Identifying the Achilles' Heels of Instrument Flight Procedures

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ABSTRACT

An Instrument Flight Procedure, as it can be retrieved from the database of the Flight Management System (FMS) is the final output of complex process, which starts with gathering of aeronautical and non-aeronautical information, continues with design of the procedure, its documentation, validation and publication in the State's Aeronautical Information Publication (AIP). Consequently, navigation Data Houses code the procedure into ARINC-424 format, and finally a Navigation Database Provider pack the procedure into specific database adapted to use by FMS of aircraft.

Position of the validation and flight inspection of instrument flight procedures in this chain is such that it represents the last barrier, which might prevents public use of potentially dangerous procedure. Therefore, flight inspection personnel must be capable to recognize, whether the instrument flight procedure is safe or not.

Better understanding of instrument procedures design, designer thinking as well as information about designer's tools, procedures and limitations enable to identify key risk issues of the procedure, which is subject of flight inspection.

The article describes instrument flight procedure lifecycle, processes inside the designer's office, and highlights factors, which affect instrument procedure design. Finally, some examples of mistakes or misunderstandings in procedures are provided.

INTRODUCTION

Flight inspection is traditionally based on in-flight measurement of signal in space produced by air navigation systems. The rationale behind is the diction of ICAO ANNEX 10 Volume I, Chapter 2, 2.7 [1], where the need of flight tests of radio navigation aids is mandated. ICAO Doc 8071, Volume I, Chapter 8, 8.3.1 [2] states, that an objective of the flight inspection evaluation of instrument flight procedures is to assure that the navigation source supports the procedure, ensures obstacle clearance, and checks the flyability of the design. As an implication, flight inspection of instrument flight procedures is mainly oriented to inspection of navigation systems. Therefore, for conventional procedures, the need for their flight inspection is not so urgent, as radio navigation systems are periodically flight-tested and eventual defect of the procedure is discovered as a part of such tests.

Different situation exists in instrument procedures based on area navigation (RNAV). These modern types of instrument flight procedures are not so apparently tied to particular navigation system how is it in conventional procedures and it is open question, whether a danger hidden within RNAV procedure will be find out and subsequently eliminated.

RNAV procedures rely on series of declared points in space and it is not always clear, what radio navigation aids are used to determine position of the aircraft. The Performance Based Navigation concept is based on navigation performance of aircraft, so it is becoming responsibility of aircrew to use navigation means suitable to intended portion of flight.

Furthermore, with introduction of area navigation, traditional risk mitigation element – physical presence of signal of ground based navigation system in space is not more effective. Reliance of area navigation on data is fundamental. Due to this reliance, any change to an instrument approach procedure has to be reviewed with skilled personnel and proper tools.

THE INSTRUMENT FLIGHT PROCEDURE LIFECYCLE

Initiation

There are many aspects, which might initiate creation of new Instrument Flight Procedure. Change of Airspace design, installation of new NAVAIDs, ATC requirements, introduction of new operations (PBN, RNAV), noise problem, change of applicable regulations are only illustrative examples of potential initiators. To have knowledge about why the new procedure is designed helps to verify, whether indented objectives are met.

Requirements

Writing requirements is important part of the Lifecycle, as it significantly affects quality of final product. An expert in Procedures of Air Navigation Services (PANS-OPS) is not always participating in writing of requirements, thus requirements are often unrealistic.

Requirements Validation

In the Procedure Designer Office, set of requirement is validated and if any of requirements can't be satisfied, it is communicated back to the Originator.

Procedure Design

Instrument Procedure Design is result of creative thinking of the Procedure Designer, who performs not only the design itself, but also manages and controls overall process of design. Not all countries have a regulation of instrument procedure design in place and there are significant differences in quality of design and comprehensiveness of procedure documentation. Ideally, procedure documentation describes entire design process.

Procedure Validation

Before releasing a procedure to public use, it has to be assured, that procedure is safe and flyable. It is done by procedure validation, which should be carried out independently of the personnel involved in the procedure design. Procedure documentation should be critically reviewed by another procedure design expert, who may than propose subsequent validation activities, as simulation by validation software for selected combination of aircraft wind and temperature conditions. Output of documentation review and results of simulation might be used to flight inspection planning. Flight inspection is the final step of validation.

