A DYNAMIC CHANNEL DEPICTION OF NAVIGATION DATA IN SYNTHETIC VISION DISPLAYS

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1. ABSTRACT

During the last years Jeppesen has developed digital terrain, obstacle and airport databases as well as different electronic displays as part of the NASA Aviation Safety Program. This paper describes the continuation of this work, which is now focused on a completely dynamic channel depiction of navigation procedures inside a SVS display.

A human factors workshop has been conducted to identify the pilot's expectations and requirements for channel guidance. Pilots from the GA, BA and CA segment and charting experts participated in the workshop. The workshop covered three main topics of the program. A general information and task analysis revealed what information the pilots need while flying a procedure. The two other sessions dealt with the generation of the channel trajectory and the depiction of the channel trajectory.

Based on the results, the channel trajectories are generated dynamically using the flight dynamics of the aircraft in order to make the trajectory easily flyable even in turns and within the performance parameters of the aircraft. Trajectories can be generated for ARINC424 coded STARs and approaches. Additional trajectories and guidance cues for intercepting or reentering a procedure are generated, as well as ATC commands like radar vectors and missed approach procedures. The generated trajectories are verified to ensure they do not conflict with special use airspaces, obstacles and terrain.

Different concepts for the trajectory depiction have been implemented. The dynamic crow's feet tunnel as suggested by NASA has been compared to inverse symbology where the tunnel walls become shorter and shorter when approaching them. This minimizes the repelling nature of the tunnel walls and avoids the discontinuity when leaving the tunnel completely. Another idea was, not to use the corner of the tunnel as guidance symbol that (crow's feet), but the medians of the four tunnel walls.

Finally, the components of the new SVS display have been compared in a simulator evaluation. An approach to Colorado Springs has been used to check three different tunnel depictions either with or without 2D guidance cues on STARs, Approaches and Radar Vectors into this airport. A scenario at Frankfurt/Germany has been used to validate different ways to generate intercept trajectories and the trajectories in the turns of the S-shaped RNAV-transition into Frankfurt. The situational awareness of the pilots has also been supported by a simple navigation display which showed the channels in front of a synthetic terrain depiction.

All displays are driven by a single database system that delivers navigation, terrain and obstacle data required by the system.

2. INTRODUCTION

During the last years, Jeppesen and TU Darmstadt have developed electronic obstacle and terrain databases as well as synthetic vision displays [1]. Over time, these displays emerged from simple viewers of pre-generated data to systems which are capable of displaying additional navigation information using flight guidance channels generated on run-time [2].

During last years flight trials, the SVS display itself has been evaluated successfully, but several aspects related to the flight guidance channel depiction have been found to need improvement.

1) The flight mechanical properties of the aircraft have not been considered in a sufficient way during the generation of the guidance channel. Pilots inadvertently left the guidance channel mainly caused by inertia of the aircraft.
2) The graphical depiction of the trajectory has not been satisfying in terms of cluttering.
3) The scope of usability of the trajectory generation has been limited to several approach procedures and simple STAR maneuvers.

These issues have been investigated in the work described here.

3. HUMAN FACTORS PILOT WORKSHOP

The intended users of SVS displays are pilots from general, business and commercial aviation (GA, BA, CA). Thus it is important to gather input from this target group. The eleven participating pilots have been selected accordingly. Four of them were ATPL licensed; seven were CPL licensed, some of them with a frozen ATPL. Due to the constraint that all pilots need to be IFR rated, no PPL licensed pilot could participate in the workshop. The average age of the pilots was 34 years, ranging from 25 to 51. The average flight experience was 2600h for the ATPL and about 600h for the CPL rated pilots (1500h / 250h under IFR conditions).

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3.1. Information required while flying a procedure

The work session “Task and Information Analysis” covered identified operational personal tasks of pilots while flying procedures. Approach procedure to Frankfurt/Main International airport (EDDF) and Cincinnati Northern Kentucky International Airport (KCVG) have been used as basis for talk-through reflections of information required while flying these kinds of procedures.

3.1.1. STARs ending at IAF

In Frankfurt, the GEDERN 3E standard arrival (STAR) with a subsequent ILS approach to runway 25R has been selected to evaluate procedure types starting with a STAR ending at an IAF, followed by a subsequent approach. RNAV transitions charts were not provided.

The first question was, what information are required prior to arriving at GEDERN (i.e. leaving en-route structure and arriving at STAR) and which steps need to be done when arriving at GEDERN.

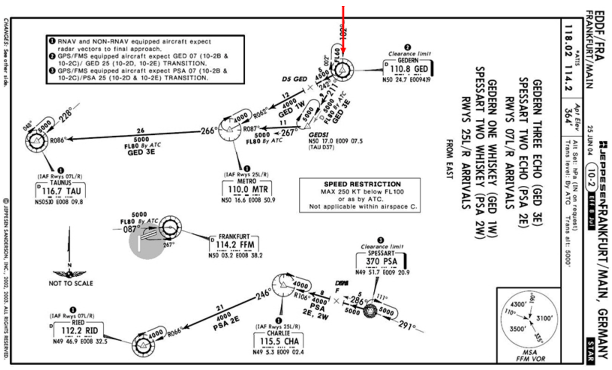

FIG 1. EDDF STAR – Approaching GEDERN

When approaching GEDERN, pilots have already checked ATIS and are entering the data into the FMS, approach checklists are read and power / speed trend is monitored closely. Information required therefore is

- Height over GEDERN
- Identifiers for VORs/NDBs
- Selected route (VORs, GPS Waypoints)
- Weather information
- Speed restrictions
- Number in holding sequence
- Pitch and power values
- MSAs for directs or abnormal procedures.

