11B.6

LINEARITY AND CALIBRATION OF LINEAR RADAR RECEIVERS

Frank Gekat*, Jürgen Mehl, Dieter Rühl, Clemens Verstappen
AMS-Gematronik, Neuss, Germany

1. INTRODUCTION

Modern Doppler weather radars are using digital receivers (DRX). The received signals are digitized at an intermediate (IF) frequency which avoids analog downconversion to baseband.

A DRX has a linear characteristic which makes accurate calibration easy. An increasing number of weather radar systems are calibrated with rain sensors, see e.g. Joss (1995). The rain sensor provides only data from its particular location a linear receiver is required to transform the local calibration to the whole radar coverage with significantly varying rain rates. Even polarimetric radars which are capable to compensate the most prominent measurement errors of weather radars, rain attenuation and Z/R-relation, require sensor calibration and thus a linear receiver to bring their advantages to bear.

However the most important calibration is still the accurate determination of the radar constant together with the periodic calibration of the receiver. A linear receiver makes calibration easy because only one signal of known power must be injected in order to get an amplitude calibration of the complete receiver dynamic range (single-point calibration, SPC).

This paper presents two methods for the measurement of the linearity of linear receivers, the comparison method and the two-tone method. The accuracy of the comparison method and of the SPC will be addressed.

2. THE COMPARISON METHOD

The comparison method compares the receiver under test with a known test instrument of equal or better linearity. The setup is shown in Fig. 1.

A test signal of constant frequency is injected into the receiver. The power is varied in order to cover the complete dynamic range of the receiver. After amplification and analog downconversion the signal is sampled at an intermediate frequency (IF) and converted to baseband by the DRX which calculates the power sample I^2+Q^2. The power sample is plotted vs the power of the test signal which is measured by a spectrum analyzer (SA) or a power meter (PM). In order to match the dynamic range of the measurement instruments to the receiver a matching attenuator is inserted.

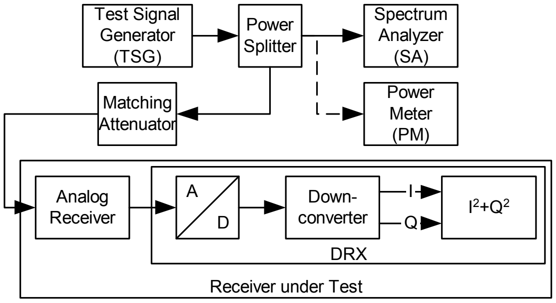

Fig. 1: Receiver Test Setup

2.1. Error Considerations

There are three categories of measurement errors which influence the accuracy of a power measurement: power and frequency independent errors, power dependent errors, and frequency dependent errors (Boonton (1996)).

Power and frequency independent errors are instrumentation error, power reference error, range-switching error and thermal drifts.

Power dependent errors change with signal power. Contributing factors are zeroing error, noise error, harmonics and linearity error.

Frequency dependent errors are calibration factor uncertainty and mismatch uncertainty.

2.2.The Linearity Measurement

The design of a setup for a linearity measurement requires an assessment of all factors which contribute to the accuracy of the measurement.

For an accurate measurement of the linearity the measurement conditions must not change when the power of the test signal is varied. Frequency dependent errors can be excluded because the frequency remains constant and the signal will not be modulated during the measurement. Power and frequency independent errors may affect the accuracy indirectly. Thermal drift during the measurement can be excluded by keeping temperature stable within ±5° during the measurement and by allowing about one hour of warm-up for the complete setup. A fast measurement using an automated setup will help in reducing drift errors. Drifts of the setup can be detected by injecting the same test signal with which the measurement was started also as final step. If both results deviate the setup has probably drifted.

Range-switching errors require some attention. If a linearity measurement is performed using the power level indicator of a TSG the frequent switching of the level attenuation due to the large dynamic range of modern weather radar receivers can cause significant deviations. These errors can only be excluded by using a separate instrument for power measurement. But also PMs or SAs require range switching. If their range is switched the level reading before and after the switching is compared. If an offset occurs it is carried over for the remaining measurement steps.

As expected the power dependent errors will determine the accuracy of this measurement. However, some of these errors can be eliminated for a linearity measurement.