Validation of RNAV based procedure could be complemented with validation ARINC-424 coding of the procedure or with validation of final electronic product. To facilitate such validation, procedure has to be already included in the FMS database, which is not always possible. Having in mind, that such validation is done with only one type of FMS equipment, the value of such validation is limited to statement, that it is possible to code the procedure correctly into one FMS.

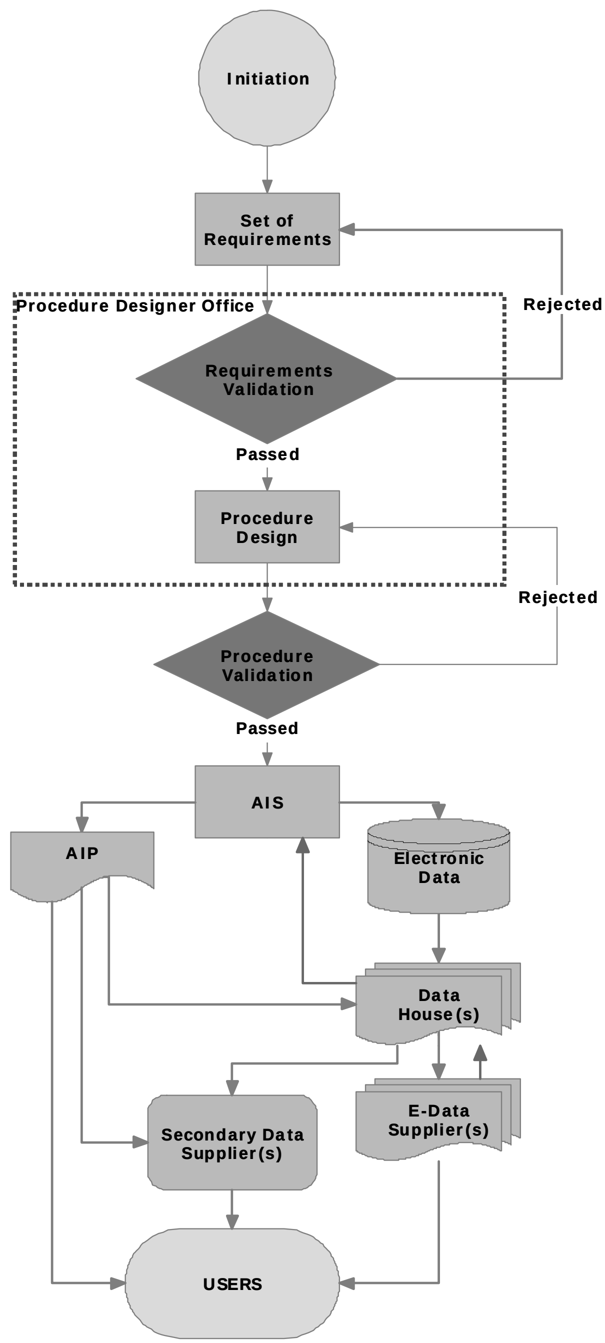

Figure 1. Instrument Flight Procedure Lifecycle

Procedure publication

Validated procedure is arranged at the Aeronautical Information Office (AIS) to agreed format and it is published in the national Aeronautical Information Publication (AIP). Beyond the point of publication in the AIP, a State takes no responsibility for quality of data. Some of AIS produce not only paper form of the AIP, but they offer also electronic data.

Procedure distribution

Procedure published in AIP is directly usable by end user, but more common practice is, that the procedure is reviewed, reformatted and charted into form, which fits needs of real operations. Data from AIP or electronic data are processed in one of Data Houses, where the procedure is coded in accordance with ARINC 424 standard. It is important to realize, that "coding advise", which could be provided in AIP is not mandatory for a Data House. These "Type 1" data from Data Houses are then adapted by Data Suppliers to meet requirement and capabilities of individual FMS equipments.

THE INSTRUMENT FLIGHT PROCEDURE DESIGN AS A PROCESS

The instrument procedure design is a chain of progressive sub-processes, as it is illustrated in Figure 2.

Requirements Validation

The instrument procedure design starts with detailed analyses of what is required. As the personnel, who prepared set of requirements are not necessary PANS-OPS experts, it has to be verified by procedure designer, whether it is feasible to design the procedure in accordance with requirements as well as with applicable regulation. Indistinctness is communicated back to the originator, who should modify set of requirements into acceptable form.

