Testing of ILS Receivers in a Multipath Propagation Environment

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ABSTRACT

ILS receivers used for conventional flight inspection purposes are normally not dedicated measurement equipment. Some parts of a receiver are sensitive to dynamic signal changes caused by multipath propagation effects, e.g. those components which apply time-dependent parameters such as gain control or filters. Measurement results may suffer from degradation effects and tend to be unreproducible.

Real conditions of a multipath-affected RF environment cannot be obtained and interpreted from the DDM curve alone but must be derived from the complex bandpass signal of a receiver being placed in that RF environment. Useful information about the scatterer such as exposure time and reflection coefficient can then be derived from both time and frequency domain analysis. Having this information, it is possible to synthesize an RF signal close to real conditions.

Since conventional ILS generators can only produce static DDM without reflections they are unable to generate complex signals. Hence, an experimental generator was designed to generate an arbitrary ILS signal on the carrier frequency containing dynamic multipath effects.

The real reflective scenario of an A380 aircraft at Frankfurt airport was taken as an example to reproduce a corresponding RF signal that was then fed into a state-of-the-art ILS measurement receiver to evaluate and to optimize its performance under these conditions.

INTRODUCTION

In the past ILS receivers were developed mainly to provide instruments aboard an aircraft that are able to generate the necessary flight guidance information for the pilot during landing. These devices used to have an analogue or semi-analogue (digital signal processing only in the baseband) receiver concept. However, the analogue components like diode demodulators or crystal filters on the intermediate frequency (IF) often cause problems due to non-linearities and temperature drift. Additionally, parts of these receivers such as filtering and AGC are sensitive to fast dynamic signal changes, caused for example by multipath effects.

Normally, flight inspection today is still performed with ILS receivers designed for flight guidance, although they are clearly not dedicated measurement equipment and lack the required accuracy of all necessary parameters (e.g. RF power) and suffer from the effects mentioned above.

The main objective of this paper is to describe a suitable method for improving even dedicated ILS measurement receivers by using the scientific findings obtained in the RF reflective scenario. The new ILS/VOR Analyzer R&S®EVS300 from Rohde&Schwarz was selected as the device under test.

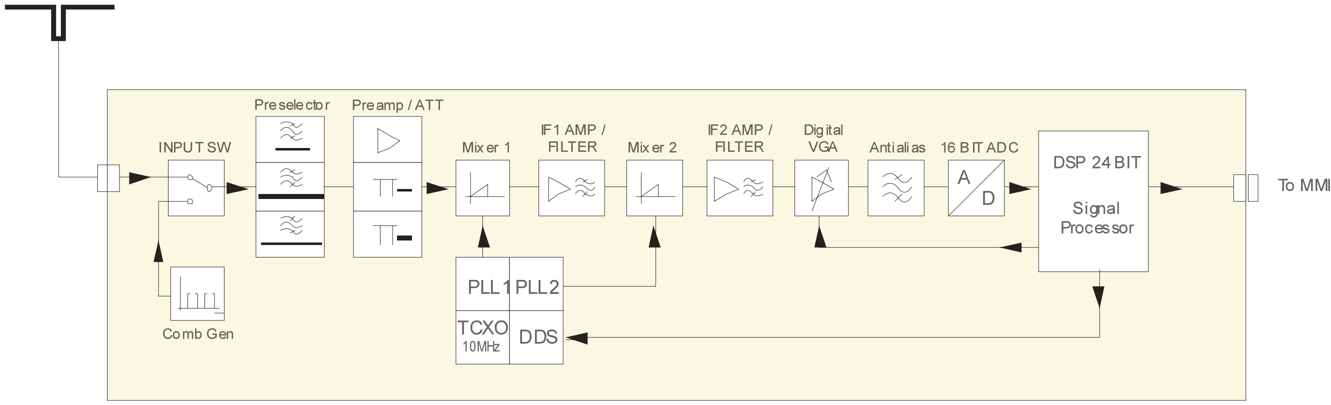

Figure 1. Block Schematic of a modern measurement receiver

CURRENT RECEIVER DESIGNS

Modern measurement receivers (see schematic in figure 1.) are using high speed and wide bandwidth A/D converters for sampling directly on the intermediate frequency (IF). Figure 2 shows in a block diagram how the signal is converted into baseband. After A/D conversion, the frequency band-of-interest is shifted to baseband using digital mixers comprising two multipliers fed by a Numerical Controlled Oscillator (NCO) that generates cosine and sine (Figure 2 A).

