THE POWER OF RECORDED FLIGHT DATA ANALYSIS TO SUPPORT ILS SUSTAINMENT STUDIES

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Abstract

The Instrument Landing System (ILS) remains a key component of today's Air Traffic Management (ATM) System. Continued ILS service is critical to all of the world's large airports, where economic developments put increasing pressure on signal quality. EUROCONTROL has been working in the ICAO Navigation Systems Panel to standardize advanced reduced localizer coverage ground systems to address these challenges. In order to determine the operational acceptability of these measures, an airline advanced Flight Operational Quality Assurance (FOQA) data recording and analysis tool was used. The tool, coupled with expert knowledge of both piloting and technical standards, proved very effective in resolving complex questions about the ILS intercept maneuver and the timing of ILS approach operations in general. A key aspect of the work focuses on the ILS IDENT[1], which still serves important safety functions. Using the FOQA tool, timing and taskload of the aircrew were studied for demanding approach geometries. The study will serve to support the technical validation of the proposed sustainment measures. In addition to giving an overview of contemporary ILS issues, the paper illustrates the benefit of advanced FOQA tools, which will become increasingly important for developing the ATM system to meet the challenges of the future, such as increased air – ground interoperability.

Introduction

Contrary to what many people believe, current ILS technology is not from the 1950's. Significant evolutions have taken place to form that radio frequency beam crucial to low visibility operations, especially on the ground side. On the other hand, the operating environment has evolved as well – aircraft size and speed, airport building density etc. paint a markedly different picture today. Thus, while its longevity has outpaced even the expectations of prudent experts, the venerable ILS certainly faces some challenges. Among the most persistent effects are reflections from airport structures at shallow angles affecting the localizer. Methods deployed to deal with such reflections today are limited to countering a single problematic reflector, and often push system performance into small margins. Additionally, in many cases it is required to restrict coverage to less than what is in a standard, ICAO Annex 10 compliant system. Although this can be easily done where necessary, it does create a market barrier since no ANSP and/or state regulator wants to acquire a non-compliant system by design – even if that design would provide a superior signal. Consequently, Air Navigation Service Providers (ANSP) and ground system manufacturers desire to limit the exposure to problematic reflectors by limiting standardized radiation requirements to what is necessary operationally. The assumption that is inherent in the previous sentence is that localizer coverage is not needed operationally in a significant portion of the required ±35 degree lateral coverage. This paper reports on the work carried out to substantiate that assumption and most importantly to quantify the operational need based on current operational data.

Technical Background

Most modern Category III ILS ground installations at developed airports use a two-frequency localizer. The two frequencies are offset by a few kHz within the 25kHz ILS channel. One frequency is used to radiate the course signal that provides lateral centerline guidance by making the needles in the cockpit display move. It should be emphasized that the sector with deviations less than full scale is only on the order of ±2 degrees. The

[1] Three letter Morse code identifier transmitted as an audible signal on the localizer frequency.

other is used for the clearance signal, which provides full fly-left or fly-right guidance on either side, out to the limit of coverage. Airborne ILS receivers switch automatically from one frequency to the other during their approach due to the capture effect. Limiting radiation to a value less than ±35 degrees reduces the impact a clearance signal reflection can have on the course signal. Due to advances in antenna pattern design in recent years, it has been possible to propose a design which shifts the peak of the clearance radiation more towards the centerline (±7 degrees instead of typically 12 to 15), while still maintaining a soft roll-off out to ±35 degrees which ensures that there will be no false courses due to course signal sidelobes. Figure 1 shows the proposed antenna pattern design.

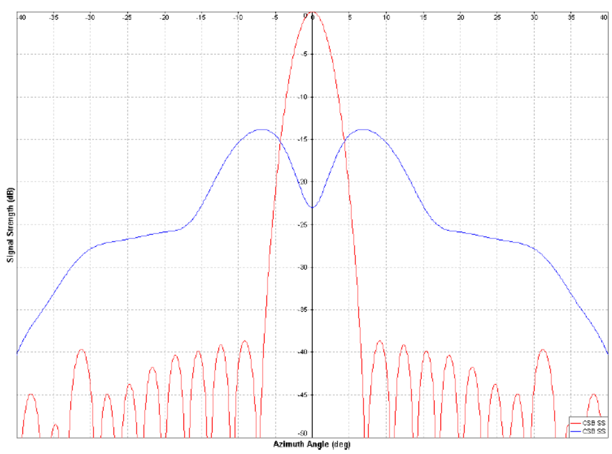

Figure 1: Reduced Coverage Localizer Design

The clearance pattern (blue) also shows a sharp cut off from ±7 to about 15 degrees, which is key to reducing airport reflections. The pattern was evaluated through simulation and modeling of a large airport site. Figure 2 shows the achievable reduction of distortions due to a terminal building. The dashed bow-tie lines show ILS Category III[2] tolerances, while the centerline curves show how a beam bend near the threshold region of the runway is reduced from barely meeting the requirements to meeting the requirements with comfortable margin. While this antenna pattern will enable maintaining low visibility landing service at challenged airports, the requirements for minimum field strength are no longer met outside of ±15 degrees. Independent from the technical feasibility and benefit evaluations, rationales were also developed to see what coverage would be needed operationally, which will be discussed in the following section. These operational rationales also support 15 degrees as a meaningful minimum coverage requirement[3].