Data Gathering

The designer has to collect all relevant data associated with Aircraft, Aerodrome, ATC, NAVAIDs, Maps, Terrain, Obstacles and Weather. Data must be reliable and current, which may not be easy to assure; or they are unacceptably expensive. Hopefully, access to reliable data will be improved after full application of ICAO ANNEX 15 requirements [3].

Data Processing

First, the designer has to choose common platform, in which the entire design will be created. Data processing in context of the design means transformation of all data into the selected Designer's Working Space and redistribution of data to different layers.

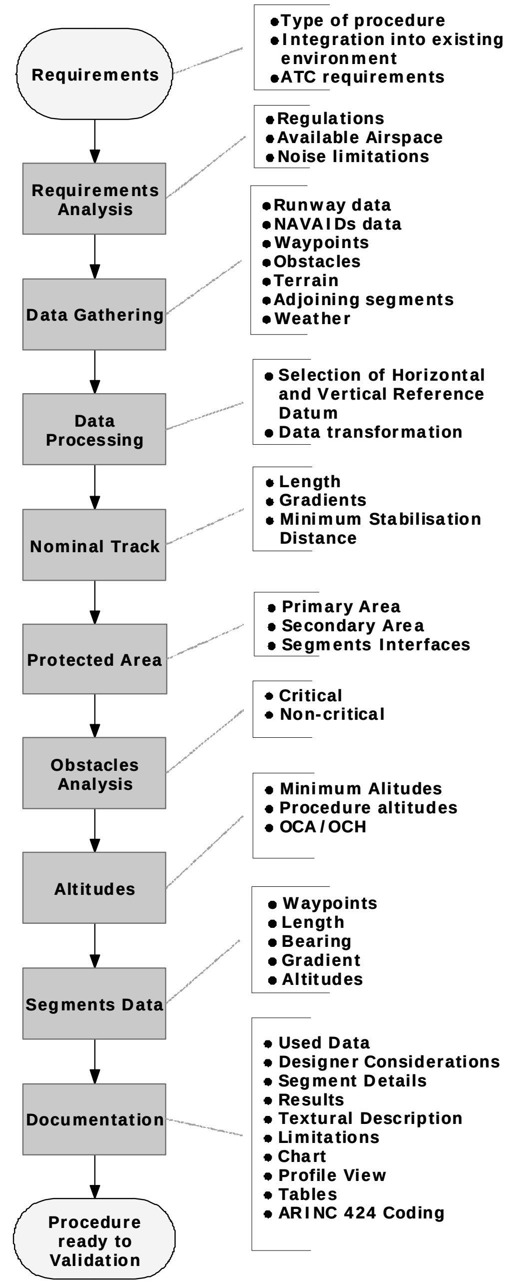

Figure 2 Instrument Procedure Design Process

Nominal Track

The construction of nominal track is an iterative course of actions, where an initial draft is progressively fine-tuned up to moment, in which the designer is fully contented with his/her work. In accordance with PANS-OPS principles [4], construction of nominal track match rather faster aircraft as slower ones. From the nominal track are calculated gradients, lengths of segments, minimum stabilization distances, and true bearings. Normally, precise geodesic calculations are applied to bearings and distances calculations.

Protected Area

To accommodate navigation uncertainties, flight technical errors and maneuvering of aircraft of different categories in any weather conditions, the nominal track is surrounded with protection area. Where positive track guidance is available, entire protection area is divided to primary and secondary area. Final and missed approach phases of precision approaches and approaches with vertical guidance are not protected with primary and secondary areas, but sloped surfaces called Obstacle Assessment Surfaces (OAS). While construction of protection areas of stand-alone segments is well unified, interfaces between segments are often problematical.

Obstacles Analysis

Applying appropriate value of Minimum Obstacle Clearance (MOC) or OAS is the obstacle situation analyzed. Correctness of the construction of protected areas and completeness of obstacle database are main factors, which determinate quality of Obstacles Survey. Obstacles are classed as critical, which affect calculation of Obstacle Clearance Altitudes/Heights (OCA/OCH) and non-critical with no impact on the procedure.

