14ème 14th SIIV IFIS
Toulouse-France 12-16 Juin/June 2006

ILS Interference Measurements and Dynamic Receiver Behaviour

Dr. Jochen Bredemeyer,
FCS Flight Calibration Services GmbH

Thomas Kleinmann,
DFS Deutsche Flugsicherung GmbH

Helmut Kraemer,
DFS Deutsche Flugsicherung GmbH

ABSTRACT

Multipath propagation of the ILS signal is still the most critical aspect, and therefore the most feared degrading influence on high performance CAT_III installations. The construction of new buildings at the airport site worsens this situation, as buildings are often a compromise between architecture and effects on electromagnetic waves.
Furthermore, the definition and verification of ILS protection zones for today's mega-aircraft (e.g. Airbus_ A380) with their large dimensions is a new additional challenge to ILS, with respect to the impact on capacity of international airports.
ILS multipath propagation comprises in-beam- as well as course-clearance interferences. The paper covers measurements of these disturbances in the time and frequency domain and the determination of reflection sources. Results of relevant flight and ground inspection parameters gained at some German airports will be shown.
Since the common ILS receiver's RF behaviour in case of multipath interference is not completely known and even a dedicated FI receiver does not stringently meet ICAO Annex 10 "green pages" requirements, the resulting DDM error in "μA" cannot be derived by means of a simplified model. The paper therefore also provides hints on receiver evaluation.

INTRODUCTION

The authors have conducted various test trials in a multipath environment. Tests were conducted threefold:
• Flight check measurement with a standard FIS
• Flight check measurement with an experimental Doppler frequency system
• Ground measurement along the runway with a field test set mounted in a vehicle.
Subsequently, the results of the three systems are correlated with each other.
In parallel to the standard FIS measurements an experimental Doppler frequency measurement system was applied. It is named "Signal-in-Space Monitoring System" (SISMOS), designed to receive and to record a bandpass signal of a Navaid as close as possible to its occurrence, compare description in[2]. Furthermore, it is a true dual channel receiver with narrow IF filters to separate course and clearance signals. Locating a scattering source is achieved in the frequency domain by analyzing the difference in Doppler shift of the direct and the reflected portions of the ILS signal. The resulting angles of incidence then can be plotted in an aerodrome chart. The locating of a scattering source by the described method works best if its dimension is small and therefore close to punctual. In this case, the scattering source is clearly identified by the crossing reflection lines which represent the angles of incidence.

ILS LOC IN-BEAM INTERFERENCES

During a Flight Inspection measurement campaign at Frankfurt airport SISMOS was mounted in the flight inspection aircraft and connected to the conventional FIS to obtain the synchronous flight path in real-time. The diagram below (fig. 1) shows the unfiltered raw data of SISMOS (green curve/big amplitudes) in comparison to the results of the filtered RNA34-AF FI receiver (blue curve/smaller amplitudes). Measurement took place during a landing of the FI aircraft in order to provide a comparison basis with a ground inspection performed with a field test set beforehand (fig. 2).

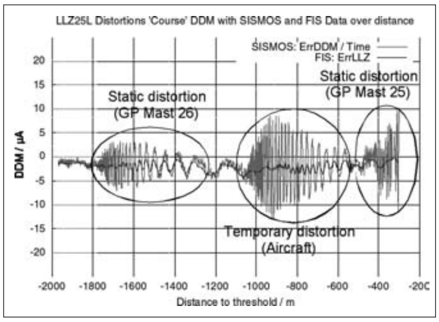

Figure 1: DDM of aircraft during landing with static and artificial distortions (EDDF LLZ25L)

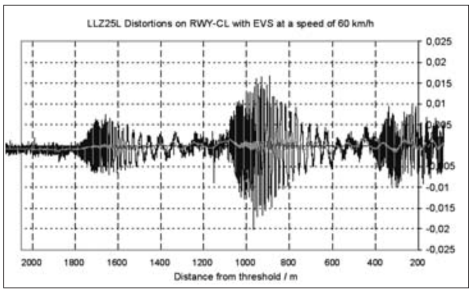

Figure 2: Corresponding DDM record of ground vehicle equipped with EVS200 (blue, big amplitude indicates raw data while the small red indicates filtered data)

The aerodrome chart plots derived from the measurements by software processing surprisingly reveal two GP masts as being the static scatterers: In each case the reflection lines cross at the GP positions in front of and behind the aircraft. While in figure 3 the mast of GP25L is identified as the scattering source, this applies for the GP26 mast of the unused HALS/DTOP facility in fig. 4. Since the GP shelter is located close to the mast, both objects were originally suspected to act as a reflector. However, this possibility was excluded by temporarily deflecting the LOC signal by placing a fire truck in the line-of-sight between LOC and the shelter with no effect on resulting DDM distortion whatsoever.