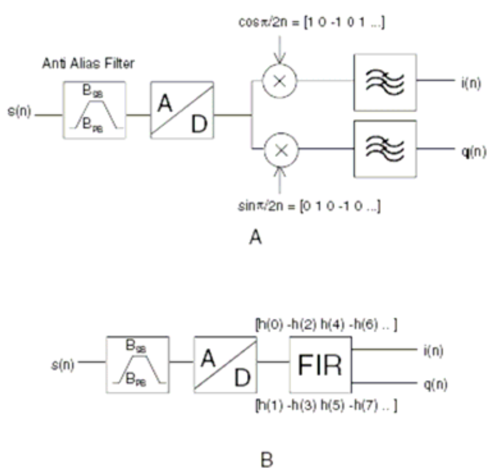

Figure 2. Schematic of a direct Digital Down Converter (DDC)

By choosing a sampling frequency that is four times higher than the frequency band-of-interest, the result of the sine and cosine operations is 1, -1 or 0.

This principle can be used for further algorithm simplification and for saving multiplier operations. The digitized data only has to be weighted with 1, -1 or 0 by a simple FIR filter that includes anti aliasing functionality (Figure 2 B). Its complex output provides pure I and Q data for further digital demodulation and signal analysis [6].

A common misconception of the Nyquist criteria is that the sampling frequency must be twice the highest frequency present in the signal s(n). In fact, the sampling frequency need be only twice the signal bandwidth to prevent alaising. Undersampling is the deliberate use of a sampling frequency which is less (often much less) than the highest frequency present in the signal. This causes frequencies higher than the sampling rate to fold back into the baseband. As long as the sampling frequency is twice the bandwidth of the signal, no signal information is lost.

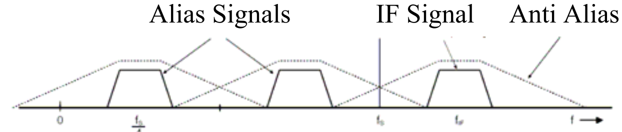

Figure 3. Spectrum of IF and alias signals

The sampling frequency must meet the following condition to obtain equidistant IF and alias signals [6] as shown in figure 3:

$$fs = \left| \frac{4 * f_{IF}}{4 * k + 1} \right|, k \in N \quad (1)$$

Problems with diode demodulators or crystal filters are eliminated. The complete demodulation and filtering is implemented by means of digital signal processing after A/D conversion. In this case A/D converters with lower speed but bigger dynamic range (16 bit) can be used.

As the receiver has to work correctly in varying RF level conditions an Automatic Gain Control (AGC) is indispensable. Potential AGC problems can be substantially reduced by a certain hysteresis. It is important that this hysteresis must not affect the accuracy of the measurements under all circumstances.

In case of non-stationary use of a measurement receiver – typical during flight inspections or in a moving ground vehicle - the speed of the dynamic signal changes of course depends on the vehicle speed v. The Doppler shift of the carrier frequency f_0 is given by:

$$\Delta f = \frac{f_0 \cdot v}{c_0} \cdot (1 - \cos\varphi) \qquad (2)$$

φ = incident angle of the reflected signal

In case of a backwards reflection (φ = 180° - worst case) the maximum Doppler shift and the corresponding scalloping frequency is 12Hz for a vehicle speed of 60km/h and 60Hz for a speed of 300km/h. According to the Nyquist sampling theorem, the sampling (e.g. measurement) rate should be higher than :

- 24 Hz for ground measurements (V = 60 km/h)
- 120 Hz for flight checks (V = 300 km/h)

In reality common field scenarios are slightly different. For reflection coefficients of r ≤ 0.3 within a range of 0°-50° a sampling rate of 100 Hz is normally sufficient.