A PM calibration using the internal reference and a quick measurement minimizes the **zeroing error** which is mainly caused by drift effects. A comparison of the level of a reference signal before and after the measurement will indicate possible drifts of the setup.

The **noise error** refers to the internal thermal noise of the SA or PM. The noise can be overcome by using an SA with an internal low-noise preamplifier and by narrowing the bandwidth of the SA or PM. It is necessary to match the dynamic range of the SA or PM to the receiver so that the signal-to-noise ratio (SNR) of the SA level measurement is at least 20 dB. Further improvement is possible by narrowing the video bandwidth and applying the sweep averaging function of the SA. The residual influence of thermal noise on the level measurement can be determined by performing about 10 subsequent level measurements.

The remaining limitation of linearity measurements is the **linearity error** of the measurement instrument. Modern power meters are specified with a linearity error of ±0.05 dB (±1.2%). The linearity error of modern SAs is ±0.2 dB corresponding to ±4.7%. Fig. 2 presents the specification window of an SA together with plots of the linearity of several sample SAs (Rhode & Schwarz (1999))

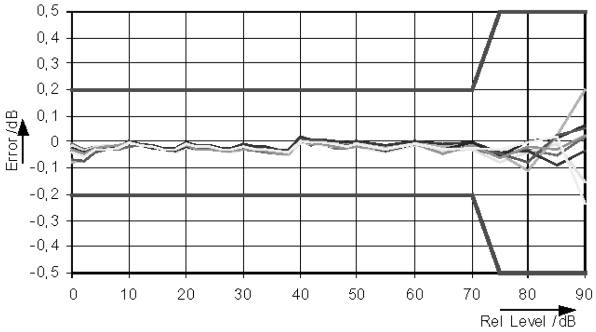

Fig. 2: SA Non-Linearity

2.3. Measurement with the Power Meter

Because of its superior linearity the power meter seems to be the ideal instrument for linearity analysis. However their dynamic range does not match the dynamic range of a radar receiver. Although power meters with 90 dB dynamic range are available the useful dynamic range is about 70 because of their high noise level. The lowest useful signal level is about –50 dB to –40 dB if the measurement shall take advantage of the excellent linearity specification. Therefore it is necessary to switch the matching attenuator at least once if not twice. The range switching error must be carried over when the matching attenuator is changed

2.4. Measurement with the Spectrum Analyzer

The SA is much more convenient because it does not require changing the matching attenuator during the measurement. However, if the reference level is changed during the measurement the range-switching error must be determined by comparing the actual with the previously measured level and must be carried over.

The SA provides sufficient dynamic range to operate well above the noise level of the instrument, if the resolution bandwidth is narrowed sufficiently. Care must be taken to measure the power at the peak of the displayed spectral line. Fortunately modern SAs provide advanced marker functions which allow tracking the small frequency variations of the TSG

3. NOISE STATISTICS

Both instruments, the PM and the SA have difficulties when the signal level is approaching the noise floor. An alternative for the investigation of low signal levels is the application of statistical techniques. The output signal of a high-quality linear receiver should be composed of the transferred test signal and thermal noise. The statistics of such a power signal are known (e.g. Gekat, (2001)). There are several possibilities to investigate a data series generated for the same input test signal. If the noise temperature is known from a noise figure measurement the theoretical numbers for mean, variance and standard deviation can be compared to the measured data. Another possibility is to fit the theoretical probability distribution function to the function of the data set and analyze the fit parameters.

Probably the easiest statistical method is the investigation of a data series with no input signal and with the receiver input terminated. The signal should be solely thermal noise with a Rayleigh distribution. This method is well suited to indicate ADC non-linearities as described by Analog Devices (Brannon (1995)). Any spurious signals, even if embedded in the noise, will result in deviations from the thermal noise statistics.

4. THE TWO-TONE METHOD

A disadvantage of the comparison method is the quite large number of data points required which results in a long measurement time. The measurement can be easily performed with an automated environment, however, this requires some programming, the accuracy may be reduced and a certain period of time is still necessary.