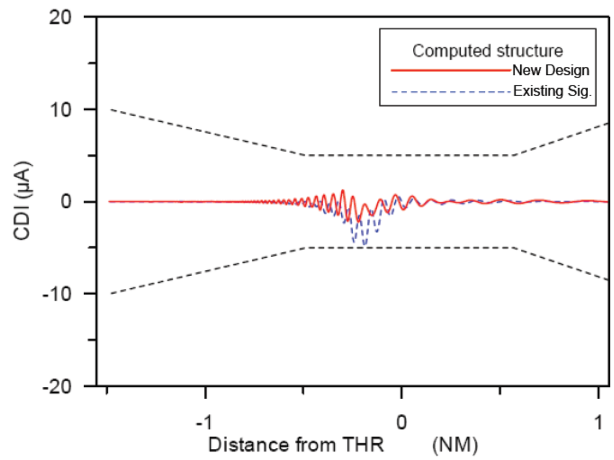

Figure 2: Modeled Reduction in Centerline Distortion

A system meeting the proposed specifications has been manufactured by Park Air Systems, Norway, and installed and tested by skyguide, ANSP of Switzerland, at Zurich airport. The localizer uses a 20 element Log Periodic Dipole antenna array and is shown in figure 3. The installation has already obtained a Category I clearance for operations, and is expected to reach Category III capability by November this year. Initial operational experience will be collected from the Zurich installation on runway 16 in the coming months.

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[2] Instrument Landing Categories relate weather minima to specific operational and technical requirements. Category III is for operations in the most difficult low visibility conditions. A good description of those categories is given in [1].

[3] While current ICAO Annex 10 Standards already permit a reduction in localizer coverage to ±10 degrees under consideration of the specific local environment and by filing a difference with ICAO, 15 degrees has been proposed as a value for global acceptance, where necessary. Current standard ILS coverage will be maintained where possible (most installations).

Figure 3: Reduced Coverage Localizer Installation at Zurich Airport

Deriving Operational Criteria for Reduced Localizer Coverage

In order to cover all operational aspects, the localizer intercept procedure was analyzed from an Air Traffic Control (ATC; procedure design and vectoring by controllers) and aircraft user (piloting and avionics) point of view. Procedure design criteria for high speed, large angle intercepts prescribe 2 NM of lead on the promulgated intercept heading. This means that the chart will indicate a reference to a navigation aid at a point 2NM prior to intercepting the localizer course line. In a worst case scenario, this point could be at 15 degrees offset. Conversely, ICAO procedures for radar vectors recommend a minimum of a 1NM vector at a 30 degree intercept angle. This leads to a value of only 5 degrees to provide coverage for the intercept procedure. On the aircraft side, current autopilots extend the use of the ILS beyond standardized bounds into the entire linear guidance region. This is done to ensure intercept turn initiation without overshoot even in tailwind situations. The linear guidance region of the localizer beam is ±5 degrees at most, depending on runway and system configuration. While ±5 degrees coverage would seem sufficient from a purely technical point of view, the pilot needs a correct signal before arming the autopilot for capture. Good airline practice is to not arm the approach before having received a correct IDENT, an ATC intercept clearance and ensured proximity to the ILS course beam. The latter is typically done with an additional navigation aid to both verify that there is no map-shift and ensure that there will be no false capture initiation turns. Consequently, it became of interest to see when pilots were arming the ILS in relation to the localizer beam, in global operations.

This is where the Event Measurement System (EMS) used by Swiss International Airlines for safety and operations optimization purposes provided an excellent source of data. Figure 4 shows pilot activations of the ILS approach mode arm button in relation to the localizer course line. The graph combines approaches from both sides as the distributions are symmetric. It represents over 50'000 flights over several years. Clearly, such data is far superior to anything that could be obtained from manual observations. While the data suggests that coverage to about 10 degrees from the course centerline would be sufficient to permit approach mode activation, another five degrees of margin was given for the prerequisite pilot tasks. This became the driving operational requirement to support reducing ILS localizer coverage from ±35 to ±15 degrees. One remaining uncertainty, however, needed more in-depth validation: is coverage to ±15 degrees sufficient in providing enough time to verify the ILS IDENT? After all, the IDENT remains a key safety mechanism to communicate the operational status of the ground facility to the pilot(s). As the remainder of this paper addresses this question by relying heavily on EMS data, a short description of the system is given below.