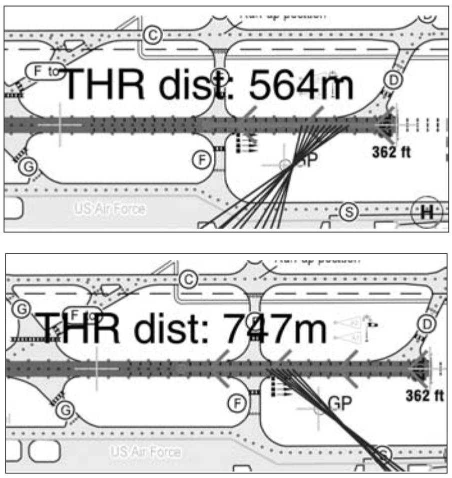

Figure 3: Locating the GP mast 25L as a punctual scatterer from the front and from behind

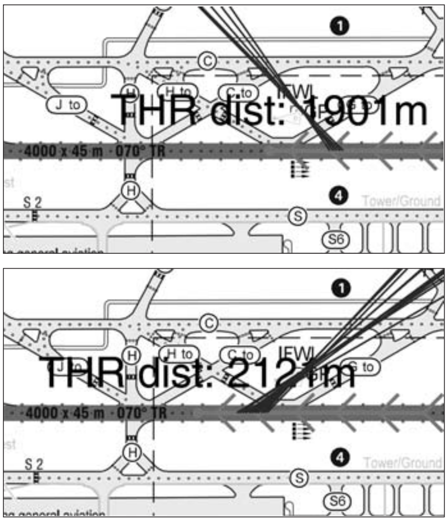

Figure 4: Locating the GP mast 26 of HALS/DTOP

The LOC signal-in-space affected by multipath propagation itself is best visualized in the frequency domain. Due to different positions and velocities the reflected portion experiences a differential Doppler shift. Both the carrier and the sidebands are affected - however, the separated line of the carrier is much larger than those of the sidebands. This can be observed in figure 5 and 6, respectively. The enlarged views in figure 6 taken at different moments show the separating spectral line moving to a higher Doppler difference while passing by the reflector. Simultaneously, the magnitude of the reflector decreases.

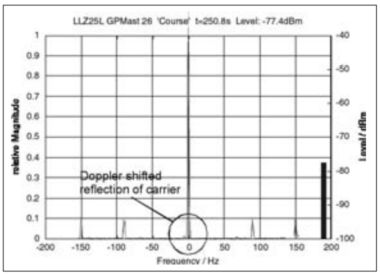

Figure 5: LLZ25L course signal spectrum with reflecting GP mast 26

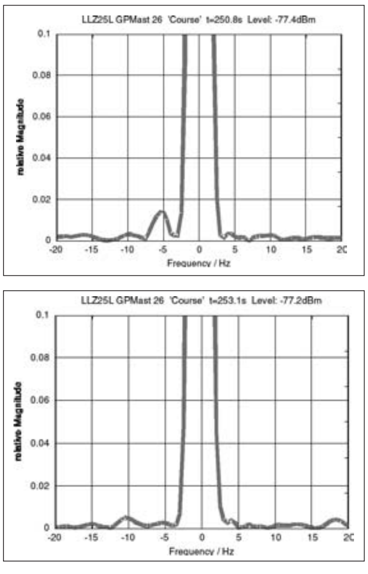

Figure 6: Spectral movement of the reflecting GP mast 26 (enlarged)

Since this spectral movement affects the sidebands 90/150Hz as well, it is worthwhile to show in which way ILS receiver processing handles those signals. As stated before, SISMOS allows to save ILS bandpass signal itself (figure 7 top). Linear rectification leads to the ILS-typical run of the baseband curve shown in figure 7 (bottom). While the spectrum is gained by an appropriate transformation of the bandpass signal, the baseband feeds the 90Hz/150Hz sideband filters. These are defined as software IIR filters delivering the advantage of a maximum flexibility and are applied as a post process to the sampled data.