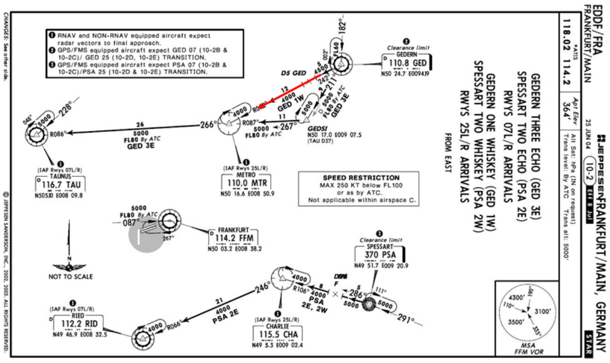

FIG 2. EDDF STAR – GEDERN to METRO

For the next segment from GEDERN to METRO, the question was which information has become obsolete, which new information is required and what else requires special attention. Answers from the pilots included

- Minimums (MSL of Taunus mountains)
- MSA
- Minimum holding altitude
- Distance to METRO
- Traffic
- Track/Distance direct to airport
- Clearance Limits

Pilots are busy with checking frequencies, heights and upcoming procedures, monitoring TCAS, changing barometer settings and flying the assigned procedure unless further notice from ATC.

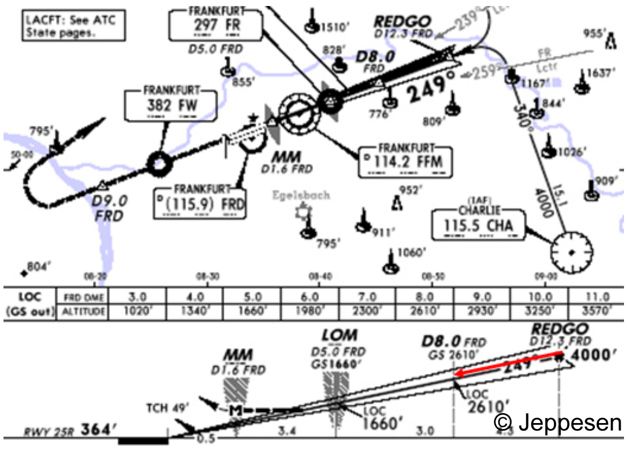

FIG 3. EDDF Approach – REDGO

For the initial approach after passing REDGO, we are assuming that MSA, height profile, MDA/DA (Minimum Descent Altitude/ Decision Altitude) and missed-approach procedure (MAP) have already been reviewed. Pilots are usually cross-checking the FMS in this phase, verifying the ILS identifier and morse code, do a mental walk-through of the height profiles and are preparing for possible runway exits and missed-approach (MA). Special attention is being paid to maximum flight height for go-around (G/A) or MAP. Pilots have requested MSA, minimums, height profile and frequencies for go-around in this stage of flight.

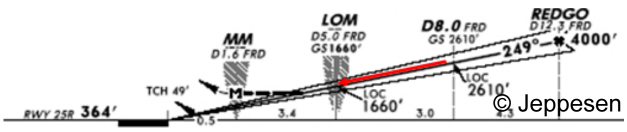

FIG 4. EDDF Approach – Loc. Outer Marker

When approaching the outer marker, pilots are intercepting the ILS glidepath, cross-checking their position and monitoring traffic. Hence they are most interested in the upcoming waypoint, the next leg altitude, time to the touchdown point, valid vertical "area", terrain, system failures.

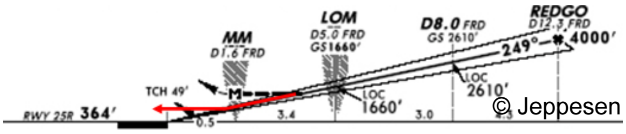

FIG 5. EDDF Approach – touch-down

In the last phase of the approach the aircraft has passed the outer marker and missed-approach point and continues it's descend to touch-down – pilots are busy keeping their aircraft on the glideslope and monitoring their sinkrate, pitch and bank closely. Information required is wind, wind correction and flight path, target speed and height above the airfield.

In general, the pilots agreed upon the necessity of additional information prior to and after touch-down. This information is bank and flare on touch-down, calculation and depiction of possible runway exits, incorporating situations like one engine out. Additionally navigation aids would be preferred by the pilots, namely arrows indicating the deviation from the intended center-line.

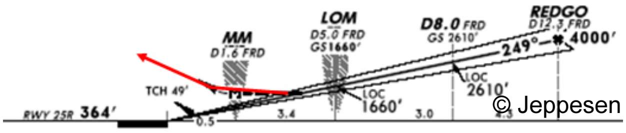

FIG 6. EDDF Approach – Missed approach

The assumption is that it is required to fly the missed approach procedure. Performed actions are reconfiguring the aircraft, checking for traffic ahead and above, switching back to radar frequency and flying the missed-approach procedure. The information required are the location of the missed-approach point, the next track and height (including minimum and maximum) and MSAs.

3.1.2. STARs ending with Radar Vectors

Similar to EDDF, a STAR and approach into Cincinnati Northern Kentucky International Airport (KCVG) has been discussed with the participating pilots. We had chosen the TIGRR arrival as an example of a STAR ending with radar vectors to the final approach.

This subsection addresses only the differences between EDDF and KCVG (i.e., radar vectors to final approach and possibility for stepped descent in KCVG).