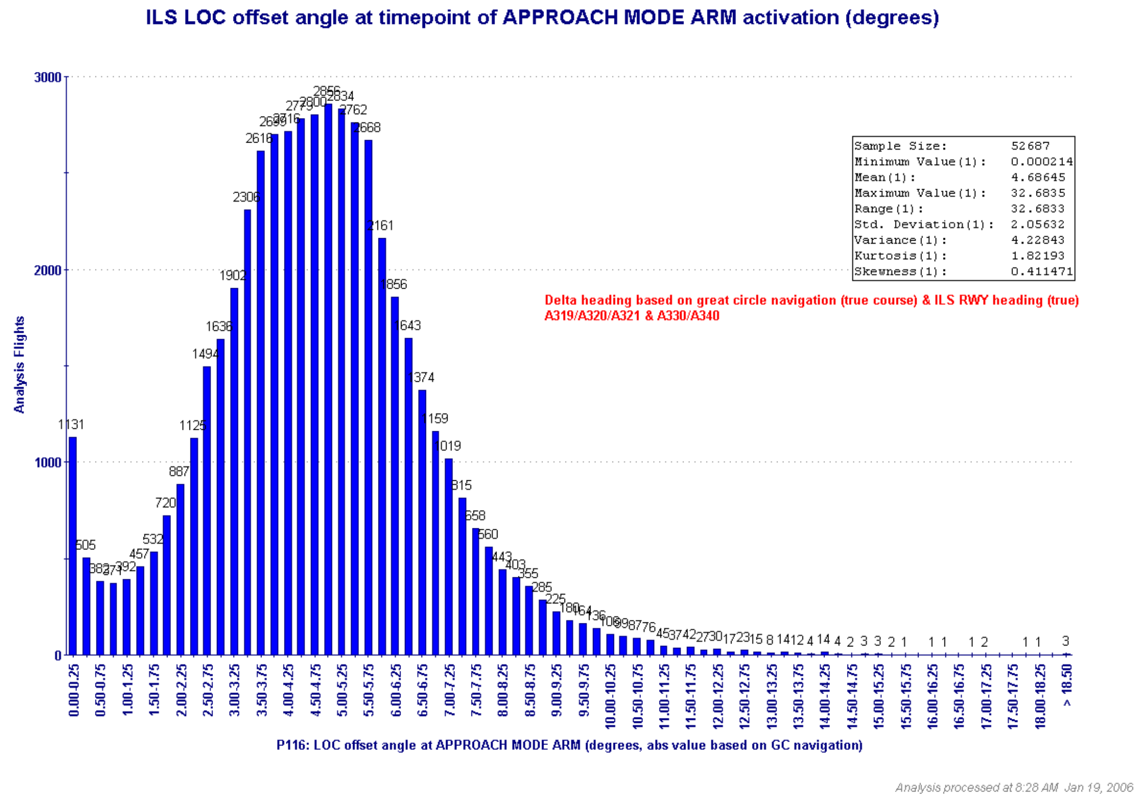

Figure 4: ILS Approach Mode Activation

Brief Overview of the Event Measurement System EMS

The Event Measurement System developed by Austin Digital Inc. is the leading technology for Flight Operational Quality Assurance (FOQA) and Flight Data Monitoring (FDM) for large airline fleet data processing.

While single-flight analyses are useful for analyzing known events, EMS facilitates the discovery of long-term trends by quickly sifting through enormous amounts of flight data. With its unique ability to numerically characterize flight operations, visualize statistical distributions, and uncover event exceedances, EMS allows preventive measures to be taken before problems can arise.

EMS is also highly configurable. This makes EMS uniquely suited to performing custom, user-designed calculations.

The Flight Data Warehouse (FDW) component handles the collection and storage of the flight data as well as additional reference data like runway dimension, navaid and weather data which is continuously updated.

The Automated Parameter Measurement (APM) component allows quantifying almost any aspect of a flight, using three extensive libraries of 143 events and 3,073 measurements, or optionally querying for user-defined exceedances and events. These libraries apply to every aircraft in the fleet, regardless of differences in airframes, Logical Frame Layouts, engine types, or onboard recording hardware. EMS's extensive query and filter features allow users to quickly navigate databases to locate desired subsets. The corresponding flight data files can easily be viewed with the Flight Data Viewer. These features, together with the extensive libraries, provide the ability to visualize flights as shown in figure 6, see weather conditions at takeoff and landing and can generate automatic reports.

