P5.4 # LINEARITY AND DYNAMIC RANGE OF A DIGITAL RECEIVER

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1 INTRODUCTION

The digital receiver is state-of-the-art of modern Doppler weather radars. A digital receiver samples the intermediate frequency (IF) signal of a radar receiver. Matched filtering, baseband conversion and phase referencing for coherent-on-receive operation are realized by digital signal processing hardware and software. Logarithmic amplifiers, analog I/Q demodulators and phase-locked coherent oscillators (COHO) are obsolete. For the first time it is possible to realize dynamic range figures with linear signal reception which were reserved to logarithmic receivers until then. A key advantage of a linear receiver is its capability to be calibrated with a stable power reference at any point of its dynamic range without the necessity to cover the complete dynamic range by calibrating more points (single-point calibration).

This paper presents some considerations in regard to the specification and performance testing of digital receivers. The key parameters of a linear receiver are its linearity and its dynamic range, which is defined by the minimum detectable signal (MDS) and the saturation of the receiver. The theory which is used to describe the linear receiver is discussed briefly. This paper focuses on the techniques which can be applied to demonstrate the receiver performance.

2 DIGITAL RECEIVER DESIGN

A digital radar receiver consists of an analog receiver front-end and the actual digital receiver. A simplified block diagram is shown in Figure 2. The analog part features at least a low-noise amplifier (LNA), a down-conversion mixer and a stable local oscillator (STALO). The received signals are mixed to an intermediate frequency (IF). The IF signal is digitized, matched filtered and I/Q-demodulated. Usually the filtering and demodulation is an integrated decimation process. The I/Q-data are clutter filtered before any further processing is performed. For the testing procedures which are subject of this paper the clutter filters are disabled. For the same purpose velocity processing is not indicated. The sample power calculation I^2+Q^2 is required for the measurement of noise and test signal power figures. In order to give a complete picture of the measurement setup, the antenna and the antenna waveguide are also shown, together with the coupler which injects the signal from the test signal generator (TSG).

3 THEORY OF THE LINEAR RECEIVER

A receiver is regarded as linear, if the complex output signal voltage $\underline{s}_{OUT}$ can be described as product of a complex input voltage $\underline{s}_{IN}$ and a complex, time independent transfer function $\underline{g}_{RX}$ according to Eq. 1:

$$s_{OUT} \exp(j\omega t + \varphi_{OUT}) = = g_{RX} \exp(j\varphi_{RX}) \cdot s_{IN} \exp(j\omega t + \varphi_{IN}) \quad \text{Eq. 1}$$

A more detailed definition of linearity can be found in e.g. [1]. The amplitude of the transfer function is the receiver voltage gain g_{RX}.

There are always two signals applied to a radar receiver: the backscattered signals and noise:

$$\underline{s}_{OUT}(t) + \underline{n}_{OUT}(t) = \underline{g}_{RX}\left(\underline{s}_{IN}(t) + \underline{n}_{IN}(t)\right) \quad \text{Eq. 2}$$

It can be shown that due to the properties of the linear receiver not only the signal and noise voltages but also the signal power S and noise power N behave additive:

$$S_{OUT}(t) + N_{OUT}(t) = G_{RX}\left(S_{IN}(t) + N_{IN}(t)\right) \quad \text{Eq. 3}$$

G_{RX} is the power gain of the receiver.

However it has to be pointed out the due to the fact that the receiver measures and processes the power of the signal rather than the I and Q voltages, it is a linear receiver with a square-law detector. Such a detector is a non-linear device and performs non-coherent integration.

4 MEASUREMENT OF RECEIVER LINEARITY

Because it is not possible to connect standard RF test instruments like spectrum analyzers and scopes to the output of a digital receiver it is important to find alternative methods to evaluate its performance. The measurement is demonstrated with a METEOR 1500S receiver featuring an AspenDRX digital receiver. The relevant setup data of the receiver are shown in Table 1.

Input Load	Matched Load, no Antenna
Temperature	26 °C
Matched Filter	0.5 MHz
TSG Insertion Loss	23.9 dB, incl. cable and coupler
Aver. power samples	204000

Table 1: Receiver Setup

The linearity is usually measured by injecting a cw microwave signal from a test signal generator (TSG) with stable frequency and known power, which is varied in equidistant steps in order to cover the complete dynamic range. For this measurement it is necessary to operate the digital receiver in a mode which provides uncalibrated and unprocessed averages of power samples. The dimension of the samples and the averages are Arbitrary Digital Units (ADU). For the evaluation of the statistical properties of the test setup it is convenient to have the probability density function (PDF) of the random power signal P generated from a sinusoidal voltage signal with power S embedded in thermal (Gaussian) noise with mean power N:

$$p(P) = \frac{1}{N} \exp\left[-\left(\frac{P}{N} + SNR\right)\right] I_0\left(\sqrt{4P\,SNR}\right) \quad \text{Eq. 4}$$

p(P) was derived from the well-known Rice distribution which describes a random voltage signal [1], [2]. SNR is the signal-to-noise power ratio and I_0 is the zero-