Any deviations from the linear transfer function willl cause harmonic signals at frequencies 2f, 3f, 4f etc. These signals are too much separated for direct acquisition with the radar receiver, but if two signals within the bandwidth of the radar receiver are injected

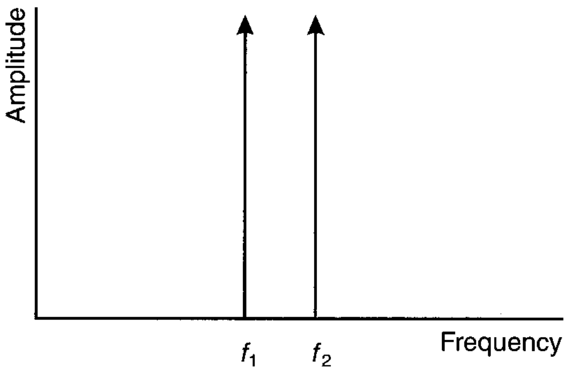

Fig. 3: Two-Tone Test Signal

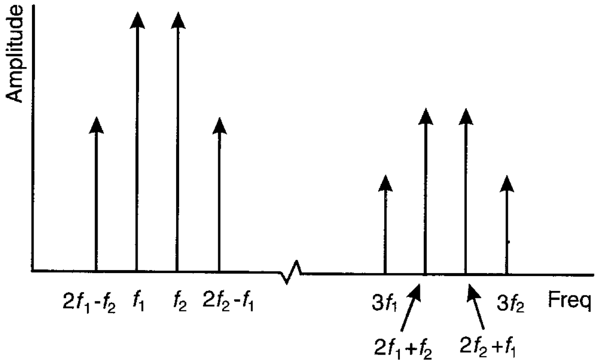

Fig. 4: Two-Tone Output Signal

simultaneously the intermodulation products of the harmonics will also appear within the bandwidth and can be analyzed. The frequency domain representation of the test signal and the output signal is shown in Figs. 3 and 4.

This technique is called two-tone method (Kenington (2000)). It covers the complete dynamic range of receiver. The signal amplitudes at the receiver input are simply added. Because the frequencies are slightly different the power level, which is the envelope of sum of both signals, permanently sweeps through the complete dynamic range of the receiver. This becomes evident when the input signal is observed in the time domain as in Fig. 5.

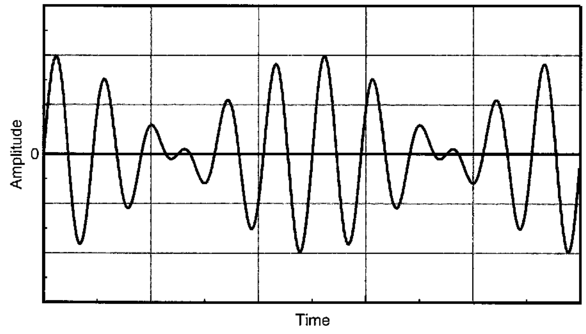

Fig. 5: Time-Domain Representation of a Two-Tone Signal

As a measure for the linearity of the receiver the compression of the 3rd order signals at $2f_1$-f_2 and $2f_2$-f_1 may be used. However microwave engineers prefer the specification of the so-called IP3 (3rd order intercept point). The IP3 is the interception of the ideal fundament transfer function with the 3rd order signal transfer function. This is demonstrated in Fig. 6. In order to calculate the IP3 at least 4 measurements are required: 2 measurements for determining the slope of the fundamental transfer function and 2 measurements for the slope of the 3rd order signal. This is much less than a conventional linearity measurement considering that each of the 3rd order signal represents the linearity of the complete receiver. A setup for a two-tone measurement is shown in Fig. 7.