Altitudes

Results of obstacles analysis are values of OCA/OCH for each segment. Minimum altitudes of segments are usually value of OCA rounded up to nearest higher feet, 50 feet or 100 feet as appropriate for particular segment. The principle of descending during Arrival/Approach procedure has to be respected in calculations of minimum altitude. For example, when OCA of initial segment is lower than OCA of intermediate segment, the minimum altitude of initial segment has to be increased to the OCA of intermediate segment or above it. These minimum altitudes might be increased to procedure altitudes in order to respect ATC requirements.

Segments data

Segment data is aggregation of: Nominal track data as are waypoints coordinates, lengths, distances, turns, radials, bearings; Nominal profile data as are OCA/OCH, minimum and procedure altitude and gradients; and Protected area data, as are dimensions of primary and secondary area and obstacles relevant to the segment.

Documentation

Entire procedure design process should be in depth explained in procedure documentation. It should be apparent, what procedure was required, what initial data were used to procedure design and what were limitations affecting the work. Procedure designer should explain, why he/she decides to design procedure by way as it is done. All segments should be described in details; calculations and analysis should be referenced to formulas and methods in the regulations. The textural description of the procedure should be provided and all applicable limitation should be clearly formulated. Graphical presentation of the procedure, i.e. charts with horizontal view and profile view should be included, as well as all related tables. The designer should prepare the ARINC 424 coding advice, which has, as was mentioned above, non-mandatory status for data houses, but it might helps data houses to understand and follow the philosophy of design.

FACTORS AFFECTING THE DESIGN

Considering the Instrument procedure design as a process with its inputs and outputs, impact of any input to the final product might by evaluated. All inputs are interpreted as effect of People, Methods, Regulations, Tools, Data and Environment. Such classification facilitates the identification of potential sources of the product deficiencies.

People

Generally, there are no obligatory requirements for formal certification of Instrument procedure designer. It is good practice to require appropriate professional background; usually a pre-requisite to attend Instrument procedure designer training course is former experience as a pilot or as an air traffic controller. This might, of course, affects designer's professional feeling. Former pilots have better understanding of workload distribution in different phases of flight, whilst the air traffic controllers have better understanding of organisation of air traffic flow.

The Instrument Procedure Designer is the most important – but not the only - person, of whom the quality of a procedure depends. The Client, who initiates the design should be familiar with operational environment and should be competent to prepare comprehensive list of requirements. The Charting expert has to arrange all data on chart respecting the safety relevance of various information and limitations and assures good readability of chart in-flight. The Procedure Validation specialist should be familiar with all applicable standards and should be capable to identify and evaluate all potential risks of the procedure and provide worth input to subsequent flight inspection. The Flight Inspection Pilot should understand to construction principles of procedures protection areas and keep in mind not only behavior of flight inspection aircraft, but capabilities of all aircraft categories. The Flight Inspector should have thorough knowledge of procedure design principles as well as flight inspection practices.

Regulations

Three levels of regulation of instrument procedure design can be recognized: international, regional and national. International level represents ICAO Doc 8168 Volume II [4], the basic guidance material for procedure designers. It has lower status as ICAO SARPs have, but it is very well accepted worldwide. Regional level represents, for example, Eurocontrol Guidance Material for the Design of Terminal Procedures for Area Navigation [5], boundary between regional and national level represent TERPS - U.S. Standard for Terminal Instrument Procedures [6] or Australian Manual of Standards Applicable to Instrument Flight Procedure Design [7]. At national level are Aviation Acts of individual States, standards and directives of national aviation authorities. Procedure has to be in compliance with all applicable regulations at airport concerned, so flight inspector must be aware of what regulations are applied to procedure.

Methods

In general, it is not possible to inspect the procedure designer office from inside. However, the quality of internal processes affect designed procedure significantly. Procedure design is a sequential process – in case it is necessary to go back to a previous step, all succeeding activities have to be performed again. It may be enticed for designer reuse some parts of his/her previous work, but it may lead to unwonted effects as are incorrect location of waypoints, deformation of protected areas, omitting relevant obstacles, inadequate lengths of segments, exceeding gradients and many other defects of the procedure.

Interpretation and application of regulation depends primarily on quality of training of the designer. The designer, of course, do all the best what he/she believe it is, but opinion of validation specialist or flight inspector may be different (but not necessary correct…). It is important to distinguish, what is an attribute of the designer's creativity and what is a lack of compliance with regulations.

