conditions and are therefore comparable. During the first test flight, the tailwind component is between 7 *kts* and 12 *kts* at a height of 3000 *ft* and decreases to 0 *kts* at stabilization height. The wind profile of the second test flight shows a relatively calm atmosphere down to 2500 *ft*. A windshear is detectable below this altitude since the headwind component increases in magnitude only to 11 *kts* and changes again to 0 *kts* below 1800 *ft*. During the last two test flights the wind conditions prevailed completely different. The approach took place with more than 22 *kts* headwind and under gusty conditions. LNAS was able to demonstrate its functionality in all wind conditions.

At Frankfurt Airport several noise monitoring stations are operated by Fraport and the Umwelt- und Nachbarschaftshaus (UNH). The approaches were performed with and without the support of LNAS display so that the noise measurements provided by UNH and Fraport need to be preprocessed. The proportion of usable measurements decreases with increasing distance to the threshold. This effect can be explained by the flown altitude and the sound attenuation by geometrical spreading. Unfortunately the noise monitoring stations are not based on the entire final approach so that not all advantages of the pilot assistance system LNAS, especially the later landing gear extension, can be shown by the noise monitoring station measurements. This circumstance only allows noise reduction prognoses in specific areas, which are shown in Fig. 12. At the intermediate altitude before the glideslope interception, the first and second configuration can be done more precisely with the aid of LNAS, so that the optimal energy balance is better achieved in order to avoid an unnecessary increase in the thrust or a later speed brake use. Depending on the current traffic volume, at high traffic densities the aircraft will probably have to follow the speed restrictions of air traffic control from a distance of approx. 15 NM until approx. 5 NM. These restrictions limit the freedom of the system to optimize the actions and reduce the expectations for noise reduction in this area. The later extension of the landing gear and the landing configuration on the final approach segment can result in a noise reduction of up to 5 dB(A) in the area of landing gear extension, as can be seen in the measurements.

Fig. 12. Noise reduction areas EDDF/RWY25R

In addition to the aim of reducing aircraft noise, a lower fuel emission was achieved. In Fig. 13 the average consumption saving of approaches with the support of the LNAS compared to approaches without the system can be seen. The graph shows the average fuel savings achieved when LNAS is used at a certain distance relative to the distance to the stabilization height (1000 *ft* above ground). For example, 10 *%* fuel can be saved if LNAS is used from a distance of 25 *NM* to the stabilization level. An Airbus A320 with a landing weight of 62 *t* requires about 300 *kg* of kerosene for the same segment, so that with the use of LNAS up to 30 *kg* of kerosene per approach can be saved.

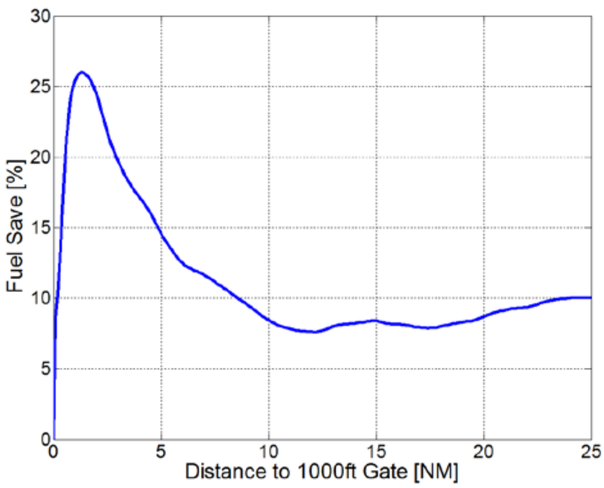

Fig. 13. Average fuel savings of all test flights with the support of LNAS

In the distance range between 1 *NM* and 3 *NM* up to the stabilization height, maximum fuel savings of more than 25 *%* are possible. This is based on the relationship between the extension of the landing gear and the final flaps configuration, as well as the subsequent necessary increase in the thrust to stabilize the final approach speed. The savings of more than 25 *%* reflects the optimal configuration setpoints and the setting of the stabilization thrust when approaching with LNAS.

The situation just described is also reflected in the fuel save during the fifth test flight in Fig. 14. In addition, a significantly higher fuel saving can be seen between 10 *NM* and 25 *NM* compared to the average fuel save for the entire test flights. That is explainable due to less requirements of air traffic control, which resulted in a precise implementation of the approach according to the optimized LNAS specifications.