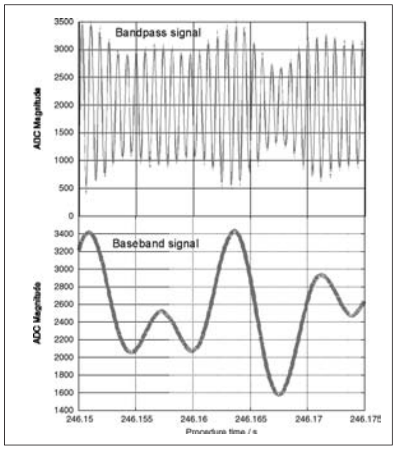

Figure 7: ILS bandpass and baseband signals

The two rectified voltages leaving the sideband filters are normally subtracted, and this result is typically sold as "ILS raw DDM data" to the ILS community. By information theory standards this is clearly not the case: separating both sideband portions already implies defined filter parameters, significantly affecting the outcoming signal.
In figure 8 the aircraft is passing by the reflector GP26 when the Doppler shift curve (top) turns its direction from right to left at t=253s. During the passage up to this point, the resulting Doppler shift breaks through the bandwidth of the narrow filter (4Hz, 4-pole butterworth IIR type) but remains within 10Hz. With respect to the spectral diagram of figure 6 the reflection is still in the bandwidth of the 30Hz filter (fig. 8, middle) while the 4Hz (filter) type attenuates the oscillation (bottom).

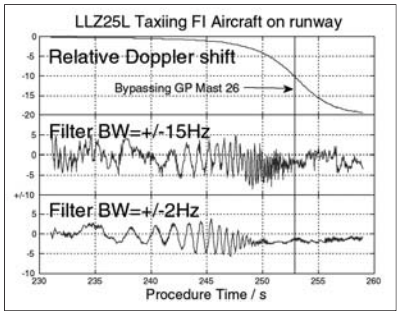

Figure 8: DDM of aircraft on ground with different 90/150Hz sideband filters affected by reflection of GP mast 26

So care must be exercised, especially when comparing results of dynamic measurements with those gained from numerical simulations, since they are mostly performed under static boundary conditions. The filter parameters before gaining the final "raw" DDM also affect the result.
Another measurement campaign was conducted on Frankfurt runway 25L with the ground inspection vehicle equipped with SISMOS and a conventional receiver type (Rohde&Schwarz EVS200) operating simultaneously. Again the behaviour of the GP26 mast was investigated, this time having "raw" data from two different receivers. Two inspections were carried out, one at 60km/h and another at a high speed of 120km/h. This is untypical for a normal ground inspection but delivers a higher

Doppler shift and therefore a better resolution in the frequency domain. Figure 9 shows the DDM curves of the two receivers in the vicinity of the GP26 mast. Both the curves of EVS200 and SISMOS with 20Hz sideband filters look nearly the same which gives a hint regarding the dimension of the EVS200 sideband filter bandwidth. At the higher speed 120km/h, the narrow 4Hz filter strongly attenuates the oscillation.
Generally, the amplitude scalloping is higher than those of the aircraft measurements. The reason for this is a different antenna pattern and, primarily, the lower ground altitude of the vehicle antenna.

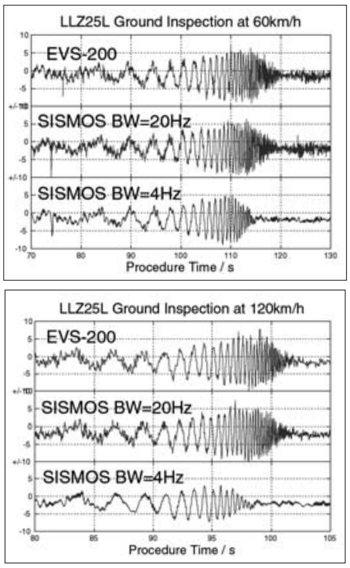

Figure 9: DDM of vehicle ground inspection at different speed and 90/150Hz sideband filters affected by reflection of GP mast 26

Examining the frequency spectrum of figure 10 (valid for 120km/h), the higher peak amplitude of the scattering GP mast can be observed as well. Taking the spectral moment and transferring it to the time scale of figure 9 (bottom), one can see the corresponding behaviour of the two filter bandwiths: The 4Hz Doppler shift is already out of the 3dB/2Hz limit (each to the center frequency) of the narrow filter but within the wider one. When the 3dB filter boundary of 10Hz is reached the error magnitude of the DDM curve (20Hz filter, middle) decreases.