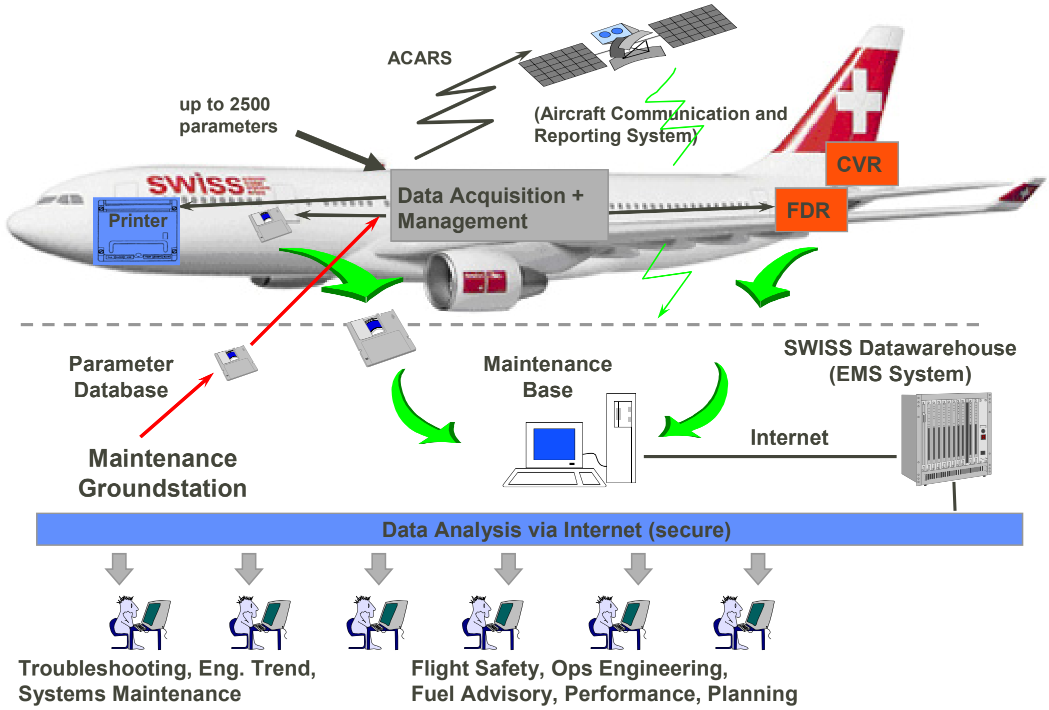

Figure 5: EMS is the ground based core part of the Aircraft Data Acquisition System (ADAS)

At Swiss Int. Air Lines the whole data process chain from airborne recording to the end-user data analysis is called the Aircraft Data Acquisition System (ADAS). EMS as the ground based core part processes the in-flight data of the full Airbus and Avro RJ fleet. On all aircraft a customized Logical Frame Layout is loaded with an extended parameter set of up to 2'500 parameters continuously recorded with high resolution and frequency.

The broad usage of the data by Flight Safety, Aircraft Maintenance, Troubleshooting and Flight Operations makes the data well tested and a consistent source to find evidence for questions. An agreement with the Pilots Union makes it possible to work on and deploy the data for research topics like this ILS sustainment study.

Operational Context of ILS IDENT

The functions of the IDENT check have evolved somewhat over the years. Initially, the IDENT check seems to have been the primary means to confirm the proper operation of both the ground facility and the avionics. With current monitoring systems and built-in test circuitry, this is not as critical anymore today. Similarly, verifying the correct morse code confirms that the pilot is indeed approaching to the intended runway, confirming the situational awareness picture. This too, is not as relevant anymore with glass cockpit navigation displays. What remains important, however, is the safety role of the IDENT as an identifier of the operational status of the ground facility. Even in busy terminal airspaces with permanent ATC supervision, it serves as a last safeguard to ensure that aircrews do not attempt an approach to a facility undergoing maintenance. This results in a two-tiered coverage requirement for the IDENT signal. First, the IDENT needs to be available some time before arming the approach as already discussed. Second and as a last resort, the IDENT needs to be verified before the aircraft is established on the approach. Otherwise, the pilot cannot (or should not) announce being established on the approach to ATC, which in turn cannot hand the responsibility for navigation and terrain separation back to the aircrew. Without this hand-over, the aircraft is not allowed to descend below the Final Approach Point (FAP) altitude for landing.

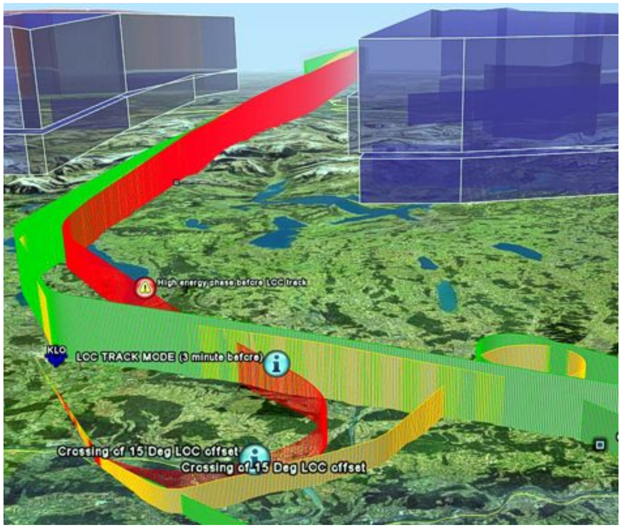

Figure 6: Visualization of ILS Approaches with Different Workload Levels

Despite the IDENT functions and requirements described above, the operational reality looks different. On the one hand, coverage volumes define a minimum level of service designed to meet safety requirements even in the most unusual operational scenarios. Consequently, the minimum field strength that corresponds to the coverage boundary defined in standards is most difficult to meet far out and low (for ILS, typically at either plus or minus 35 degrees and 17NM from the localizer antenna, and 2000 feet above the runway threshold, corresponding to an approach angle of one degree). At nominal approach angles, the signal is stronger and will reach further than the minimum requirement. On the other hand, pilots desire to get the IDENT check "out of the way" as early as possible to balance their workload, and thus have gotten used to doing the IDENT check shortly after the approach briefing at around FL100[4]. Even though there is no guarantee or obligation for an ANSP to provide such signals, pilots have gotten used to this because ILS equipment exceeds minimum requirements with margin. This poses a quandary for standardization, as operational experts have difficulty to give up something that they perceive as normal operations, even if normal operations is to perform the IDENT on a localizer sidelobe and well outside of formal coverage.

[4] FL = Flight Level. Mean Sea Level altitude expressed in hundreds of feet at standard pressure.