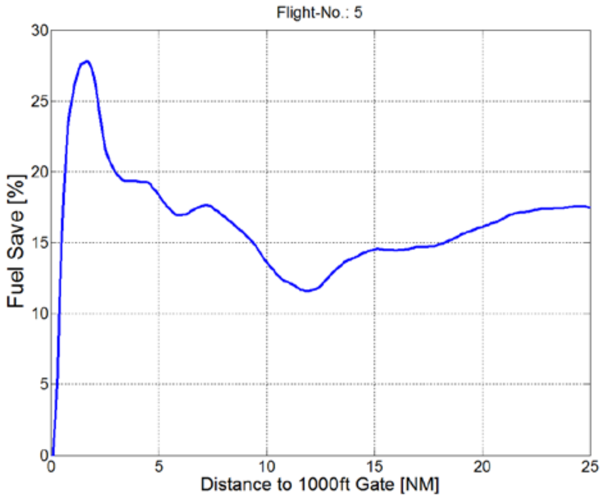

Fig. 14. Fuel savings with more freedom of decision of the pilots

6 Summary and Outlook

The design of low-noise flight procedures is a complex process. Even under ideal conditions (calm atmosphere, not influenced by other traffic or air traffic control) the generation of sound at the different main sound sources of the aircraft cannot be influenced independently. The aircraft-specific design of the approach profiles is therefore of great importance; it requires a sufficiently accurate calculation or simulation of the trajectory in order to achieve the optimum noise reduction. These include adapting the method to the weight of the aircraft and the prevailing wind and weather conditions, as well as changing the configuration to the resulting exact times. Additionally actual flight operations are subject to the need to reach the touchdown point timely as precisely as possible for capacity reasons. For this purpose, course and speed specifications are given by the air traffic control. In all of this, it should be noted that from an economical viewpoint inefficient procedures have no chance of practical implementation.

One promising approach is the on-board assistance system LNAS that helps pilots to manage their energy budgets, thus enabling a more accurate approach. This is an indication of the so-called energy level, which sums up potential and kinetic energy over the vertical profile of the flight path. Taking into account the (usually given) setpoints for speed reduction, optimal times for the extension of the flaps and landing gear are calculated. The pilots are informed about the energy error from the system at any time during the approach. Effects caused by changes in wind conditions or new instructions from air traffic control are immediately visualized. If the constantly updated forecast predicts a sufficient energy reduction up to the stabilization height, the precautionary, noisy use of spoilers and too early extension of the landing gear can be avoided.

The LNAS assistance system has been tested by pilots during real approaches at Frankfurt Airport. After the flight trials all pilots confirmed that LNAS has a huge potential to optimize approaches especially in difficult situations like strong tailwind or speed restrictions. This success is also due to the fact that pilots were already involved in the development of the system within simulator experiments and thus also contributed to the conception.

In summary, LNAS has a general tendency to avoid aircraft noise, improve speed and configuration management and reduces fuel consumption. A reduction in the influence of the air traffic control with regard to restrictive instructions would result in significantly higher fuel savings, as the evaluation of the flight data shows. Above all, the areas of setting the final landing configuration as well as the landing gear could be moved further towards the runway threshold. A closer look to the noise measurements reveals a noise reduction potential in certain areas along the approach path, thus confirming the positive effects of the improvements described above.

LNAS was able to prove its applicability in simulator tests and was tested under operational conditions at Frankfurt International Airport. The system proved to be a useful contribution for:

- temporal or local precision when setting the flaps and landing gear
- speed management
- noise reduction by up to 5 dB(A) in the area of landing gear extension
- the greatest possible avoidance of the noiseless spoilers
- reduction of the average engine speed N1 or the average thrust level
- fuel consumption
- stable approaches to the "1000 feet" gate

Despite the successfully completed flight trials at Frankfurt Airport in September 2016, cooperation between airlines, airport operators and authorities is essential to identify more closely noise and economic effects by long-term tests. Such a project is necessary to further develop LNAS from the concept stage to a prototype assistance system. A new test phase in operational flights at various international airports has been started. Therefore, the German airline Lufthansa equipped up to 86 aircraft of the A320 family with LNAS for a long-term test of one year.

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