It is usually not possible to make the design in real 3D world. Designer has to set up a coordinate system, which is the most appropriate for airport location for purpose of the design. Such system is called Designer Work Space, in which entire design is done. Only some important geodesic calculations are performed outside of this Work Space using precise formulas.

Environment

Designer has to deal with number of environment related restrictions, as are airspace availability, noise restrictions, areas with sensitive fauna and potentially dangerous areas. It has to be clear, what must fall into available airspace: entire protection area, primary area only or nominal track only.

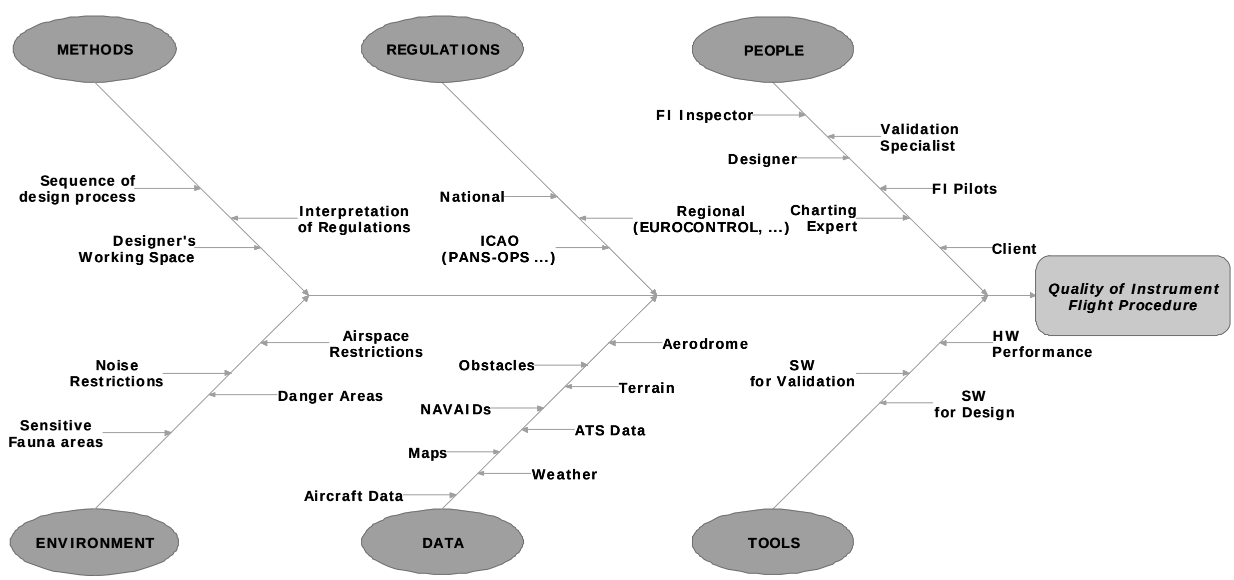

Figure 3 Ishikawa Diagram of the Instrument Procedure Design

Data

Quality and completeness of data have the most critical impact on safety of procedure. It is typical, that data comes from different sources and it is task of designer to transform them into common platform of the Designer Work Space.

Aircraft data, as are aircraft category, wing span, distance between path of the GP antenna and the lowest part of wheels, Minimum Equipment List are factors affecting procedures. In some cases, for example where non-standard missed approach or departure gradient is required or in case of airspeed or altitude restrictions consultations with operators should take place. It is role of validation to verify, whether such consultations were done.

Relevant Aerodrome Data are: horizontal position and elevation of runway ends, runway thresholds, Departure End of Runway (DER), Aerodrome Reference Point. These data are usually declared as WGS-84 data; in reality they were directly surveyed or transformed to some realization of International Terrestrial Reference System (ITRS) – European Terrestrial Reference System 89 (ETRS-89) for instance.

NAVAIDs Database should include horizontal position, elevation, frequency, identification, Designated Operational Coverage, DME offset, GP angle, ILS Reference Datum Height (RDH). There are usually no problems with quality of NAVAIDs Data. However, it shall be assured, that navigation systems performance is sufficient to support the procedure. Especially, initial phases of departure procedures are important from this point of view.

Data, as are fixes/waypoints, which are required be used in procedure, interfaces with other procedures, procedure altitudes and other ATS related data should be judged in the earliest phases of the design work.