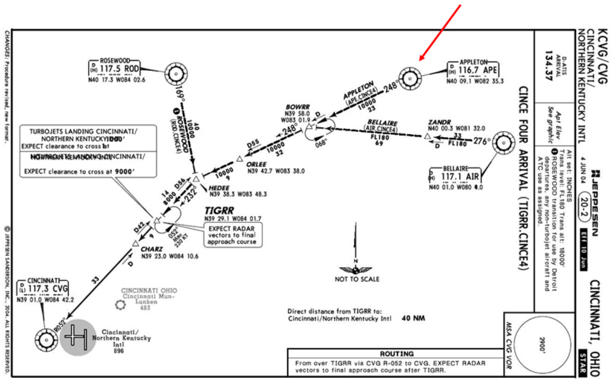

FIG 7. KCVG STAR – arriving at APPLETON

The aircraft arrives at APPLETON. Pilots would not make differences in procedure workflow compared to EDDF except that an approach to CVG is considered easier because ATC has to assign flight vectors.

The aircraft leaves the holding pattern at BOWRR and continues its flight to TIGRR. Pilots are flying the published procedure but are expecting radar vectors at any time. Pilots need speed information and the distance to TIGRR because of expected radar vectors to the final approach.

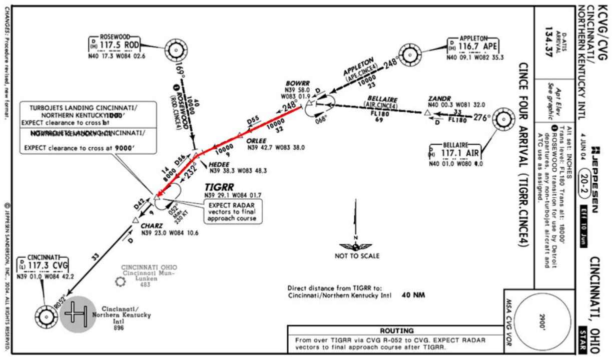

FIG 8. KCVG STAR – arriving at TIGRR

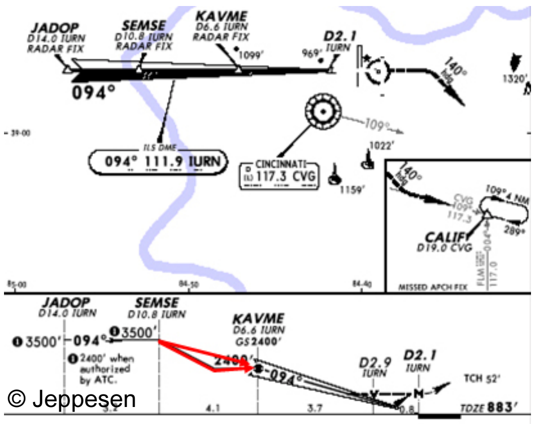

FIG 9. KCVF Approach – approaching KAVME

In our scenario we assumed a direct to SEMSE. After SEMSE the aircraft is descending to KAVME. For this type of approach both a stepped and a continuous descent are possible. All pilots preferred a straight descent.

3.1.3. Summary of the Task and Information Analysis

From the operational personnel tasks, a few information can be summarized, which should be presented to the pilot at all times, i.e.

- minimum and maximum heights
- ILS glide-slope interception
- MSA
- Speed restrictions

Pilots also stated that they would like to have a kind of virtual pre-flight of the scenario, meaning that they would like to see a virtual landing or missed-approach for briefing purposes prior leaving the en-route structure.

3.2. Requirements for the Generation of Channel Trajectories

The second session of the workshop dealt with use cases for trajectory generation. While there are numerous regulations concerning guidance precision, handling of fly-over- and fly-by-waypoints and response to ATC commands, objective of this section was the gathering of practical experience from pilots, e.g. detection/avoiding/minimizing deviations from the nominal path, maneuvers “for passengers comfort” etc.

The following subjects have been discussed with pilots for standard maneuvers:

- Possible indications of a deviation
- Tolerance of deviations in practical experience
- Counteractive measures in case of deviation
- Impacts and dependencies: Flight phase, altitude, wind etc.
- Realization of fly-over- respectively fly-by-attributes of fixes and waypoints
- Pilot’s response time to ATC commands

In a first step, pilots should collect factors influencing their tolerance regarding deviations or influencing their scanning behavior, i.e. their scanning frequency of certain instruments.

An unexpected statement, agreed by eight of eleven pilots, was that pilots try to achieve a “null-tolerance” flight path. “Even smallest deviations have to be corrected”, otherwise pilots would feel a “discomfort”. On the other hand these pilots admitted, that this behavior actually would not be essential from an operational standpoint (does it make sense to react on each small gust?!). Only three, *very experienced* pilots characterized their guidance to accord to “rules of thumb”, tolerating certain deviations, depending on a lot of factors. However, this tolerance requires the existence of accurate depiction of deviations.

Thus, a lot of influencing factors have been found. While these factors only influence the scanning behavior of the “null-tolerance” pilots, the same factors have an effect on the tolerance level of the “deviation-tolerant” pilots.

Most important factors found are:

- Altitude
- Distance to a fix
- Distance to runway
- A/C speed
- A/C performance
- Weather (wind, sight, ceiling)
- Experience (knowledge of (geographical) environment)
- Traffic

Pilots agreed that particularly combinations of negative factors, e.g. a heavy, inert A/C, low altitude and dense traffic, lead to exhaustive workload regarding their effort scanning the instruments.

Consequently, especially the inexperienced pilots might benefit from a channel display since it provides enhanced situation awareness, reducing the workload of checking several separated instruments repetitively. However, all pilots ask for “deviation scales” within the SVS display (similar to Glideslope and Localizer), additional to the channel.

