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Introduction

Radar cross section measurements at small wavelengths present a number of special challenges related to available instrumentation and detection. This issue’s Measurements Column features a paper by Mikko Puranen, Pekka Eskelinen, and Jukka Ruokokanen that demonstrates a significant variance among available receiver instruments at these wavelengths. It serves to illustrate the importance of system characterization for even a supposedly “straightforward” test setup.

Practical Uncertainty of Pulse Power Measurements in Ka-Band RCS Instrumentation

Mikko Puranen\(^1\), Pekka Eskelinen\(^2\), and Jukka Ruokokanen\(^3\)

\(^1\)Helsinki University of Technology, Metrology Research Institute
Otakaari 5 A, FI-02150 Espoo Finland
E-mail: mpuranen@cc.hut.fi

\(^2\)Helsinki University of Technology, Applied Electronics Laboratory

\(^3\)Finnish Defense Forces, Technical Research Center
PL 3000, 02015 TKK, Finland

Abstract

The output level of pulsed radar transmitter and receiver test sets can be defined with spectrum analyzers and diode detectors. Modern analyzers, which have 10 MHz or wider resolution bandwidths and cover appropriate input frequency ranges, can be used in the Ka- and V-band radar domains for pulse widths above about 200 ns. A practical uncertainty of 2 dB is obtainable. External mixers seem to show larger-level discrepancies, up to 5 dB, and may give only 20 dB of dynamic range. Their conversion loss may vary by 8 dB over just 500 MHz. Diodes work at higher power levels, but rise-time definitions are complicated. Above \(-15\) dBm input levels, we can get uncertainties comparable to spectrum analyzers, but the true dynamic range can be just 15 dB, and temperature effects may hamper outdoor trials. Below 200 ns pulse widths, radar-receiver test generator level calibration remains very challenging in the millimeter-wave bands due to inadequate sensitivity, regardless of the measuring instrumentation.

Keywords: Microwave devices; microwave measurements; radar; power measurement; millimeter wave measurements; millimeter wave radar; radar measurements; radar cross sections
1. Introduction

Radar-reflectivity measurements often utilize a combination of on-site calibration targets, having known radar cross sections, and electronic injection of defined RF power levels and detection of generated output powers [1]. The first process may be technically somewhat more robust, but it certainly is very tedious, partly due to multipath issues [2]. Of course, the aim in all of these efforts is to provide a means of reducing amplitude-related errors in the final RCS test documentation. An example of an expected error budget was given in [3]. The introduction of millimeter-wave radars in defense and civilian use has further complicated the situation. Much is attributed to the general difficulties in making costs-effective yet precise components, such as detectors, for these radar bands [4].

One of the ultimate challenges in power-level measurement is met in such instrumentation radars, where the system mimics the characteristics of realistic tactical devices. Very short pulse widths—below 100 ns—are typical, and the radar service volume is often generated by modest-to-low transmitted power, combined with good to super receiver sensitivity [5]. Naturally, we would like to have calibration electronics extending the performance of our test radar. Particularly problematic is the level definition of receiver test signals, because their maximum amplitude can be somewhere around -40 to -50 dBm. Quite understandable, the aim here is to avoid large and hard-to-calibrate attenuation values that would be mandatory if starting with higher power, say 0 dBm or even more. The following discussion highlights some practical issues found by the authors when performing straightforward equipment alignment in the amplitude domain, with commercially available measuring instruments and components in the Ka and V bands. Experiments covered transmitter power measurements, receiver amplitude-response measurements, and some considerations of unwanted emissions. The idea was not to prove metrology-grade traceability to primary standards, but to compare results obtainable with readily available devices, and to discuss the uncertainty issues of the microwave power measurements. The variations between the results acquired with different instruments were surprisingly large, and they showed that calibrating the measurement instruments individually for each measured frequency is necessary.