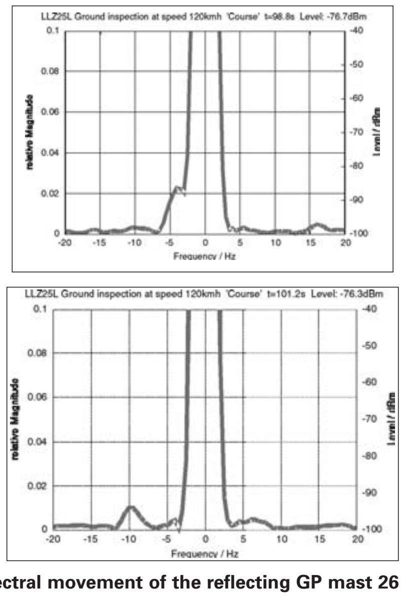

Figure 10: Spectral movement of the reflecting GP mast 26 during vehicle ground inspection

Figure 11: Antenna mast GP26. Mast joining elements are partially conductive and may have a high dielectricity constant

Important note:
The DDM error in the preceding examples is (well) below CAT III thresholds. However, the GP26 mast served as a reliable static scattering source for the duration of the experiments, granting reproducible measurement results at all times. A temporary obstacle with larger dimensions (see figure 1) would of course significantly affect both the resulting and filtered DDM, while being rather less suitable for investigation purposes.

COURSE/CLEARANCE INTERFERENCES

In contrast to the preceding pure in-beam distortions this example is a classical course/clearance interference. It concerns another German CAT III installation under wet weather conditions resulting in an autopilot error of several metres off the THR centerline. The critical issue is that the error was not reproducible in flight inspection and affected only one airline so far. Since the runway has a medium aperture antenna only (12+3V element) the assumption was that an obstacle scatters the clearance signal resulting in a decreased course/clearance ratio during approach. The measured ratio of an approach on centerline is given in figure 12. The scalloping run of the curve is noticeable while the ratio is close to 14dB at the threshold - according to the recommen- dation in ICAO Annex 10 ([1], 3.1.3.3.5) it should be at least 16dB for CAT III installations.

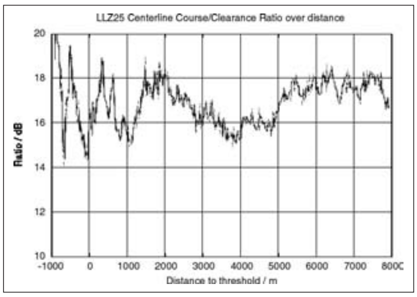

Figure 12: Course/clearance ratio on centerline

A clearance spectrum close to the threshold (figure 13) shows a strong line beneath the carrier which is even visible on the 90Hz sideband. Since the strength of the carrier itself is heavily affected by a close-by spectral line, the clearance signal strength in total oscillates, leading to an oscillating of the course/clearance ratio as well.
The resulting effect in the approaching aircraft depends on the type of receiver and its effective capture ratio on the concerned channel frequency. Also, the installed antenna performance in its electromagnetic airborne environment has an influence.

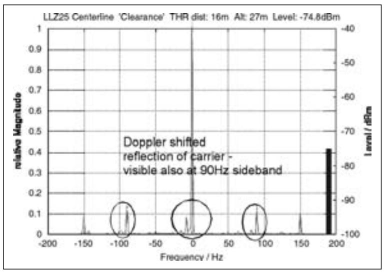

Figure 13: Clearance spectrum close to THR

Locating the scatterer was achieved by the same means as described in the section before, this time the clearance signal generating the reflecting lines. As shown in figure 13, the crossing lines clearly identified a building outside the aerodrome perimeter as the source of reflections. Its reflecting aperture has a dimension of 46m height / 15m width and is located within the clearance beam width (35°).