The discussion led to the following, important conclusion: At least during straight flight, the calculated nominal trajectory has to match exactly the information given in charts (e.g. radials), if both, SVS and paper chart are available in the cockpit. This is a restriction for calculation of a desired path, since, for instance, radials are given without decimal places in charts, but have one decimal in ARINC 424. This deviation might lead to discomfort of the pilot if he desires a “null-deviation”. On the other hand, also the standard instruments indication is unavoidably a little inaccurate and thus differences within a cross-check are not totally avoidable.

3.2.1. Use case 1: Entering a procedure

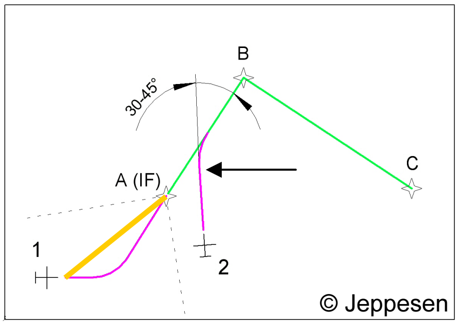

FIG 10. Entering a procedure.

All pilots rated a guidance channel for the “entering a procedure” use case to be important and helpful. But pilots stated, that in case 1 (flight to initial fix) the trajectory should be the shortest possible connection of A/C and IF (orange line in FIG 10). It is not necessary, that the “lead-In” ends tangential in the subsequent channel. In case 2, pilots recommended to hide the part of the static tunnel, which will be cut (marked with an arrow in FIG 10).

3.2.2. Use case 2: Intercepting a holding pattern

It turned out, that almost all pilots admitted to be unable to intercept a holding pattern manually, if it is not be a direct entry. Ten of eleven pilots are relying on the FMS or support from ATC in teardrop or parallel entries.

Consequently this use case has been rated to be very helpful.

Furthermore there was a discussion, if the holding pattern itself should be depicted as well. Most pilots agreed that a depicted holding pattern could be a valuable support, because during a holding, usually a lot of other tasks have to be handled. It was not generally agreed, if the depicted, nominal maneuver should provide for wind compensations. Finally it is supposed to disregard wind in a first implementation, since the trajectory should be a *nominal* path, neglecting wind generally.

3.2.3. Use case 3: Intercept after Fly-Over waypoint

Since intercepting a given radial is a standard maneuver, pilots do not rate an intercept after a fly-over waypoint as challenging. But for two reasons, this use case should be implemented anyway. First, it is needed for being consistent with other use cases like “re-intercept the channel”. Secondly, pilots stated that the fly-over-case arises very rarely, but if it arises, there is a distinct reason and pilots try to overfly that waypoint very exactly. Thus, a precise guidance to and over the waypoint is essential, and the intercept to the next radial a just consequence.

3.2.4. Use case 4: Re-enter the channel

All pilots agreed that a hint how to get back into the tunnel is necessary after inadvertently leaving the track, particularly if the tunnel moved out of the field of view. Discussions arose about the amount of dynamics of the trajectory – which is a question of interpreting the term *guidance*: Some pilots preferred a highly dynamic guidance trajectory, which is updated every frame and always starts at the nose of the A/C. Independent of the pilots action – the trajectory always leads back to the original channel. The other pilots have been concerned about confusion in this case (“a wobbling worm” in front of the A/C) and would prefer a quasi-static, additional trajectory which is generated only once on demand and which then represents the nominal path until the original path is reached. The further discussion indicated that the appropriate amount of dynamics seems to be depending on the kind of representation of the channel, which is discussed within the third session of the workshop. Finally, both concepts should be kept in mind and be investigated in simulator trials if possible.

All pilots agreed that, in case of a lost channel, the system is expected to find an appropriate re-entry-point automatically, even if the calculated point lies within one of the subsequent legs.

3.2.5. Use case 5: Missed Approach

This use case turned out to be one of the most valuable, particularly in cases of a critical missed-approach, caused by technical problems, problems on the runway etc. The workload in this case is excessive and a support in terms of a trajectory depiction would be appreciated.

3.2.6. Use case 6: ATC assigned path

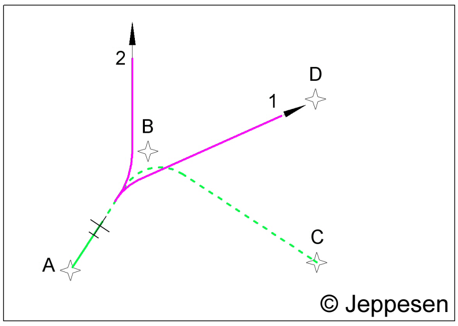

FIG 11. ATC assigned path

As expected, pilots would appreciate to get a guidance trajectory in the case of a “direct to …” assignment from ATC, modifying the planned procedure (case 1 in FIG 11). Pilots recommended deleting the original path (dashed line) completely from the display in this case: “Once ATC has modified a procedure, all plannings made before are obsolete and worthless”.

Contrary to expectations, pilots also would appreciate guidance for case 2, a very simple assignment like “turn left to heading 360”. Although this (open-ended) task obviously is not challenging, pilots recommended supporting this case as well. Otherwise it would be unclear, if there is no guidance available, no guidance necessary or if there is a system failure.

3.2.7. Use case 7: Step down

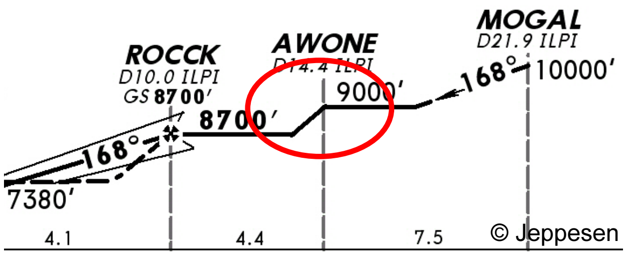

FIG 12. Step down

The question in this use case was: How do pilots handle this step-down maneuver?