Figure 7 shows ILS approaches at 3 minutes before localizer track mode with respect to conventional ILS coverage. Blue dots are flights within coverage, red dots are outside (64%). At this point in the approach, the IDENT check has long been completed.

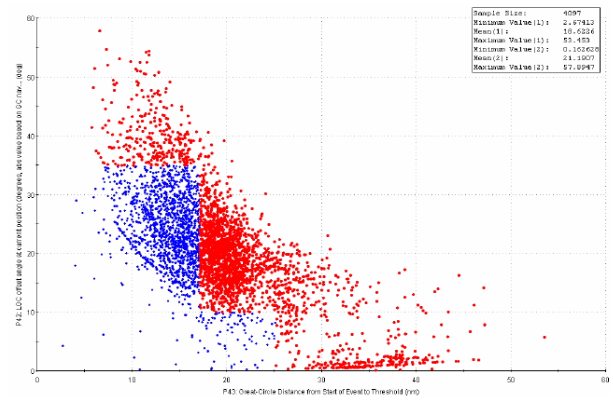

Figure 7: ILS Approach Distribution

IDENT Workload Study

Even though the proposed change to coverage requirements is minor, the excellent safety record of ILS demands scrutiny and care. The main concern when reducing angular coverage requirements of the full scale fly left or fly right areas is that the (geographic) availability of the IDENT is delayed into a period of high pilot workload. Consequently, it was sought to determine if such a delay is acceptable. For this purpose, a worst case scenario was constructed. This scenario is a combination of both high cockpit workload and "fast" approach geometry. This combination was chosen because pilots felt that under most circumstances, even if the IDENT was available later than usual, it would still be possible to quickly complete the check – it is an easy and routine task after all. In order to identify "fast" approach geometries, it is useful to recall ILS coverage and compare it with approach paths.

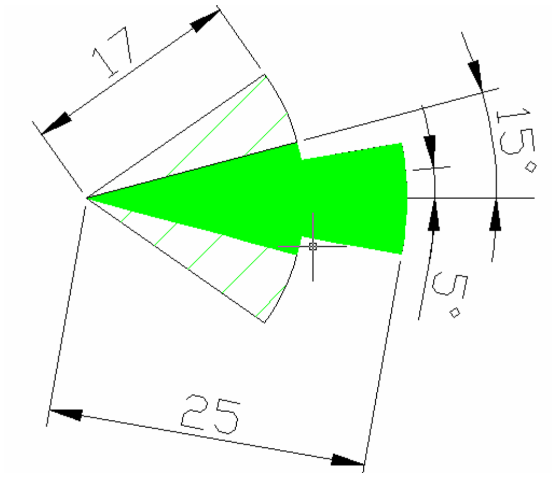

Figure 8: Proposed ILS Coverage Requirements (Ranges in NM)

Selection Criteria for High Workload

Figure 8 shows the proposed reduction as a hatched area in comparison to the conventional coverage of ±35 degrees to 17 NM and ±10 degrees to 25 NM. While there is no formal guarantee for signal reception in the hatched sectors, the signal will be received by typical avionics and be correct. Outside of ±35 degrees, there are no significant differences in sidelobe levels between a conventional and a reduced coverage system. This means that a classical downwind approach even to a short base and final will pick up the IDENT well ahead of formal coverage. The same is true for straight-in approaches as they are within the main lobe of radiation. The quickest approach geometry is thus a T-approach, where the aircraft approaches in the 35 to 90 degree sector to the final approach course and just outside of 17 NM, which is not untypical. Due to the soft roll off in the antenna pattern required to mask false courses, the area from 15 to 35 degrees is not critical because the aircraft has sufficient time to acquire a slightly weaker signal. This fact has been confirmed by flight testing. As all ILS ground facilities have a null in the antenna pattern around ±40 degrees, the worst case assumption of the T-approach is that the IDENT has not yet been picked up before crossing the 35 degree line and is now rapidly closing in towards the centerline. EMS data allowed identifying such flights by looking for those that have the shortest time between crossing the 35 degree line and localizer track mode. For the Airbus fleet, all flights had more than 120 seconds. Between the 15 degree line and localizer track mode, 71% of the flights still had 120 seconds or more. The 120 seconds were chosen as a key value in the subsequent workload analysis.

So what constitutes a high workload approach? A standard criteria that is used in airline safety analysis and accepted by pilots is called "excess energy to bleed" or "excess drag to weight ratio". These are high and short approaches, where the aircraft needs to descend on the steep side of the operational envelope, typically to meet a shortcut offered by ATC. The measurement "first determines the required reduction of the total mechanical energy before touchdown. It is assumed that the ground speed at touchdown must not exceed that from which the aircraft can decelerate to a stop within the available landing distance without exceeding 0.2g's. Then this required decrease in mechanical energy is divided by the actual air distance to go until touchdown. This gives the average retarding force needed. This result is then divided by the gross weight to determine the average longitudinal load-factor required during the approach."[2]. This formula was slightly modified in this study to only look at the flight phase from 30 NM before touchdown up to localizer track mode in order to find local maxima of high energy situations shortly before the ILS intercept maneuver occurs. The distribution of the excess energy to bleed across all recorded ILS approaches is perfectly Gaussian. All events above the mean plus one standard deviation (resulting in a level 0.07g) were considered high workload approaches.