2. Test Arrangements

All experiments described here were performed with millimeter-wave signals coming from (or suitable for) instrumentation radars outlined by the authors in [6]. The basic waveform was pulse modulated, and had an adjustable pulse repetition frequency from 5 to 50 kHz. The pulse width could be adjusted as well, down to 40 ns. Conventional power meters, with thermocouple or diode sensors [7], are quite useless here, because of their long time constants [8]. The time constant of a thermocouple sensor can even be seconds [4], and modern diode sensors (such as Rohde & Schwarz NRV-Z) are able to measure the peak envelope power (PEP) of signals during peaks longer than 2 μs [9].

Five different real-time sensing devices were used to define the power level that either came from the radar transmitter itself, or was used as a reference signal for defining the associated receiver response. Two devices, A and B, were recently introduced commercial spectrum analyzers, directly covering the frequency range of interest. Device A had no preselector [10], but employed a special digital scheme to remove undesired responses. Device C was a high-end spectrum analyzer with an external harmonic mixer.

Two commercially available modern diode detectors, D and E, were used together with a digital sampling oscilloscope having an internal 50 ohm termination possibility that was required for acceptable rise times [11]. Diode D was of the so-called zero-bias type in a wideband coaxial 3.5 mm format, whereas the low-cost diode E could use a biasing current of about 50 μA, and had a direct UG-599 waveguide interface. However, biasing was not applied. Additional hardware included fixed, calibrated waveguide attenuators with 6, 10, 20, and 30 dB terminations, plus a calibrated mechanically adjustable unit going down to 40 dB. A narrowband amplifier (again having a manufacturer’s calibration chart for this particular unit) was necessary when evaluating the reference signal level with detector diodes. Commercial analyzers come with coaxial 2.4 mm or 3.5 mm interfaces, and therefore a piece of individually manufactured and calibrated semi-flexible cable, together with one waveguide transition, had to be accepted. For some comparisons, we used a high-performance microwave synthesizer. The two basic setups for the spectrum analyzer and diode measurements are outlined in Figures 1 to 4.

An external synthesized microwave generator could be used in CW mode to generate a calibration signal that enabled us to set the amplitude scale of the diode detectors. It also helped in getting an independent view of the performance of the spectrum analyzers. Naturally, a pure sine wave could be measured in the analyzer with very narrow resolution bandwidths, if desired, and so one was able
and the sweep bandwidth was 1000 MHz. Here, the loss of 2.5 dB caused by the cable and the transition has been taken into account. The use of an external mixer produced the set of curves illustrated in Figure 6, when the input level coming from the reference signal generator was adjusted with external attenuators. The effects of the local-oscillator buffer amplifier are documented here as well, but the attenuator values or conversion-loss biases were not subtracted; only the change of loss as a function of frequency was arithmetically removed.

The modulated transmitter power was recorded with the same devices. An example of the time-domain waveform with analyzer B is in Figure 7. The same situation as seen by diode D is depicted in Figure 8. An attempt was made to define the reference signal level with devices A, B, C, D, and E. The recorded values were collected into Table 1. At test frequency $f_2$, we saw a discrepancy in the device-B results when compared to other spectrum analyzers. During this particular measurement, the resolution bandwidth was set at 100 kHz, whereas with devices A and C, it was 3 MHz, to demonstrate the effect of the change in resolution filter.

Figure 6. The results from the reference source obtained with analyzer C and an external mixer. The solid lines were with the LO amplifier not in use.

3. Results

First, an evaluation of power-level measuring differences among various instruments was carried out, with a CW-like signal that was formed in an up-converter. An example of the results obtained with spectrum analyzers A and B and diode detector D is given in Figure 5. The dynamic range covered was about 30 dB to lower the noise level and reach sensitivities comparable to that of many radar receivers. However, switching of the resolution filters unavoidably caused some level changes, and we thereby would have lost our reference. If, on the other hand, we tried with a pulsed waveform, we would very soon have faced the upper limit of the filter bank.

Figure 7. The radar output in the time domain with spectrum analyzer B.
Table 1. Results of measuring the level of the reference signal source output power.