Generally pilots answered, they would prefer a constant glide slope to reach the next altitude instead of a steep step-motion. They justified their opinion with the importance of the passenger comfort.

Maybe, “sportive” pilots in general aviation, being the only person on board, would prefer the second alternative, because after the step-down-task there is more time remaining for other tasks. One pilot mentioned an additional reason for stepping down with a steeper angle, if he could expect the ceiling to lie within both altitudes. This pilot would prefer the enhanced safety, leaving the clouds quickly, instead of preventing passengers from inconvenience. Indeed, the amount of safety enhancement through leaving the clouds is depending on the type of A/C.

3.2.8. Use case 8: Intercepting a glide slope

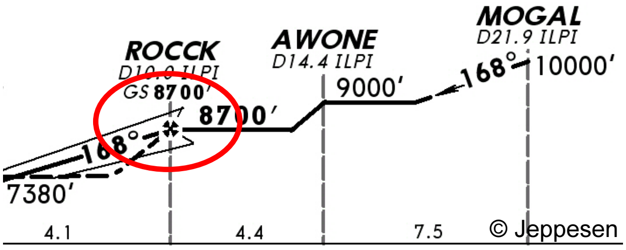

FIG 13. Intercepting the glide slope

In this use case, there are three possible ways of intercepting the depicted glide slope.

1) If the altitude of 8700' is reached before the FAF, the glide slope is initialized exactly at ROCCK. As a consequence, an overshooting over the nominal glide slope is inevitable due to the inertia of the aircraft.
2) If the altitude of 8700' is reached before the FAF, the glide slope is initialized shortly before reaching ROCCK. Consequence: It is possible to reach the glide slope without overshoot, but for a certain time, the minimum altitude of 8700' is under-run
3) The previous step down from AWONE is conducted to an altitude of slightly above 8700'. The glide slope is initialized shortly before reaching ROCCK. It is possible to reach the glide slope without overshoot and without under-running the minimum altitude. But the appropriate point in time to descend as well as the necessary plus size of the altitude have to be estimated.

All pilots agreed, that 2) has to be excluded, because under-running a minimum altitude is never allowed, not even for seconds.

Generally pilots would prefer way 3), but they agree that the estimations necessary for this maneuver are challenging. Therefore an enhanced situation awareness in terms of a channel depiction and deviation displays would be appreciated.

Method 1) would be an easy alternative as long as the overshoot can be compensated easily. This compensation is the more difficult for fast and inert A/C.

Overall conclusion was that an SVS supported glide slope intercept should aim at way 1).

3.2.9. Summary for generation of trajectories

– During straight flight, the calculated trajectory has to match exactly with information given in charts and navigation instruments for cross-checking.
– Needless or obsolete segments of a trajectory should not be depicted.
– No clear opinion regarding the amount of dynamics of the trajectory has been found. Several concepts should be implemented and evaluated.
– Different step-down-maneuvers should be implemented.
– All identified use cases have been evaluated to be considerable.

3.3. Requirements for the Depiction of Channel Trajectories

The goal for work session 3 – "Use Cases for Trajectory Depiction" was to identify situations that have to be considered for the depiction of a 3D trajectory. Pilots have discussed the identified use cases using already existing tunnel concepts (see FIG 14, FIG 15) as well as novel ones (see FIG 16, FIG 17).

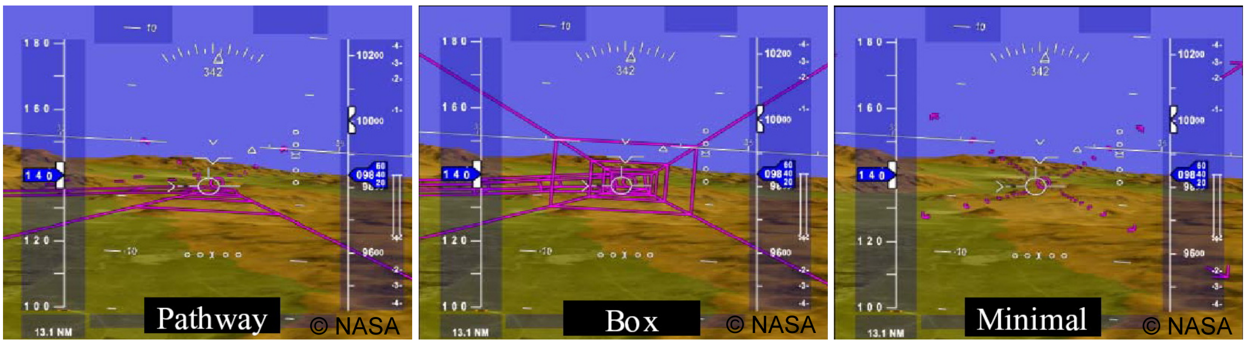

FIG 14. Different NASA channel concepts [3].