ILS receivers are usually tested in the laboratory with common ILS generators. In this setup even receivers that are not suitable for field measurements (e.g. measurement speed, gain control, dynamic range) in general show correct results. The main reason for this is that these generators are only able to generate a single static RF carrier with static ILS modulation. Right up to now general purpose signal generators are unable to reproduce a complex two frequency ILS scenario with fading and multipath effects .

Because of this well known problem technicians in measurement technology tend to do a lot of field testing with their ILS measurement equipment. Often, there is no other way but to compare "old" measurements results with the current ones. Unfortunally it is impossible to reproduce the same measurement result twice - even with the same receiver. Even worse, field measurements show that different receivers react differently to multipath scenarios. This has mainly three reasons:

1. It is in general impossible provide an identical RF scenario more than once at a given location.
2. Driving along the runway (or doing flight inspection) the receiver faces high speed dynamic signal changes (e.g. level, DDM). This must be analyzed without any impact on the device internal signal quality by permanent AGC variations. The worst case occurs when the frequency of the AGC switches is in the range of the Doppler shift frequency. In that case the level value can be at maximum when the AGC just switched to the opposite direction. This can cause clipping of the A/D converter.
3. According to the Nyquist theorem, a suitable sampling rate (in this case measurements per second) is necessary to avoid alias effects. Various receivers do not have a sufficient measurement rate to guarantee this.

ADVANCED ILS RECEIVER TESTING

As described before, modern ILS receivers are a complex system placing most of its functionality into digital signal processing. All critical time-dependent parameters such as AGC, low-pass filtering and data reduction are realized in software, resulting in a number of degrees of freedom and mutual dependencies. As a result, a real ILS radio field environment affected by multipath propagation might stimulate the receiver in a way not foreseen during the development process [2]. The superimposition of direct signal and reflection may cause very dynamic level oscillations and a distorted DDM which is interpreted by a receiver according to its time-dependent parameters. Hence, two conceptually different receivers may deliver two different results for a DDM below or above the CAT limits.

For testing and tuning the time-critical parameters of ILS receivers, a dynamic RF scenario generating test bench is necessary. Conventional ILS generators do not have this capability. They produce a selectable but fixed DDM at a specific level to be fed into the receiver under test. Just switching over to a different DDM or level during a measurement interval is not suitable to reproduce a changing multipath scenario, since the dynamic system then would follow a step function instead of a continuous sequence. An arbitrary ILS generator is needed instead.

Reconstruction of a Multipath Scenario

With the emergence of new large aircraft, such as the Airbus A380, additional challenges for the ILS signal-in-space arise, since this aircraft can act as a potential scatterer due to its sheer size. Being aware of this situation, tests with the A380 were conducted at three European airports (London Heathrow, Frankfurt, Toulouse) concerning the ILS localizer and glideslope [3].

In this context, the results of Frankfurt LOC25L were taken to reconstruct a specific scenario. At position P5 on taxiway S the A380 was turned by 23° according to the (contorted) two-dimensional view of the airport surface which is given by figure 4 (all coordinates referenced to threshold Rwy 25L). The relevant portion of the A380 localizer reflection is caused by its tailfin. At position P5, it is a pure in-beam reflection due to low angle, which results in misleading DDM=0.328 being scattered to the centerline. A receiver effect to be explained later caused the resulting DDM to rise above CAT III limits during ground inspection at 60km/h [3,4].

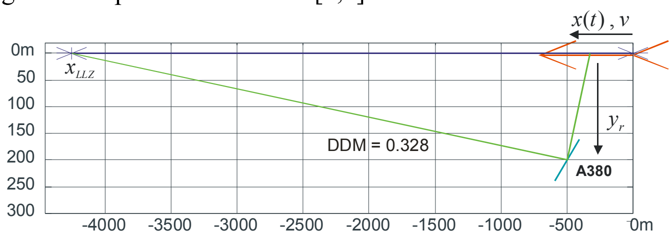

Figure 4. 2D-Geometry of A380 tailfin scatterer left of Frankfurt runway 25L (not to scale)

Signal synthesis

The arbitrary ILS generator should deliver a signal which represents ground inspection where the vehicle moves along the way x(t). In case of a constant velocity v there is a time-dependent threshold distance following

$$x(t) = x_0 - v \cdot t - x_r \qquad (3)$$

where x_0 is the initial distance and x_r=500m the lengthwise distance of the A380.