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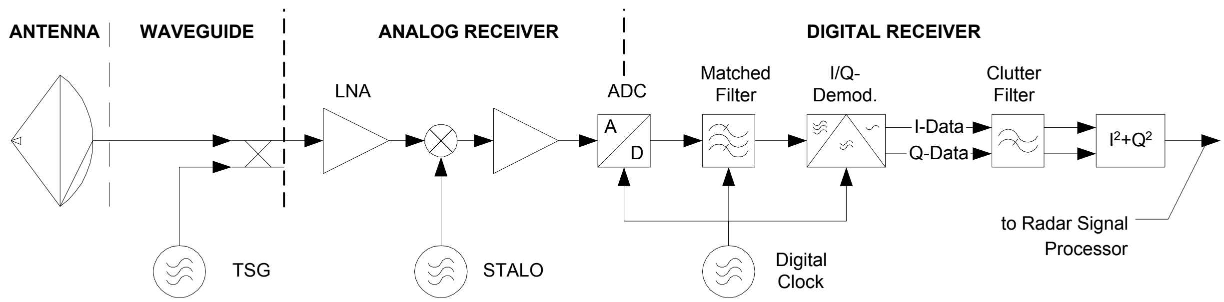

Figure 2: Digital Receiver

order modified Bessel function of the first kind. The mean power P_{AV} calculated from Eq. 4 is simply [1]:

$$P_{AV} = S + N \qquad \text{Eq. 5}$$

Eq. 5 is an inevitable result because Eq. 3 must be satisfied.

Because multiple power samples are taken the standard deviation of the power measurement is reduced according to [1]:

$$\sigma_M = \sigma(P) \Big/ \sqrt{M} \qquad \text{Eq. 6}$$

The standard deviation for small SNR's is provided in Table 2.

SNR	SNR/dB	σ/N	σ_M/N
0	n.a.	1	0.007
1	0	1.732	0.012
1.26	1	1.876	0.013
1.59	2	2.042	0.014
2	3	2.234	0.016
10	10	4.583	0.032

Table 2: Standard Deviation of measured Data

The receiver is regarded as linear according to Eq. 1 and Eq. 2 if the data pairs form a straight line. The steps of the measurement are listed below. The measured and calculated data are plotted in Figure 1.

1. The noise power is measured. The TSG should be disconnected and its port should be terminated for this measurement. Another possibility is to set the TSG to maximum attenuation and compare the noise power (in ADU) with the noise power measured when the injection port is terminated. If there is no difference the TSG must not be disconnected for future noise measurements.
2. Measurement of 2-4 data pairs at power levels which are at least two orders of magnitude higher than the noise power. The noise power is subtracted from measured output power. The noise power-corrected data pairs are used to calculate a regression line which is forced to cross the (0 W; 0 ADU) pair.
3. The TSG is set to maximum attenuation and the attenuation is increased in steps of e.g. 1 dB. The resulting data pairs are plotted into the same diagram which shows the regression line.
4. The noise power is subtracted from measured power figures and the corrected data pairs are plotted. If they are on or very close to the regression line the receiver can be regarded as linear.
5. The saturation region is evaluated at least. The upper limit of the dynamic range is usually defined in terms of the deviation of the measured data to the regression line. The point where the measured data are 1 dB below the regression line is referred to as "1 dB compression point". The evaluation of the saturation region is not addressed in this paper.
6. The final step is a repeated mesurement of the noise power as described with step 1. The figure must be the same to ensure that no drifts occured during the measurement.

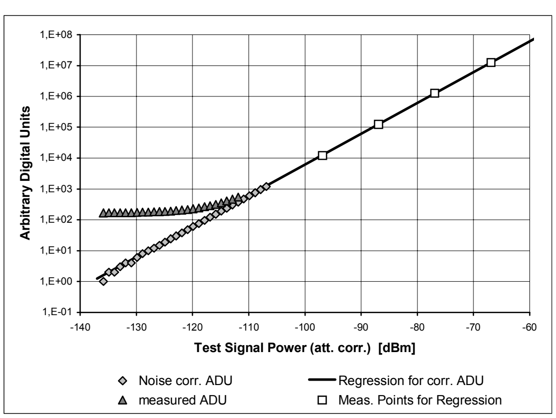

Figure 1: Evaluation of Receiver Linearity

5 CALIBRATION OF A LINEAR RECEIVER

Once it is ensured that the receiver is linear and that its response can be described by Eq. 2 it can be calibrated by a "single-point calibration". During a single-point calibration a test signal with a stable, known power level is injected into the receiver. The power of the test signal has to be much stronger than the receiver noise so that the noise term can be neglected. The receiver constant RC is given by:

$$RC = \frac{\textit{test signal power}\,[W]}{\textit{measured output power}\,[ADU]} \qquad \text{Eq. 7}$$