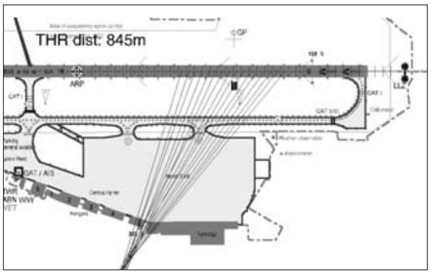

Figure13: Locating Clearance Scattering Source

A typical counter-measure to address this problem is the modification the antenna array to improve the clearance pattern. Future course/clearance Flight Inspection measurements will reveal the effectiveness. Furthermore, the suspected ILS receiver model, employed only by the affected airline, will be subject to investigation regarding its capture effect and poor course/clearance ratio performance.

ONGOING RECEIVER INVESTIGATIONS

Modelling ILS receivers by computer simulation has been shown to be of little value in the past, due to hidden or unconsidered essential RF parameters and receiver characteristics. Therefore, the only means to fully describe a receiver is feeding it with a genuine RF signal-in-space recorded as a bandpass signal under real multipath conditions. An according scientific study has been launched to compare the performance of a variety of ILS receivers used both aboard commercial aircraft and for testing purposes. The study comprises of, amongst others, the application of different digital filtering techniques and the effectiveness of the capture effect which strongly depends on the AGC and demodulation process of each individual receiver. Most common FI receivers have a non-linear (diode) rectification characteristic which is not specified in any documentation.

EFFECTS OF RECEIVER SPEED ON RUNWAY GROUNDCHECK MEASUREMENTS

It is a common practice to ground-check course line position and structure of the ILS DDM signal of a CAT III ILS by driving a measurement vehicle along the runway centreline. For this measurement a field receiver together with an appropriate antenna is installed in a vehicle and the DDM is recorded while driving down the runway at a specified speed. The recording is then evaluated with respect to course line position and structure, i.e. bends and scalloping. Course line position and course structure have to fulfil the requirements of para. 3.1.3.4 of ICAO SARPS, Annex 10, otherwise the ILS may no longer be used for CAT III operations. Therefore rigorous measurement techniques become an essential issue.
Since such a measurement is a dynamic one, the dynamic behaviour of the receiver itself, the sample rate and the correct filtering of the recorded DDM must be considered. These measurement parameters, beside capture effect and antenna pattern of the receiver equipment, play a major role in the evaluation of the recorded DDM curve. A wrong interpretation of the measurement especially in a strong multipath environment can easily jeopardize ILS CAT III performance.
Figure 14 shows a measurement where a large aircraft is close to the border of the ILS Sensitive Area. The aircraft causes substanial in-beam reflections of the ILS signal. Measured on runway centreline, DDM distortions in form of DDM oscillations with increasing frequency can be observed. For evaluation purposes the receiver's raw data were recorded only and thereafter a filtered DDM curve was calculated, employing a digital filter algorithm. The filter algorithm had been adapted to the vehicle/receiver speed at each case.

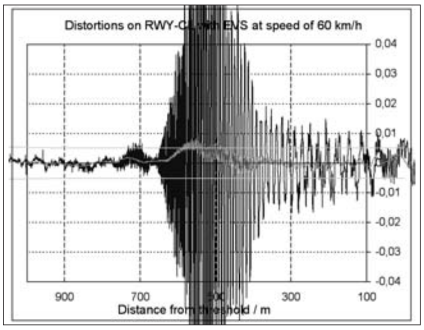

Figure 14.1: Distortion measured on RWY centreline with a speed of 60 km/h (Receiver EVS 200), with raw data in blue (big amplitudes) and filtered data in red (small amplitudes).

Although the filter was adjusted to the receiver's speed, the filtered data showed a different magnitude: With the low speed of 10 km/h the DDM distortions are within the 5µA tolerance limit while the same scattering source measured at a speed of 60 km/h causes distortion amplitudes exceeding the 5µA limit.
The above example illustrates the difficult situation of the ILS engineer or inspector to evaluate ILS performance in the presence of a reflecting object, respectively to dimension the size of the ILS Sensitive Area.