During motion, the Doppler shift towards the A380 decreases due to its lateral distance y_r=200m, so the difference in Doppler shift against the LLZ antenna is given by

$$\Delta f(t) = \frac{f_0 \cdot v}{c_0} \cdot \frac{x(t)}{\sqrt{x^2(t) + y_r^2}} \qquad (4)$$

with f_0 = 110.7MHz and the speed of light c_0 .

For the following we assume that f_{IF} is an intermediate frequency (IF) which is either used for simulation purposes and for the generation of the real RF signal to be fed into the ILS receiver. Its angular frequency is then described by

$$\omega_r(t) = 2\pi \cdot f_{IF} + 2\pi \cdot \Delta f(t) \ . \qquad (5)$$

Since the momentary frequency is time-varying we need its integral to obtain the momentary phase

$$\begin{aligned} \Phi_r(t) &= \int \omega_r(t) dt + \Psi_r = \\ & 2\pi \left(f_{IF} \cdot t + \frac{f_0}{c_0} \sqrt{x^2(t) + y_r^2} \right) + \Psi_r \end{aligned} \qquad (6)$$

wherein Ψ_r is the initial phase.

The complete AM modulated signal in the time domain is the superimposition of the direct signal (index d) and the reflected portion (index r):

$$y(t) = s_d(t) \cdot \cos(\Phi_d(t)) + s_r(t) \cdot \cos(\Phi_r(t)) \qquad (7)$$

where s(t) describes the modulation. Moving along a centerline (DDM=0) the direct modulation is given by

$$s_d(t) = 1 + 0.2 \cdot (\sin(3\Omega \cdot t) + \sin(5\Omega \cdot t)) \qquad (8)$$

and the reflected, attenuated AM is

$$\begin{aligned} s_r(t) &= a_r(t) + \\ & a_r(t) \frac{0.4 + ddm_r}{2} \cdot \sin(3\Omega \cdot t) + \\ & a_r(t) \frac{0.4 - ddm_r}{2} \cdot \sin(5\Omega \cdot t) \end{aligned} \qquad (9)$$

with $\Omega = 2\pi \cdot 30 Hz$.

The generation of a comprehensive ILS signal according to equation (7) is implemented in Direct Digital Synthesis (DDS) [5] and performed in two steps. In the programming step, the controller fills the memory with data. Each data item is a binary word representing the amplitude of the signal at an instant of time. The array of data in the memory then forms a table of amplitudes, with time implied by the position in the table. Any wave shape that is needed according to equation (7) can be created by altering the data. In case of the employed ILS generator, the memory is a large file on a hard disk holding the uninterrupted amplitudes.

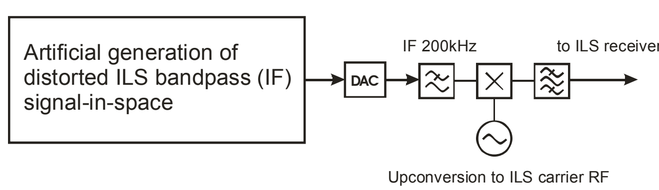

Figure 5. Arbitrary ILS generator on DDS basis

In the running step, the counter (properly called the phase accumulator) is instructed to advance by a certain increment on each pulse from the reference frequency. The output of the phase accumulator (the phase) is used to select each item in the data table coming from the file.

Finally, the Digital-Analog Converter (DAC) converts this sequence of data to an analogue waveform at a chosen IF of 200kHz. After low-pass filtering this signal is then up-converted to the ILS carrier frequency, in this case 110.7MHz. The usage of a 16Bit DAC leaves enough room for high level dynamics within a passage. The resulting complex RF signal constitutes a virtually true model of the real radio field environment.

A block schematic given by figure 5 provides a rough overview on the generator hardware.