Obstacles data might be obtained from various sources of different accuracy, completeness and reliability. While completeness of obstacle data is critical, uncertainty of position can be taken into account by virtual increasing of obstacle dimensions. Important is to consider effectiveness of obstacle control policy to be sure, that all obstacles were included. Height of trees, other vegetation and possible uncontrolled structures should be evaluated and incorporated into obstacle data.

3D terrain data are useful to visualize procedure and it helps designer to optimize placement of the procedure into surrounding terrain. From terrain data is also derived information, whether mountainous terrain criteria - increasing of MOC - shall be applied or not.

Historical records of temperature and wind speed can be used instead of standard values. In some cases, standard values are not conservative enough, for example in equatorial area should not be use International Standard Atmosphere +15°C figure, but higher. Special situation represent procedures based on radar vectoring, where cold weather corrections have to be accommodated into minimum vectoring altitudes.

Maps or satellite images are used in procedure design to digitize terrain contours, spot heights, or to provide background graphic. Maps are available in electronic form or in paper form. Paper maps have to be scanned before using in the design. Regardless of map is electronic or scanned; it has to be transformed into designer Work Space. This transformation brings risks of transformation error, which can be interpreted as an error of translation, rotation, zoom or a combination of above.

Tools

Nowadays, an age of drawing board and tracing paper is irrevocably away. Number of software tools with different degree of automation for procedure designers are available on the market. Generally, more automation in the software raises more prudence in use of it. A manner of validation of such functionalities should be in place - as a minimum, inside the designer's office. It is extremely important to keep control over the design and not fully rely on automation.

A performance of hardware might have an influence not only on time of work, but on quality of the design. If the hardware is not able to work with large obstacle databases, detailed maps and 3D models in reasonable timeframes, designer is forced to apply some kind of filtering of data, which could potentially lead to exclusion of safety relevant element from the design.

Obviously, it is not possible to simulate behavior of all aircraft in all weather conditions in one flight inspection flight. Suitable simulations tools are very useful for validation of procedures. A lot of problems might be discovered using simulation software, because broad range of combination of aircraft, wind and temperature can be tested.

SOME ISSUES OF INSTRUMENT PROCEDURES DESIGN

Below are provided some examples of problematic aspects of procedures, which can be experienced in procedures validation and their flight inspection.

Height above THR

RDH of 15.0m shall be optionally used for non-precision approach procedures. For APV and precision procedures, actual RDH or 15.0m can be used, when RDH is greater than 15.0m. But the use of RDH is mandatory, if it is less than 15.0m.

Length of Segments

An intention to reduce the volume of the airspace occupied by the procedure to minimum, often leads to reductions of segments lengths. It has to be verified, whether segments are long enough to perform all required aircraft maneuvers including changes of aircraft configuration, speed or altitude.

Descend or Climb Gradients

The length of segment shall be sufficient to bring aircraft from the altitude at the end of the previous segment to the initial altitude of the succeeding segment. This is the most often problem at the boundaries of the design, i.e. at points, where the work of designer starts or ends.

Numbers of misunderstandings arise from calculation of descent gradients. Problems are with location of the Final Approach Fix (FAF), which should be based on altitude of intermediate segment increased by 50ft; with altitude/distance tables, where the Earth curvature should not be considered in non-precision approaches; with Step-down Fixes, which should be annotated both with procedure altitude as well as minimum altitude.

In departure procedures, when the Procedure Design Gradient (PDG) is required due to airspace only, appropriate note indicating, that PDG X.Y% is required due to airspace only, is from time to time missing.

Insufficient Analyze of Segments Overlap

Interfaces between segments have to be evaluated carefully, when needed two times – using criteria current segment as well as using criteria for previous or succeeding segment. Typically sensitive parts are interfaces between initial and intermediate segment, between intermediate and final approach segment and between final and missed approach segment, i.e. in situations, where different MOC are applied to the same obstacle.

Use of the FAF in Precision Procedure

Normally, the FAF is not used in precision procedures, only nominal position of the Final Approach Point (FAP) might be published. Whenever FAF is used within precision procedure, it has specific meaning - an aircraft is not allowed to descent below an intermediate altitude even if the FAP is identified. This is practicable, where an obstacle penetrates OAS under the intermediate segment of the precision approach. In other cases, FAF should be annotated as “LLZ Only” in case of ILS approach.