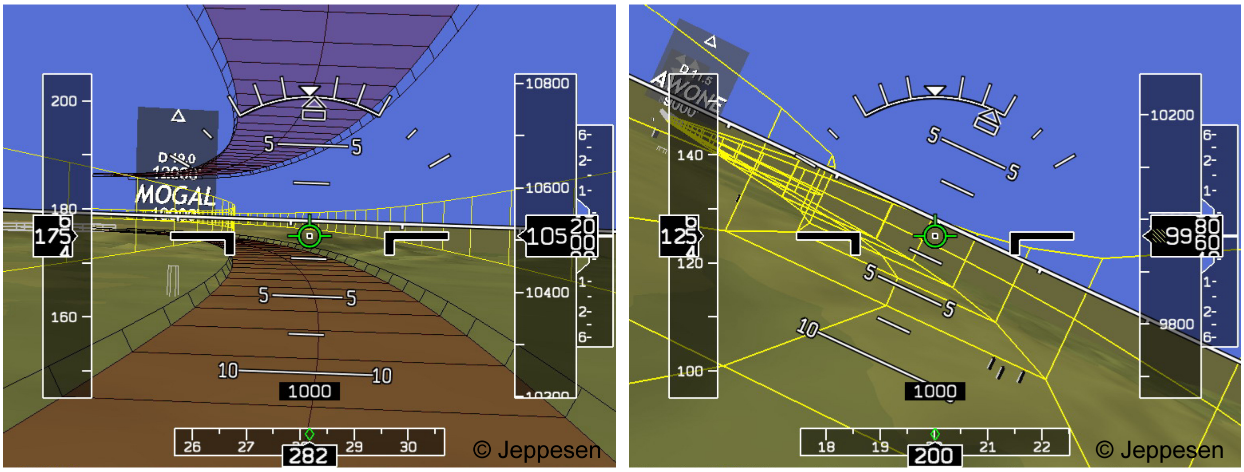

FIG 15. Two existing Jeppesen SVS tunnel concepts.

3.3.1. Static guidance elements

The presentation of and discussion about static guidance elements included the following subjects:

- Pro/contra tunnel depiction
- Alternatives to tunnel concepts
- Longitudinal and/or cross elements
- Shape/Width/ height of the guidance elements depending on flight phase
- Spacing of longitudinal elements
- Color
- Geometrical elements (straight lines, curved lines, planes (opaque, transparent))
- Additional guidance elements like ghost aircraft, flying “square”
- Shadows

3.3.2. Dynamic guidance elements

For dynamic guidance elements the following topics have additionally been discussed:

- Degree of dynamic
- Disappearance of closest element
- Length of tunnel depiction part
- Prediction/Preview

Further on, different depictions for (re-)entry or interception of procedures, assignment of ATC commands, turn accentuation and use of fix vs. leg information have been discussed with the pilots.

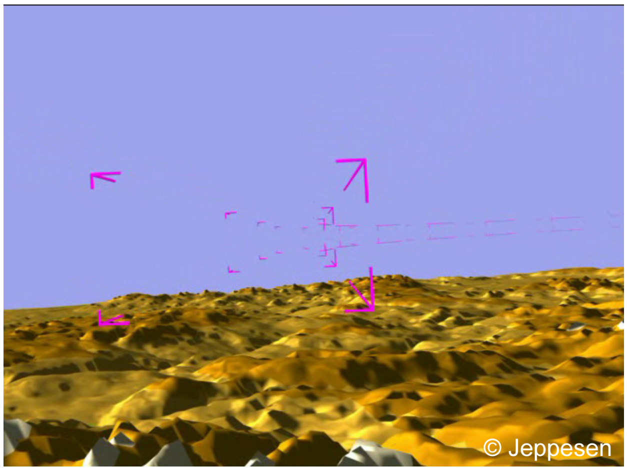

FIG 16. Example of a dynamic display concept using NASA’s crow’s feet concept.

3.3.3. Less restrictive channels

In cases of a less restrictive guidance, a tunnel depiction does not seem to be applicable. For example if the user receives radar vectors from ATC or a re-entry trajectory is calculated a generated tunnel might be prescriptive. Therefore the concept of an aircraft fixed tube has been discussed during the workshop: the tube will always begin as it were connected to the aircrafts nose bending towards the desired direction.

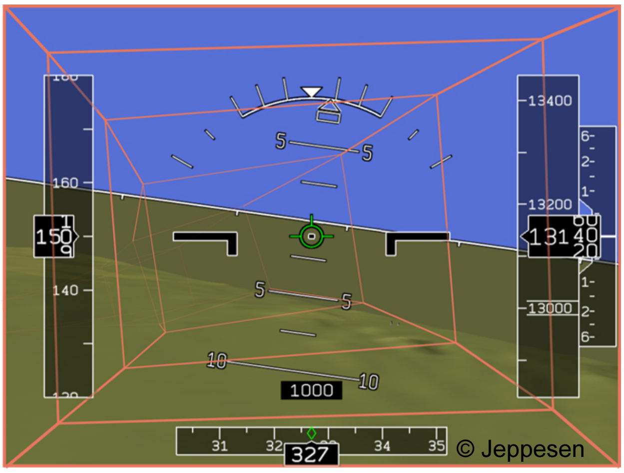

FIG 17. Example of an aircraft fixed tube.

3.3.4. General comments and suggestions

Generally the pilots were open for the suggestions and ideas. But since only images and videos were presented they often pointed out, that a simulator flight would be needed in order to evaluate a concept.

All pilots were convinced that a good implementation of 3D guidance elements would improve the situational awareness since e.g. turns can be seen on the PFD prior to execution.

Dynamic concepts were preferred to static implementations due to reduced clutter and a lighter depiction.

Most pilots pointed out that they needed “direct guidance” information like a flight director in addition to 3D guidance elements. Especially the turn initiation would be by far easier to identify using a flight director than just flying the channel. It seemed as if especially experienced airline pilots strongly recommended direct guidance information.