Tuning the simulation parameters

A good reconstruction of the location (and thus time)-dependent scattering parameter a_r of equation (9) is important for the generated signal to be realistic. Hence, the DDM values from ground inspection gained at Frankfurt P5 were taken as a reference [4]. The same type of receiver used during the measurement campaign (Rohde&Schwarz R&S®EVS200) was chosen to reproduce nearly the same DDM displacement with the arbitrary signal generator (figure 5). It could be experimentally shown that Gaussian pulse with a reflection maximum a_r=0.3 at a certain distance and an impact along 200m between the half-amplitude points best matches the measurement results. The reflection pulse is shown in figure 6 with reference to the airport geometry as from before (figure 4). The implementation of a Gaussian pulse in equation (9) can be simply realized as a time function $a_r(t)$.

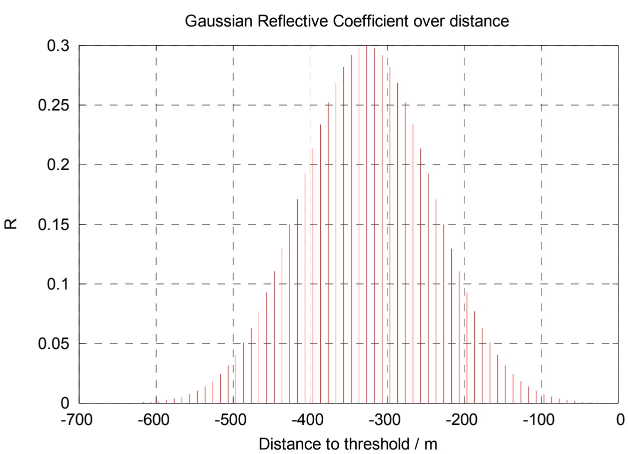

Figure 6. Simplified A380 tailfin reflection coefficient considered as a Gaussian pulse with maximum 0.3

Probing on AGC parameters

The maximum expected reflection factor and the worst reflection angle provide enough information to calculate and simulate a complex arbitrary ILS signal on the carrier frequency containing dynamic multipath effects. These lab generated signals are close to reality, can be reproduced as often as necessary and help to define a hysteresis of the gain control that meets all expectations.

For the EVS300 several tests were performed with different values for the AGC hysteresis. A constant-level direct signal superimposed with a reflection according figure 6 was fed into the receiver. Figure 7 shows the volatile AGC impact which tries to over-compensate the scatterer's influence (blue curve). Therefore, the raw DDM (red) is affected and the low pass-filtered DDM (filter parameters according to ICAO [1]) bounces as well. A hysteresis of ±1 dB seems to be definitely too low for real scenarios.

Re-parametrizing the hysteresis, it could be shown that ±3dB is normally sufficient. To be on the safe side and using a 16 bit A/D converter it is - without any problems in accuracy - possible to use a hysteresis of ±6dB. This hysteresis is implemented in the current FW version of the EVS300. The results in figure shows the scalloping raw DDM and AGC curves which now clearly follow the level oscillations.