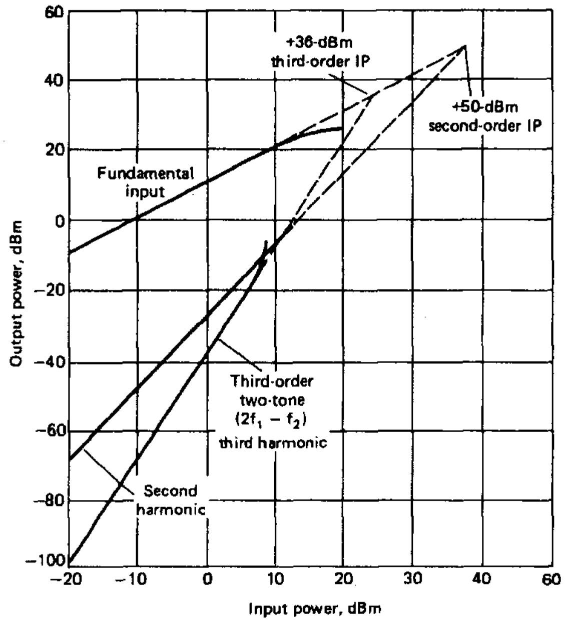

Fig. 6: Definiton of IP3

5. CALIBRATION

Once the linearity of the receiver is confirmed it can be calibrated with a single-point calibration (SPC, Gekat, (2001)). Unlike the linearity measurement, which is a relative measurement the calibration requires an absolute measurement. A relative measurement is based on the comparison of power levels whereas the absolute measurements measures the level. This requires an accurate power meter with a valid traceable calibration. Modern power meters provide an absolute accuracy which is only slightly higher than their relative accuracy, about ±0.07 dB (±1.6%). However, an absolute power measurement needs also calibrated cables, splitters and couplers with known or measured VSWRs. The calibration of a coupler with large coupling attenuation, like a waveguide coupler requires a vector network analyzer because of the limited dynamic range of scalar analyzers.

Another problem which is typical for waveguide couplers must also be mentioned. The measurement path of a waveguide coupler usually includes a waveguide flange and a coaxial port. This means that

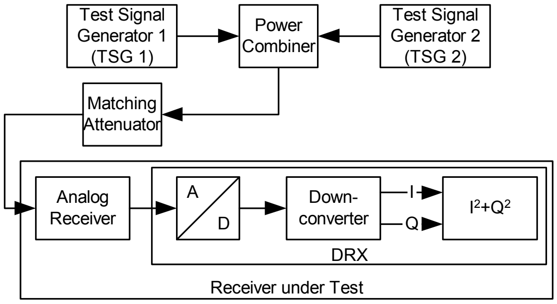

Fig. 7: Two-Tone Measurement Setup

the very important transmission calibration is impossible. A waveguide coupler is a so-called "non-insertable device". The advanced techniques which are required for calibrating such a components can only be applied with a vector network analyzer. The overall accuracy of absolute measurements is compromised if a waveguide coupler is involved.

6. CONCLUSIONS

Several methods for measuring and analyzing the linearity of weather radar receivers were shown. Accurate and precise measurements do not necessarily require extremely expensive equipment. Due to the rapid growth of the mobile phone and wireless markets and the advanced accuracy requirements which are required by these technologies the accuracy of RF and microwave measurements has increased significantly while the prices have effectively dropped. Therefore instruments with an accuracy became affordable which outperforms older equipment by far.

Examples of measurements performed with these techniques will be presented. But whatever the accuracy of the receiver calibration is the user of the radar should always have the application in mind. There are two issues in regard to the operation of weather radars which are directly related to the linearity of the receiver.

First, any reflectivity measurement assumes a Rayleigh distribution of the backscattered signals. A Rayleigh distribution is characterized by the long "tail" which represents the probability of strong signals. For accurate reflectivity measurements the receiver should transfer the complete dynamic range covered by the local distribution of the respective range bin in a linear manner. This leads directly to the second issue.

The linearity and the dynamic range of a receiver is traditionally limited by the specification of the 1dB compression point which represents the onset of saturation. However 1 dB compression means 1 dB deviation from linearity! The reflectivity estimation of strong signals with a mean power close to the receiver saturation will inevitably become distorted because the "tail" of the Rayleigh distribution will be limited to the compression level.

7. REFERENCES

Boonton, 1996: Power Sensor Manual P/N 98501900A

Brannon, B., 1995: Analog Devices Application Note AN-410 "Overcoming Converter Nonlinearities with Dither"

Joss, J et al., 1995: Seven years of dis-agreement between radar, rain gauges and river flow: possible improvements? 27. Conf. Radar Met., Vail, Colorado

Gekat, F. et al., 2001: Linearity and Dynamic Range of a Linear Receiver, 30. Int. Conf. Radar Met., Munich, Germany

Kenington, P.,2000: High-Linearity RF Amplifier Design, Artech House, Norwood, Massachusetts

Rhode & Schwarz , 1999: Application Note "RF Level Test System +20 dBm to –130 dBm"