GP Verification Point(s)

GP verification points have to be published to enable pilots to verify correctness of GP indication. These points are sometimes missing. Presentation of these points on chart should avoid their misinterpretation as Step-down fixes or vice versa.

Step-Down Fix Altitude

Step-down Fix (SDF) Altitude shall be lower than corresponding procedure altitude. If step-down fix penetrates nominal descent path, it results to variation of nominal descent gradient before and after the step-down fix.

The other mistake is, that the procedure altitude is published in lie of SDF altitude. This practice disable the use of the Continues Descent Concept, because a pilot shall interrupt the descent before the step-down fix, as it is not allowed infringing the SDF altitude before reaching of the SDF.

NAVAIDs Performance

The designer assumes, that Radio Navigation Aids works within their Designated Operational Coverage correctly. Typical mistakes are placing of the FAP outside of 10NM without confirmed ILS GP performance, placing of Intermediate Fix outside of LLZ coverage when LLZ coverage is reduced to 10NM/18NM, without respecting the ILS coverage in procedures based on radar vectoring. In departure procedures, initiation of the track guidance is often assumed below vertical coverage of system used.

Minimum Equipment List

A procedure has to be flyable with aircraft meeting minimum requirements on equipments on board. If procedure requires additional onboard equipment, it should be clearly stated in procedure description. For example, if in NDB procedure is FAF defined as an intersection with bearing to other NDB, two sets of Automatic Directional Finder (ADF) should be required.

Slow Aircraft

It as assumed, that procedure designed for the fastest aircraft category sufficiently covers needs of slow aircraft. It is not always true and some provisions related to slow aircraft are contained in the PANS-OPS [4]. Slower aircraft complete turns much earlier than fast aircraft and in some cases, slow aircraft experience track discontinuity after turns.

Missed approach Text

Only one missed approach procedure shall be established for each approach procedure. It has been observed, that some approaches that are the same but missed approach climb gradient, have published different missed approach procedure. When there is a need to distinguish between different missed approaches, single letter suffix shall be used. When RNAV procedure overlays conventional one, in some cases RNAV related text represents different track as conventional missed approach.

Speed restrictions

Speed restrictions are mainly use to reduce turns protection areas. Any speed limitation below margins provided in PANS-OPS [4] or combination of speed restriction with higher required bank angle is non-PANS-OPS feature of procedure are to be justified individually.

ARINC-424 Coding

Instrument procedure designers are generally not experts at ARINC-424 coding. The Coding Advice provided with the procedure might not be utilizable in a Data House. If FMS with real database is used in the procedure flight inspection, differences between the Coding Advice and the FMS Database should be identified.

Location of the Departure End of Runway

Departure End of Runway (DER) is the end of the area declared suitable for take-off, i.e. the end of the runway or clearway as appropriate. Positions of DER need not be published in AIP in WGS-84 format, so the designer must compute this data. If position of the end of runway is used instead the end of clearway, the design is not conservative enough.

Environmental Aspect

In populated areas, noise abatement considerations should be taken into account in the design of departure procedures. To support noise abatement procedures, an average flight path can be constructed. Sometimes, the procedure generates noise problem, which could be fixed with minor modification of the procedure.

Magnetic Variation

Entire instrument procedure design is done with reference to true north. The Magnetic Variation is accommodated in process of charting procedure, usually outside of the designer's office. Basically, two problems are related to the magnetic variation: firstly, value of magnetic variation is not accommodated, as the charting expert believes, that it is already included in the design. The second problem arises from rounding of magnetic bearings to whole degrees. Consequently, published tracks are not exactly the same, as designed ones.

CONCLUSIONS

With no doubt, instrument procedure design plays significant role in safety of aircraft operations. Huge amount of safety sensitive work lie on shoulder of sole person - instrument procedure designer.

Validation and flight inspection of flight procedures represents a barrier, which mitigates risks associated with the instrument procedures design. Effectiveness of such risk mitigation strongly depends on skills of validation specialists and flight inspectors.

To identify critical aspect of the design, it is necessary to understand applicable regulation, apprehend processes inside the designer office as well as see the procedure from onboard point of view.

Having in mind continuous transformation of flight inspection from flight inspection of systems to flight inspection of procedures, flight inspectors should become experts in instrument procedures design.

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