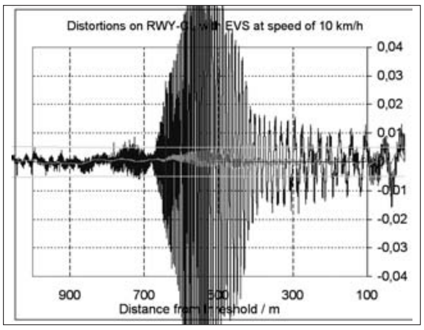

Figure 14.2: Distortion measured on RWY centreline with a speed of 10 km/h (Receiver EVS 200), with raw data in blue (big amplitudes) and filtered data in red (small amplitudes)

DIGITAL FILTERING ACCORDING TO ICAO CONSTRAINTS

ICAO Annex 10 points out in Attachment C Chapter 2.1.7 to consider the characteristics of navigation receivers and in particular the frequency response of the overall system in the evaluation of ILS beam bends. For this it is recommended to filter the measured DDM values with a total time constant T_1 [s] of 92,6/V whereby V represents the speed of the aircraft or ground vehicle in km/h. No further recommendations are given e.g. for the filter order. Due to the characteristics of high order filters with several time constants and complex frequency responses, a first-order lowpass filter with a corner frequency $\omega_c = \frac{1}{T_1}$ is preferred for further use.

SAMPLING OF ILS SIGNALS

Modern navigation receivers and ILS measuring equipment use digital signal processing. To avoid signal distortions (aliasing) the analog signal has to be sampled by a sample rate $f_A = \frac{1}{T_A}$ which must be at least twice the bandwidth of the analog signal (Nyquist sampling theorem, Nyquist rate).

The ILS beam bend (scallop) of a LLZ DDM distortion caused by a lateral reflector is λ_{LLZ} due to physical reasons, in special cases (back incident reflections) $\frac{1}{2}\lambda_{LLZ}$.

Therefore analog LLZ measurements have to be sampled with a rate of

$$f_{A_{LLZ}}[Hz] \geq 2 \cdot \frac{V[km/h]/3{,}6}{\lambda_{LLZ}/2\,[m]} .$$

Examples:
(f_{LLZ} = 110.7 $\Rightarrow \lambda_{LLZ} \approx$ MHz 2.71 m)
Runway check with 60 km/h:
$\Rightarrow f_{A_{LLZ}} \geq$ 24 Hz,
Flight check with 150 kn:
V=277.8 km/h $\Rightarrow f_{A_{LLZ}} \geq$ 113.9 Hz.

DIGITAL FILTER DESIGN

A suitable and commonly used method of digital lowpass filter design is the so called bilinear transformation which leads to the following lowpass first-order IIR-filter:

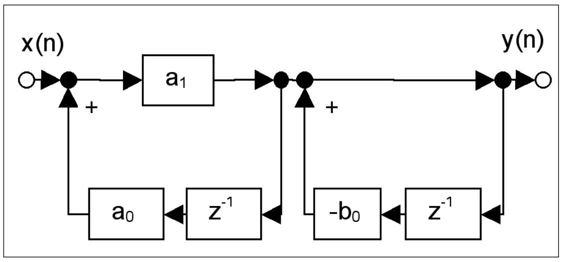

Figure 15 Digital Filter (Bilinear Transformation)

z^{-1} represents a simple buffer of one sample,

$$a_0 = a_1 = \frac{T_A}{T_A + 2T_1} \quad \text{and} \quad b_0 = \frac{T_A - 2T_1}{T_A + 2T_1} .$$

The design can be easily programmed and at the same time permits a simple post processing of raw data by MS Excel.
However a frequency distortion occurs because in this design method the infinite frequency axis is transferred into the interval $0 \leq f \leq f_A/2$.

In any application of the bilinear transformation this effect should be examined, regarding the frequency response of the overall system.

ANALYSIS OF THE FILTER DESIGN

In order to evaluate the described digital filter design method the respective step response and logarithmic magnitude are compared to the analog filter case. For this the ICAO recommendation is applied to the runway check performed by a velocity of 60km/h. The time constant T_1 can be calculated by $T_1[s] = 92{,}6/V[km/h] \approx 1{,}54s$.