Most 3D guidance concepts implement a tunnel or channel depiction of the procedure. A lot of pilots criticized the presented channel implementations for not providing accurate guidance. The channel profile represents an area of tolerance while falling out of the channel implies a highly undesirable event, which may lead to overreaction. In contrast, systems pilots use today provide the nominal path and the current deviation. Especially in turns pilots doubted if a 3D guidance channel could replace guidance elements like a flight director that indicates the momentarily needed input.

For turns a more distinct channel depiction compared with the dynamic concepts for straight elements was suggested. One positive rated example was to depict the outer and lower walls of the tunnel static.

Some pilots had an issue with the depiction of channel elements until flying through them. They had the feeling they were forced to fly through the elements which may lead to overreactions. The pilots suggested letting the elements disappear before reaching them. The NASA implementation of disappearing elements was rated to be too distracting, since they disappear very abruptly. The suggestion was to fade the elements out the closer they come.

3.3.5. Summary for depiction of trajectories

It can be stated that today’s pilots are used to have flight directors and deviation indicators. They regard 3D elements more as means to provide additional situational awareness than as guidance elements. 2D guidance elements and deviation indicators should be implemented to achieve a wide acceptance under the pilots.

The following aspects should be regarded for the implementation:

– See the tunnel as additional information in the SVS, not as the main part.
– Dynamic profile recommended by the pilots
– Centerlines (horizontal and vertical) were strongly recommended by the pilots.
– Ability to describe the behavior of dynamic profiles externally accommodates easy integration of new concepts.
– Static tunnels, the dynamic NASA concept, its “opposite” as well as novel concepts should be evaluated by the pilots
– Near and far clipping planes – with fading at the near clipping plane – reduce clutter and could prevent pilots from over reacting.
– 2D fix/leg information in addition to a 3D reference should be shown in the PFD.
– Additional guidance and deviation indicators as pilots use today are required by most of the pilots.
– A “preview function” like highlighting the profile in certain distance could “calm” the display.
– Crows feet may be enough for straight elements; curved elements need to be depicted more obviously.

4. CHANNEL TRAJECTORIES

4.1. Generation of Channel Trajectories

Concluding from the results of the flight trials conducted within the Data Driven Project, an improved flight mechanic modeling of the trajectories has been developed. The channel trajectories are generated dynamically using the flight dynamics of the aircraft in order to make the trajectory easy to fly even in turns and within the performance parameters of the aircraft. Trajectories can be generated for ARINC424 coded STARs and approaches. Additional trajectories and guidance cues for intercepting or re-entering a procedure are generated, as well as ATC commands like radar vectors and missed approach procedures. The generated trajectories are verified to ensure they do not conflict with special use airspaces, obstacles and terrain.

Different channel depictions have already been shown in the previous chapters. The following three depictions have been chosen and implemented with the new trajectory generation mechanism. Additional 2D guidance cues and preview elements could be overlaid on all display concepts.

4.2. Static "open box" depiction

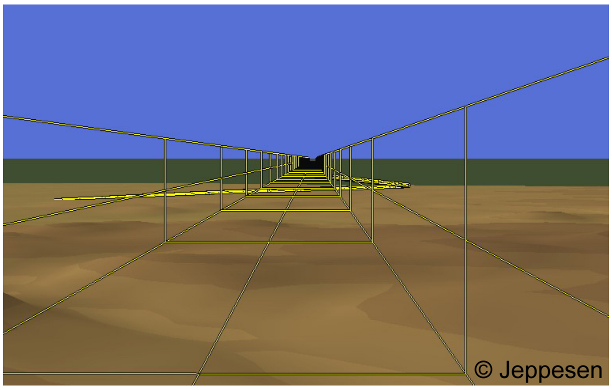

FIG 18. Static "open box" depiction.

This tunnel depiction concept is similar to those used for the test flights in Reno 2003 and Colorado 2004. The tunnels cross section remains the same independent from deviations. It is always an open box with longitudinal lines at the corners and the center of each side.

This concept does not have a preview geometry. Furthermore the whole procedure is shown without being clipped at a near or far plane. The geometry does not show roll angles in turns.

This concept was chosen to compare new dynamic concepts with "traditional" static concepts. Although the trajectory generation is advanced compared to the Reno or Colorado trials the influence of the tunnel geometry can be examined.

4.3. Crow's feet depiction

The crows feet concept is a re-implementation of the NASA dynamic tunnel implementation described in [3]. It is the first published tunnel-in-the-sky geometry which is fully dynamic. While flying in the center of the tunnel, only so called crows feet at the corner of each segment are depicted. If the aircrafts position moves towards one border of the tunnel, this border is visually emphasized. When flying outside the tunnel geometry, it is shown as a box with an open side towards the aircraft.

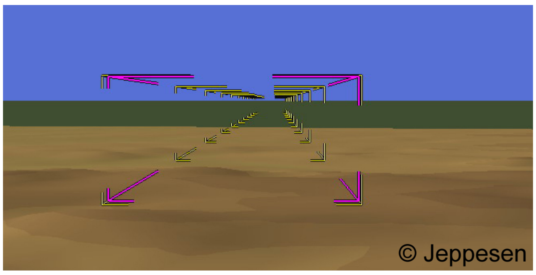

FIG 19. Crow's feet depiction.

In this concept, the crows feet implementation will be used throughout the whole procedure. One crows feet segment flying several seconds in front of the aircraft will be shown as preview (purple). The tunnel will be clipped at a near and a far plane without fading. Since pilots expressed their demand for an explicit deviation scale, this was implemented and will be shown in this concept (FIG 21).

This concept was chosen because it is the first and only published dynamic tunnel concept. Therefore it can be used to compare other dynamic implementations with.