The receiver constant allows the calibration of the complete receiver with respect to its input. This is an important advantage of a linear receiver. A complex calibration of the complete dynamic range and generation or a lookup table as described in [4] is not necessary any more. As an example the data used for the evaluation of the linearity are calibrated. Figure 3 provides a plot of the calibrated data / test signal power ratio over test signal power. For a perfect calibration the ratio should be 1.0 over the complete dynamic range. The scattering of the low-power data is caused by the large variance of the signal at these levels which is

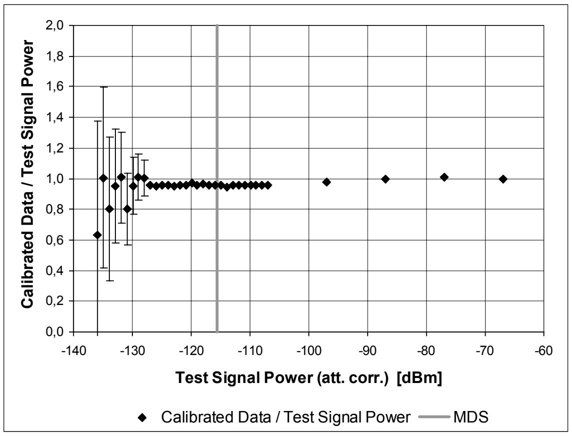

Figure 3: Calibrated Data / Test Signal Power

indicated by the standard deviation error bars, however the ideal calibration is resembled quite closely. The nearly constant deviation of about 0.05 in the –125 dBm to -115 dBm region is interesting. The reason could be an offset of displayed versus real signal power of the TSG due to an attenuator offset. The accuracy of the test instruments is not considered in this paper.

6 NOISE FIGURE AND MDS MEASUREMENT

Another nice feature of the linear digital receiver is the simplicity of the noise figure measurement. Commercial noise figure test sets are only useful for analog designs and cannot be used here. Again it is important to find an alternative method. The noise figure F is defined by:

$$F = \frac{(S/N)_{IN}}{(S/N)_{OUT}} \quad \text{Eq. 8}$$

$(S/N)_{IN}$ and $(S/N)_{OUT}$ are the signal-to-noise ratios at the receiver input and output. If no signal is applied to the input Eq. 8 reads:

$$F = \frac{N_{OUT}}{N_{IN}} \quad \text{Eq. 9}$$

If the receiver input is terminated with a matched load the input noise power is:

$$N_{IN} = T_0 k_B B \quad \text{Eq. 10}$$

The input noise power is only determined by the temperature of the environment T_0 and by the receiver bandwidth B which is the bandwidth of the matched filter in this case. k_B is the Boltzmann constant.

The output noise power can be calculated from:

$$N_{OUT} = noise\,power\,[ADU] \cdot RC \quad \text{Eq. 11}$$

It is of course possible to perform a noise figure measurement according to the Y-factor method [5]. But the proposed method does not require an expensive noise source and is supposed to provide a comparable accuracy.

The lower limit of the dynamic range of a linear receiver is the minimum discernible signal (MDS). The MDS is defined as the signal power which produces a signal-to-noise ratio (SNR) of 1 or 0 dB, i.e. the signal power P_{IN} equals the noise power at the receiver output:

$$P_{MDS} = N_{OUT} \quad \text{Eq. 12}$$

Obviously the MDS of a radar system and its noise figure are closely related. If the matched load is removed and the receiver input is connected to the antenna, the system can be described by the concept of noise temperature [1]. This concept allows to calculate the noise power N_{IN} which would be present at the receiver input if the receiver would be without any losses and which would generate the same noise power N_{OUT} at the receiver output as the real receiver. This input noise power is expressed in terms of the temperature of a matched load connected to the input terminals. If an antenna is connected to the receiver, its output terminal is taken as reference point for the calculation of the noise temperature in order to include the noise received by the antenna. It is important to point out that all calculations based on the concept of noise temperature require that the respective subsystems are *impedance matched*.

The noise temperature T_{SYS} of a radar system can be calculated from the environment temperature T_0 and noise temperatures of the antenna T_A, the receiver T_{RX} and the antenna waveguide attenuation L_{WG} [2], [3]:

$$T_{SYS} = T_A + T_0(L_{WG} - 1) + L_{WG} T_{RX} \quad \text{Eq. 13}$$

whereas the receiver noise temperature is determined by the noise figure F.

$$T_{RX} = T_0(F - 1) \quad \text{Eq. 14}$$

The system noise temperature for a receiver with 2 dB noise figure, 10 m waveguide and 0° antenna elevation is about 400 K. That temperature can drop to 330 K if the antenna is a –10°C and at 90° elevation.

MDS and noise figure can be applied both to the complete system or only to the receiver. We propose to use the MDS to describe the sensitivity of a complete system including antenna, waveguides and complete receiver. The MDS will vary with the radar site (waveguide), with the daytime and the temperature of the outdoor environment. The noise figure should only applied to the receiver and will be independent of any variations of the operational conditions.

7 REFERENCES

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