Finally, the approach geometry analysis that identified short time windows to complete the IDENT was combined with the high energy to bleed sample described above. This was done by selecting only those flights that also had a localizer course offset angle of more than 35 degrees at three minutes prior to reaching localizer track mode. Various cross-checks were done on this data to ensure that the assumptions about the operating environment were correct. One example is shown in figure 9, which shows those flights well above the nominal 3 degree glide path angle (red line). The term "high workload approaches" will subsequently be used herein to refer to approaches both with excess energy to bleed and quick approach geometry critical to IDENT completion.

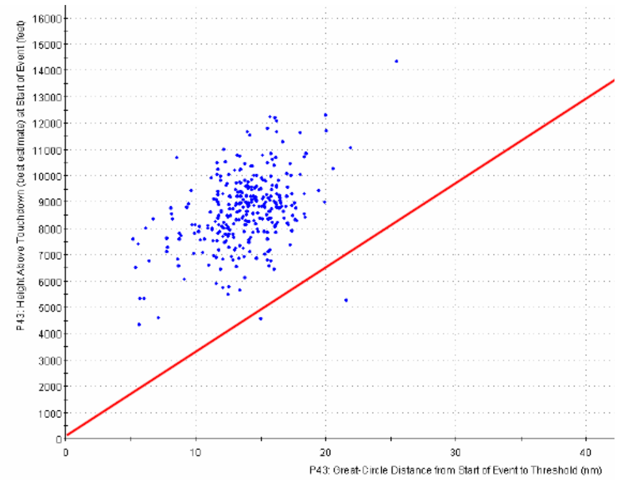

Figure 9: Vertical Distribution of High Workload T-Approaches (Height Above Touchdown [ft] vs. Distance to Threshold [NM])

Fleet and Airport Considerations

The most detailed data is available from the Swiss Airbus fleet. However, there are other birds in the sky. Consequently, the criteria for approach geometries and energy to bleed were also applied to the Avro RJ fleet, which well represents regional jet operations. Not surprisingly, the range of dynamics and approach geometries is much greater. For example, the time left from crossing the 35 degree line to localizer track mode can be as short as 75 seconds (instead of 120 for the Airbus). While operational feedback will certainly be sought from regional pilots, the regional fleet was not further considered in the workload analysis for the following reasons:

- In contrast to Airbus and Boeing aircraft where the IDENT is detected by an audio decoder and displayed on the Primary Flight Display (PFD), pilots of smaller aircraft listen to the real audio through activation of the ILS channel on the audio panel. The audio signal is audible earlier than the PFD display.
- Pilots of regional aircraft are flying with higher dynamics because it is easier for them to bleed excess energy, while the complexity of avionics is generally lower.
- If late availability of IDENT really poses a problem, an alternate procedure is available to pick up the IDENT on the ILS associated DME. This is not possible on the large airline fleet.

When looking at the sample of high workload approach geometries, it is also possible to sort them according to airports, where some have higher percentages of such approaches than others. These more demanding approach geometries can be easily explained when evaluating the terminal airspace design of the particular airport. For example, the steep London City approach produced many outliers that needed to be filtered out in order to preserve a globally representative sample.

Workload and Taskload

Human Factors differentiate between workload and taskload. Taskload are the actual tasks being done, such as manipulating a control or pushing a button. Taskload is measurable with EMS, whereas workload includes all the mental processes that are going on which lead up to a specific action or an evaluation of a completed action. To take an extreme example, if a pilot would have a mental block, he or she may just be sitting there while not having any spare mental capacity to perform tasks such as pushing any buttons. Nonetheless, taskload can be a rough indirect measure of workload. This is confirmed by EMS which shows that the task density directly correlates with the excess energy to bleed criteria.

Cockpit Taskload during ILS Intercept

In order to study localizer intercept taskload with EMS, the five minutes leading up to localizer track mode were split into five second bins. If any activity took place, such as a radio transmission, setting flaps, manipulating the flight guidance system etc., the pilot was considered busy completing tasks. The five seconds give some margin for task execution and feedback, even if the measured event is typically shorter. Generally, only one task takes place during a five second bin. If the bin has two events, it is typically due to a radio transmission. Additionally, the task distribution was “inverted” to find periods without any pilot manipulations. It was assumed that a period of 30 seconds or more without manipulations should qualify as one where even the workload was low enough to enable the pilot to complete an IDENT check.