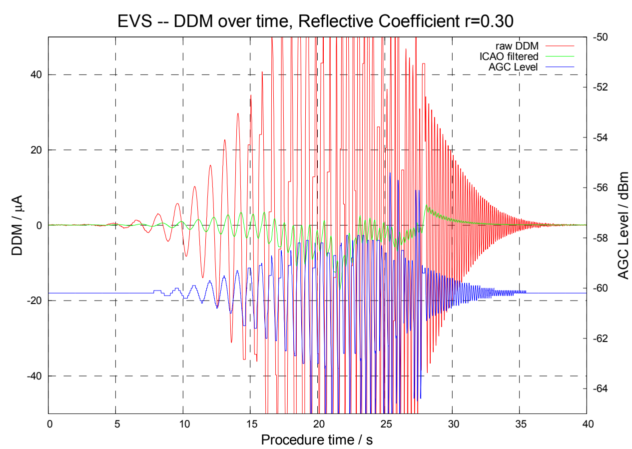

Figure 7. DDM and AGC curves using critical AGC parameters

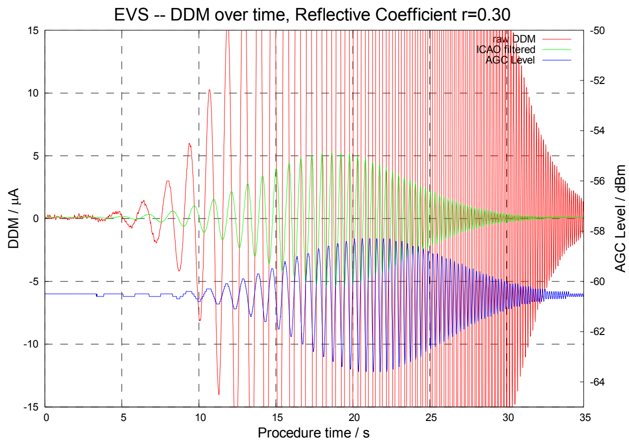

Figure 8. Correct AGC parameters

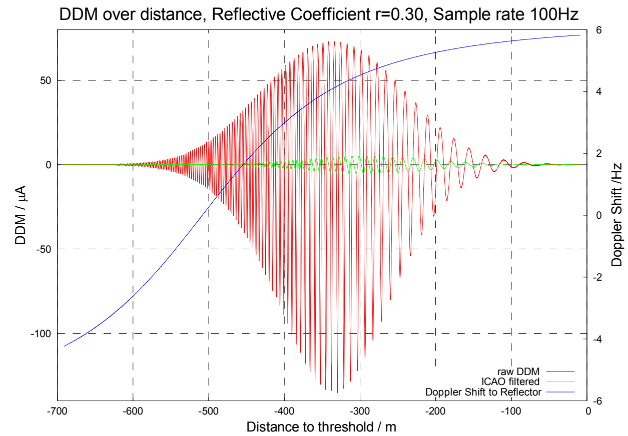

Figure 9. Simulated DDM at 60km/h

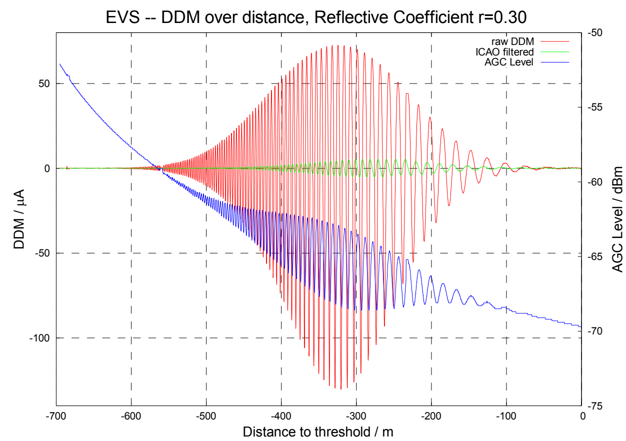

Figure 10. Measured DDM at 60km/h

Comparison of simulation and measurements

The ILS generator software has another feature which allows the user to derive the theoretical DDM directly when generating the corresponding DDS data. The result is shown at a sample rate of 100Hz for a vehicle velocity of 60km/h in compliance with the geometrical specifications shown in figure 9 wherein the blue curve indicates the absolute Doppler shift during motion towards the reflector. When reaching the distance -500m this value turns zero because the reflector is abeam.

The corresponding measurement result is shown in the next figure (10) and the almost perfect accordance of the DDM curves, even of the raw data (red), is evident. This was achieved by adapting the 90/150Hz sideband filter parameters to those of the R&S®EVS300.

In contrast to the pure AGC test curves in the section above where the level was fixed, we now increase it by 20dB passing by 700m along the scatterer. The generator's 16 bit DAC has enough dynamic reserve to cover more than 50dB and the output is still well above noise.

The applied level dynamic of 20dB is much higher than in the reality of runway 25L at Frankfurt. During the whole CAT III inspection drive on Rwy 25L (4km) starting from close to the threshold, the dynamic level is about 30dB. This depends on the LOC vertical pattern and the distance to the antenna. However, the real LOC antenna pattern has not yet been implemented in the signal generation since it is irrelevant to what was to be shown.