4.4. Modified crow's feet

Within the SVS pilot workshop, two major deficiencies of the crow's feet were identified:

– Lack of direct flight error retrieval
– Possible risk for overreactions due to closing tunnel sides

To resolve these issues, a third concept has been developed for the simulator trials. While flying on the centerline of the calculated trajectory, elements similar to the crow's feet are depicted. One major difference is the position of the crow's feet: differently from the NASA implementation they are not depicted at the corners of the tunnel but at the center of each side.

The second major difference is the behavior of the geometry while deviating from the centerline. The elements the aircraft is moving to are becoming shorter, those farther away are becoming longer. While flying outside the tunnel, the side to enter the tunnel is open while the remaining sides are completely closed. This overcomes two possible issues of the NASA concept: the "closing" tunnel sides which may lead to overreactions and the complete switch of the tunnel geometry when flying from inside the tunnel to outside the tunnel.

Since the recognition of the small crows feet elements is not easy in turns, this concepts uses the static open box in turns.

This concept uses one segment as preview flying several seconds in front of the aircraft. All tunnel segments are clipped and faded at a near and a far clipping plane. As well as in concept 2 explicit deviation scales are shown.

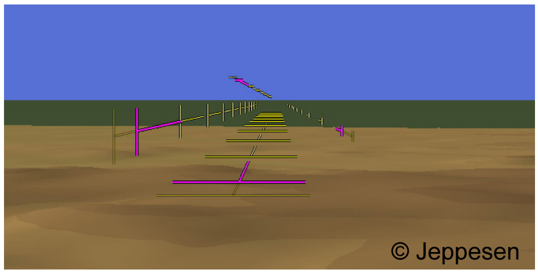

FIG 20. Modified crow's feet depiction.

As many pilots had requested a flight director for better turn initiation, a flight path marker (green circle in the middle of FIG 21) and a deviation marker (purple circle) have also been added to the display.

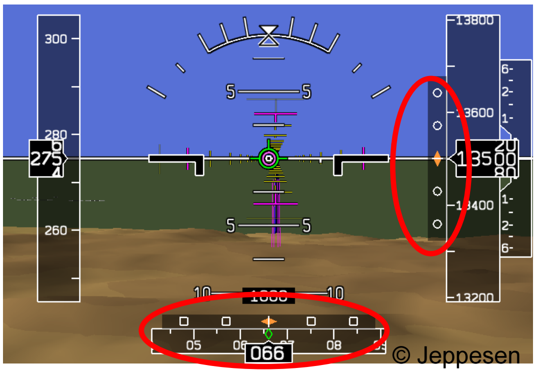

FIG 21. SVS display with deviation scales, 2D flight path marker and 2D deviation marker.

5. SIMULATOR TRIALS

The newly developed trajectory generation and trajectory depiction algorithms have been evaluated in simulator trials, which have been completed recently. 12 pilots completed all test scenarios, 7 were active airline pilots, and 5 were CPL rated with frozen ATPL. Their flight experience ranged from 250 to 15500 flight hours at an average 4983 flight hours. IFR flight experience ranged from 0 to 15400 hours at an average of 2871 hour.

A STAR/App. scenario into Colorado Springs (KCOS) using the DEBERRY1 arrival, followed by a RNAV (GPS) approach to runway 17L has been used to evaluate the different *trajectory depictions* including radar vectors.

Preliminary results show that the flight technical error is quite small for all concepts. Therefore, the statement can be made that through the depiction of the flight path alone, precise navigation is possible.

On straight elements, the additional overlay information had significant influence on the performance. Concepts using deviation bars/ predictor had a significantly lower standard deviation of the vertical error than those flying without this information. For curved segments, the additional overlay information generated a significantly lower variance of the vertical error as well, but has negative influence on the roll velocities (significantly higher). For all depiction concepts, pilots tended to fly towards the inside of the depicted trajectory in turns. The modified crow's feet concept showed higher lateral deviations as well as a wider distribution of lateral deviations although having a significantly lower variation in roll velocities.

Generally, the pilots preferred the static open box concepts. In terms of dynamic elements, the crow's feet were preferred to the modified crow's feet.

The 3D ATC vector depiction shows positive effects for the vertical navigation accuracy. Pilots using theses elements have a significantly smaller standard deviation and therefore stay closer to the assigned altitude.

An arrival/approach scenario into Frankfurt/Main (EDDF) has been used to verify *trajectory generation* in the various turns of these procedures (GEDERN Rwys 25L / R RNAV Transitions STAR; RNAV (GPS) 25R). Additionally the newly developed re-entry-feature has been tested in two different ways. The deviations from the nominal path in the Frankfurt scenario have been quite small. Situations where pilots left the channels entirely have been very rare. However this accuracy could only be accomplished with partially intensive steering inputs and therefore excessive bank rates.

The basic hypothesis that a successful, accurate initiation of a turn affects the entire turn in a positive way could not be confirmed. Results during the stationary parts of the turns varied strongly, reducing the significance of the total results. A separate evaluation of the actual curve initiations showed tendencies confirming the hypothesis: The lower aircraft's inertia and pilot's delay have been assumed for calculation of the trajectory, the higher the resulting roll-angle-error was. It can be assumed, that accumulated roll-angle-errors are causing heading errors, accumulated heading errors causing position deviations – or intensive compensating steering inputs. The indication of the appropriate moment of rolling input shows a slight tendency to have a positive influence.

Detailed results including Cooper Harper Rating, NASA TLX, Situational Awareness Rating and Stress and Terrain Awareness Test, Display readability and flyability rating will be presented next year.

6. REFERENCES

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