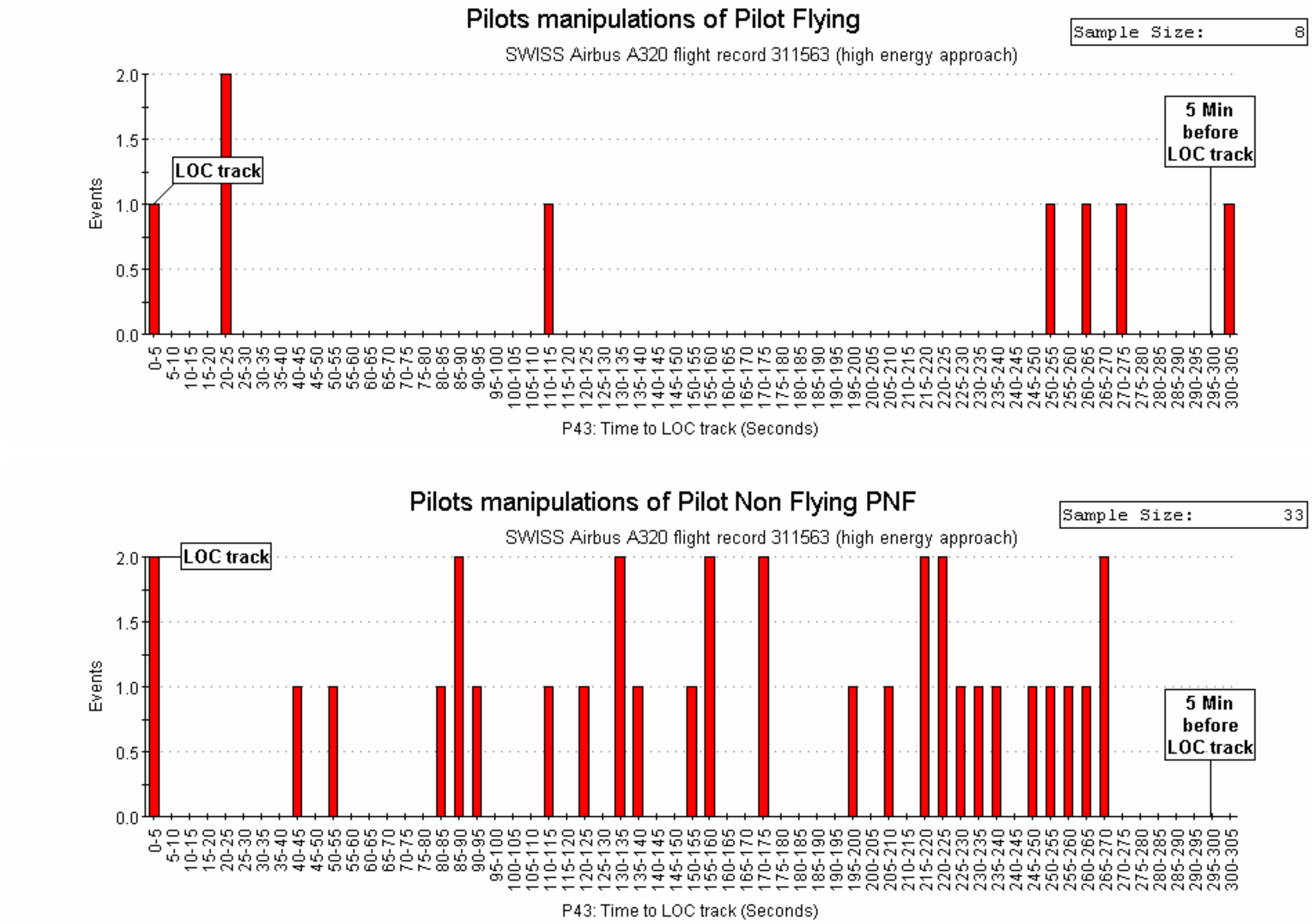

Figure 10: Measurable Taskload Distribution during High Workload Approach

Another necessary distinction is if the crew was using the autopilot, and the corresponding impact on the task distribution between the Pilot Flying (PF) and the Pilot Non-Flying (PNF). When the autopilot is engaged, the PF manipulates the flight guidance and FMS himself or herself. When the autopilot is off, the PF is flying the aircraft with the sidestick (or yoke) while generally commanding all manipulations to the PNF. Normally, the PNF handles voice communication with ATC. This means that with the autopilot off, the PF can still be quite busy even if the measurable taskload is low. Conversely, the taskload of the PNF then represents a worst case and is higher than the two PF / PNF task distributions when the autopilot is on. This case is also more typical in high workload approaches in Airbus A320 aircraft, because the autopilot needs to be disengaged in order to fully deploy the speed brakes. In fact, the measurable task distribution shifts remarkably as a function of the energy state of the approach. While the PNF has only a few more measurable tasks than the PF on a low energy approach, this more than triples in the high energy cases. Figure 10 shows the measurable task distribution for a particular high workload flight.

When looking at the time distribution of tasks between the pilots in the five minutes leading up to localizer track mode, the PF is least busy at three minutes before intercept. The tasking peaks between 90 and 60 seconds, and eases up again towards localizer capture. The PNF has a more equalized taskload, except for 30 seconds prior to the localizer course, where things get busiest.

Finally, figure 11 is looking at the latest "no manipulation windows" of 30 seconds prior to localizer tracking, for the PNF with the autopilot off. According to the approach geometry timing, it would be desirable if each flight would have one such event within 120 seconds before tracking the localizer. As can be seen from the histogram, this is the case for the majority of cases, which account for 71%.