DFS German Air Navigation Services employs the popular Rhode&Schwarz EVS 200 digital test set with a sample rate f_A 34 Hz.
This results in the following step responses and magnitudes in decibels:

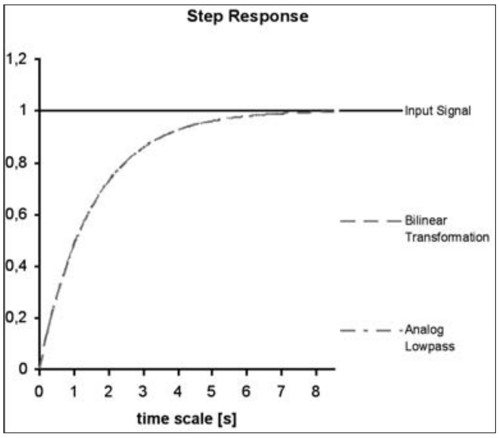

Figure 16 Analysis of step response

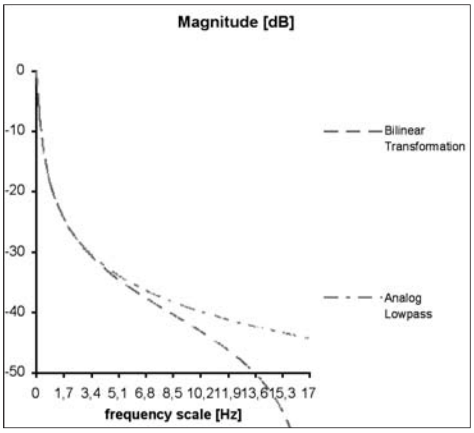

Figure 17 Analysis of frequency response

While the digital filter does not exhibit recognizable differences in the step response, the described characteristics of the bilinear transformation can be clearly seen from the frequency response. In particular in the stopband area the frequency distortion results in lower gain compared to the analog filter.
In the passband no considerable difference is recognizable, which is confirmed by the analysis of the step response.
An examination of the digital filter design by application to raw data of ILS runway checks shows very small differences within the range of hundreds of (A which is negligible in practice. Therefore, this filter is in principle suitable for the use in ILS runway checks.

RECONSTRUCTION FROM DIGITAL SIGNALS

The sampled signal is characterized in the frequency domain by spectra of the analog signal repeating with the sampling rate . To avoid aliasing an additional lowpass filter must be used for the reconstruction of the continuous signal from its samples. This lowpass filter removes the spectral portions beyond the half sampling rate (anti-aliasing filter). With a minimum sample rate selected at the border of the Nyquist theorem an ideal low-pass filter with a transition band of zero width would have to be selected (ideal interpolation). Stable systems with these characteristics can only be designed by active networks normally not used in practice. In order to be able to use more simple interpolations, a higher sample rate should therefore be selected. A sample rate of at least 5 times the bandwidth of the sampled signal is recommended.

CONCLUSIONS

• Care has to be taken of the dynamic contribution of the field receiver when used for measurements along the runway at a certain speed.
• Knowledge of the receiver's behavior in a strong multipath environment

is essential before categorising the ILS system.

• Filtering process and time constant for runway measurement should be clearly determined.

• Sample rate of the dynamic digital measurement process should be 5 times the bandwidth of the scallop frequency.

• To prove ILS CAT III structure performance on the runway, ground measurements should be employed rather than a flight inspection "level run" at 50ft above the runway. A runway rollout by the FI aircraft showed results comparable with vehicle measurements.

REFERENCES

1. ICAO: Annex 10 to the Convention of International Civil Aviation, Volume I: Radio Navigation Aids, Montreal, 2003

2. J. Bredemeyer, P. Form: ILS quality control referred to national standards and detection of disturbing sources. In: Proceedings of 11th International Flight Inspection Symposium (IFIS 2000).

3. Oppenheim, Schafer: Discrete time signal processing, International Edition, Prentice Hall international 1989

4. Kammeyer, Kroschel: Digitale Signalverarbeitung, Filterung und Spektralanalyse, 2nd Edition, Teubner 1992

5. H. W. Schüßler: Digitale Signalverarbeitung 1", 4th Edition, Springer 1994

6. N. Fliege: Multiraten-Signalverarbeitung, B. G. Teubner Stuttgart 1993

7. O. Mildenberger: Entwurf analoger und digitaler Filter, Vieweg 1992

8. A. Lacroix: Digitale Filter, 3rd Edition, R. Oldenbourg 1988