A spectral diagram of the simulated ILS bandpass signal is generated by the software at any distance. For the internal simulation it is assumed to have an IF of 1kHz, and figure 11 (top) shows the ILS spectrum at –420m. The carrier is 6Hz Doppler shifted and the scattering portion becomes visible as a much smaller spectral line. Since the reflector is located on the 90Hz side, small lines of the scatterer's spectrum are separating from the direct 90Hz sideband.

The corresponding (audio) spectrum of the baseband is given by the lower graph in figure 11. The reflected carrier itself is close to zero on the X axis whereas the two modulation sidebands are located at their specific frequencies. The 90Hz sideband itself acts like a further carrier with the amplitude modulated reflection.

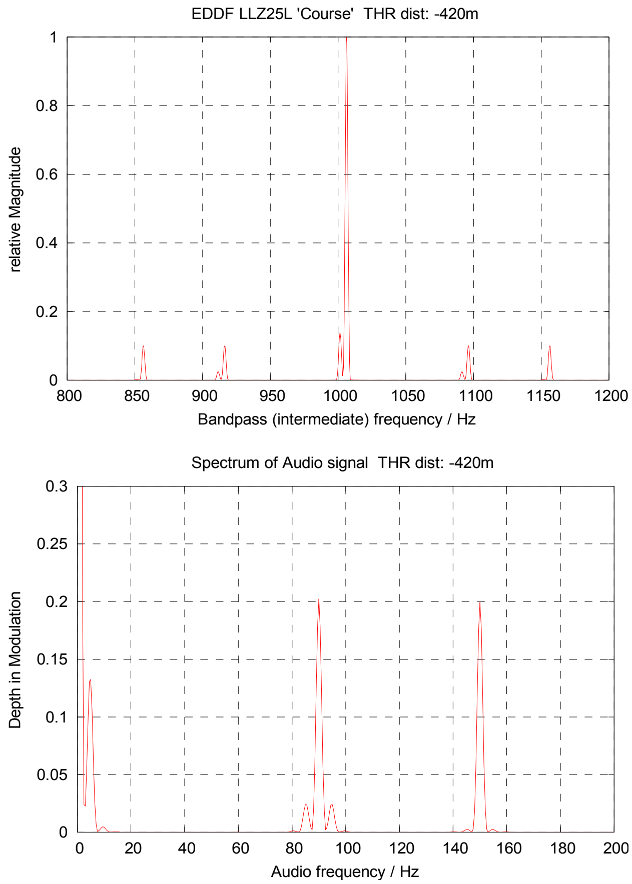

Figure 11. IF and Audio Spectrum in presence of scatterer

Selecting a much higher speed (360km/h) and leaving all other parameters untouched, the simulated DDM diagram is given by figure 12. The Doppler shift towards the scatterer (blue curve) increases considerably whereas the scalloping maxima remain at the same distances, since they are not a function of time but of geometry. The resulting ILS receiver measurements show again a good conformance to the simulation (see figure 13).

Bias effect

The most significant difference between the DDM curves gained at the two velocities 60km/h and 360km/h, especially those of the ICAO filtered data (green), is visible through a bias towards positive (90Hz) DDM values. This effect can be explained by the following:

Generally, if the differential Doppler shift remains within the sideband filter bandwidth, a significant scalloping of the raw DDM occurs since direct signal and reflection superimpose in different phases depending on the momentary location. With respect to figure 11 (bottom) this means that the filter covers the main 90Hz line including its reflected sidebands so the envelope of a secondary AM becomes visible after rectification.