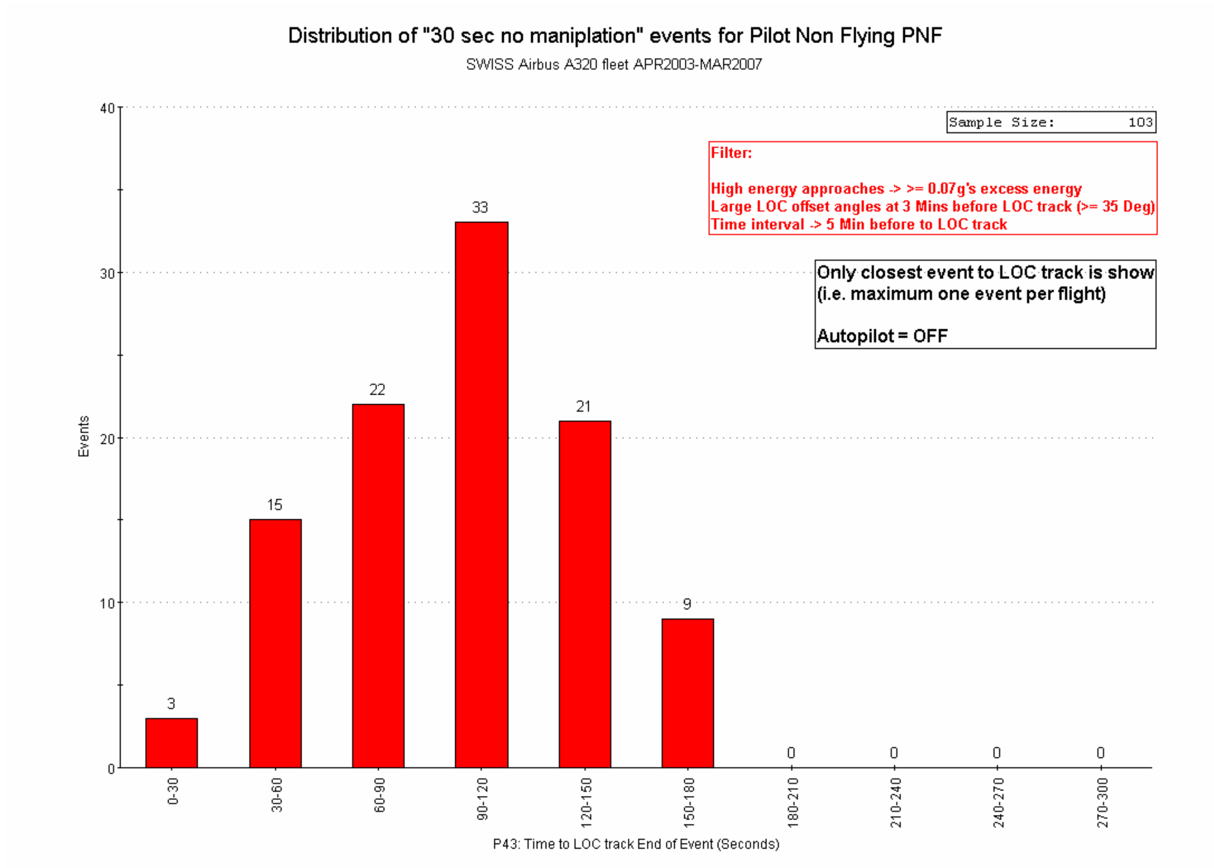

Figure 11: IDENT Windows for High Workload Approaches within Coverage

It would be desirable if each high workload flight had a 30 second window without measurable tasks by the PNF within 120 seconds before tracking the localizer. However, it needs to be kept in mind that this does represent a combination of worst case criteria. Also, it is possible for both pilots to initiate and perform the IDENT check. While possible with EMS data, it would go too far into the realm of theoretical constructs to derive cumulative probabilities for a crew to complete the IDENT check within the 120 seconds of coverage. Instead, those few approaches without suitable "no manipulation events" were analyzed individually. Expert pilot judgment still supports that the IDENT should be possible even in such high workload situations. This judgment will be complemented by operational experience to round out the validation of the ILS sustainment proposal.

Conclusions

Regardless of the actual ILS subject, the paper demonstrates the amazing analytical capabilities of recorded flight data. This provides invaluable support to operational improvement studies. However, it is contingent on an advanced toolset in recording and database capabilities that need to be easily combinable with visualization and graphics software. In the age of FOQA tools being mandatory, it is highly recommended to airlines to provide such flexible analysis capabilities for the use in improvement initiatives such as SESAR and NGATS.

With respect to ILS then, this work hopes to bring some innovation to the very conservative field of ILS development in order to maintain low visibility operations within safe technical margins even at highly developed airports. Further, while it is not appropriate to address the intricacies of air – ground interoperability and the implications on the interpretation and use of standards here, the paper shows that especially precision approach operations depend on a mutual understanding of the technical constraints of ground facilities and avionics.

References

[1] Carel, Olivier, October 2002, Les Origines des Categories d'Atterrissage: Cat I, Cat II, Cat III, IIIA, IIIB, IIIC, Revue Navigation Vol. 50, No. 200, Paris, Institut Français de Navigation, pages 66 to 83.

[2] Internal contract deliverable report provided to EUROCONTROL by SWISS49. Explanation of measurement provided courtesy of Austin Digital.

[NOTE] More details of this work are available through a variety of ICAO and Eurocontrol papers and presentations. As they are not formally published references, they are available on request from the EUROCONTROL author.

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Disclaimer

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