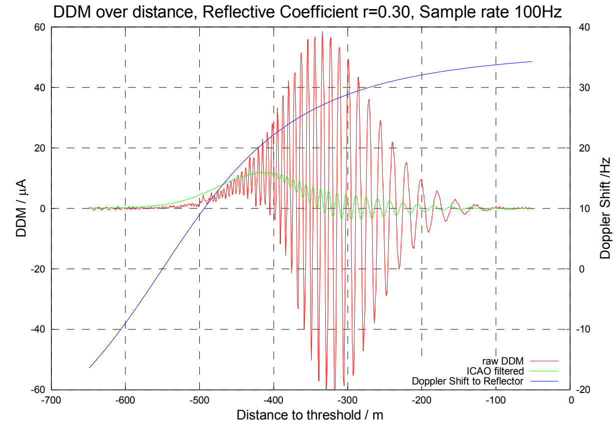

Figure 12. Simulated DDM at 360km/h

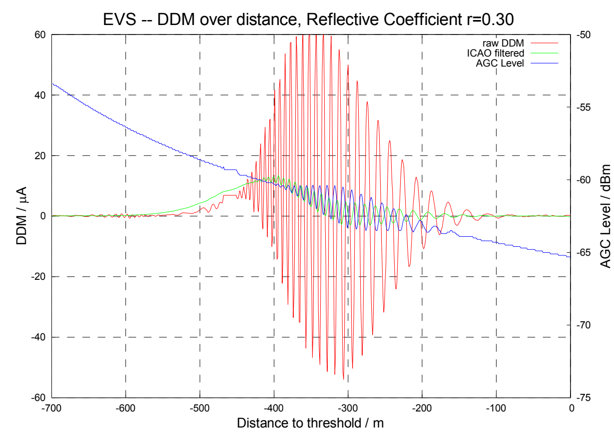

Figure 13. Measured DDM at 360km/h

However, another small portion, barely visible in figure 11, is on top of the 90Hz spectral line and makes it greater than the 150Hz line. During scalloping, this small portion does not have a significant influence on the raw DDM curve because the scallop oscillations are predominant.

When the Doppler shift increases and breaks through the bandwidth barrier, the reflection sidebands of figure 11 are out of effect to the 90Hz sideband filter output but the small overhead, the bias, remains. The ICAO conforming DDM low pass filter suppresses the scalloping effectively but lets the DC-like bias pass.

In order to derive the absolute bias value, one must mathematically pass through the receiver's rectification process which is represented by an envelope detector. With respect to equation (7) the rectified signal is given by:

$$|y_T(t)| = \sqrt{s_d^2(t) + s_r^2(t) + 2s_d(t)s_r(t)\cos(\phi_d(t) - \phi_r(t))} \tag{10}$$

To eliminate the root, a number of simplifications must be performed, including a Taylor series expansion and a partial fraction decomposition. These applied operations were originally described in [7] and followed by the authors. In this context however, only the final euqation which is given by

$$DDM_{bias} = DDM_d \left(1 - \frac{a_r^2}{4}\right) + DDM_r \frac{a_r^2}{2} \qquad (11)$$

will be applied to calculate the resulting value. On centerline, the left term of equation 11 is zero. Taking the values of DDM_r and $a_{r,max}$ from the simulation parameters, we would obtain

$$DDM_{bias} = DDM_r \frac{a_r^2}{2} = 0.328 \cdot \frac{0.3^2}{2} = 0.01476 \approx 14\mu\text{A} \qquad (12)$$

as a maximum for the bias offset. This value is not fully reached by ICAO filtered DDM curves, since the effective reflection coefficient already decreases before the Doppler shift is sufficiently large.

Current software status

The current version of the ILS bandpass signal generation software allows only to implement very simple, two-dimensional scatterers. It is not intended to compete with any other complex simulation software available on the market since the main focus of this work is clearly aimed at the generation of ILS RF signals to be fed into various receivers to examine their behaviour under dynamic effects. However, results of complex hybrid numerical computations might be converted into a suitable bandpass signal which then can be used with the developed arbitrary ILS signal generator.

CONCLUSIONS

It was shown that it is highly useful to apply synthetically generated ILS signals-in-space integrating multipath components to the development or improvement phase of a complex navigation measurement receiver in laboratory conditions. This must be considered a major technological achievement, since equipment manufacturers are rarely able to perform extensive field tests with real ILS installations. As a prerequisite, a sufficient number of ILS field measurements under various multipath conditions are required as real radio field condition inputs for the development of the signal generation software. These inputs must necessarily come from the field, e.g. from regularly performed the flight and ground inspections, or special mission calibrations. The clear benefit from improved measurement receivers with respect to their defined performance in dynamic conditions is that measurement results are fully comparable. This improves the safety level of the well-established ILS technology, despite todays increasing difficulties in maintaining established ILS service levels.

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