<table>
<thead>
<tr>
<th>Device</th>
<th>Device A</th>
<th>Device B</th>
<th>Device C</th>
<th>Device D</th>
<th>Device E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>-20.0</td>
<td>-21.7</td>
<td>-18.0</td>
<td>-21.5</td>
<td>-17.0</td>
</tr>
<tr>
<td>$f_2$</td>
<td>-34.0</td>
<td>-36.4</td>
<td>-26.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$f_3$</td>
<td>-30.0</td>
<td>-31.0</td>
<td>-31.0</td>
<td>-21.0</td>
<td>-</td>
</tr>
<tr>
<td>$f_4$</td>
<td>-28.0</td>
<td>-28.0</td>
<td>-29.0</td>
<td>-24.0</td>
<td>-</td>
</tr>
<tr>
<td>$f_5$</td>
<td>-30.8</td>
<td>-34.5</td>
<td>-28.7</td>
<td>-26.0</td>
<td>-24.0</td>
</tr>
</tbody>
</table>

Figure 8. The radar output measured with detector D.

A further study of the detector-reference source combination gave the waveforms of Figures 9 and 10. An accurate interpretation requires a calibration chart, partly shown in Figure 11, for both diodes and reasonable power levels. With its output entirely disabled, the test source showed a dc bias of 14 mV, caused by the preamplifier’s noise in the millimeter-wave band. Figure 12 is a plot from analyzer B when the signal came from the reference source in pulse mode. Because the reference-source recordings with analyzer C caused some confusion, we also measured the true sine-wave response of this combination. Our findings are collected in Table 2, which suggested an average conversion loss of 20 dB. However, the calibration should still be performed individually for each frequency. Here, the practical minimum level for an S/N ratio of about 20 dB was –43 or –33 dBm, depending on the usage of an LO amplifier, if we selected a 3 MHz resolution bandwidth for pulsed waveforms.

4. Discussion

Present state-of-the-art instrumentation seems to be capable of giving a practical power-level uncertainty of 1 dB to 2 dB for CW and long pulses in the Kα and V bands, for suitable power ranges. This is in good agreement with the manufacturer’s data (see, e.g., [12] and [13]), but can seem confusing for the requirements of [3]. Here, “long” should be understood as something five to 10 times the inverse of the analyzer resolution bandwidth. An uncertainty of 2 dB in our case implies that between any of the five devices, a maximum difference of 4 dB has to be accepted. A “suitable” power range is defined here as “around –15 dBm,” because at lower levels, diode detectors have far too poor sensitivity. Spectrum analyzers also start to suffer from noise that is hard to avoid in an instrument having such a wide input filter and a wide resolution bandwidth to cope with the pulse-width requirement. On the other hand, levels considerably above –5 dBm or so tend to compromise the square-law characteristics of diodes, and numerical correction (post-processing) has to be applied.

Interestingly – for example, in [14] – spectrum-analyzer manufacturers seem to suggest that spectra coming from short pulses should normally be handled mathematically, by employing a bandwidth-based correction factor to the recorded/displayed level. System C, with its external harmonic mixer, turned out to be most complicated. It was an exception to the rule, because in this case, the input power couldn’t be much above –20 dBm in order to avoid saturation. This means that pulse widths below about 1 μs would be easily buried in system noise, as indicated by curve C3 in Figure 6. The practical dynamic range, with 300 ns pulses and an LO amplifier, was about 24 dB, and without an amplifier, on 14 dB. Careful experiments revealed problems with the feed-through of LO harmonics to the signal source under test. The effective conversion loss varied by 8 dB, although the bandwidth was only 500 MHz.

Figure 9. The output of our reference-signal source, recorded with detector D.

Figure 10. The same source signal as in Figure 9, but observed with detector E and a buffer preamplifier.
Table 2. Level measurements with a synthesized CW source and analyzer C connected to the external mixer (with/without LO amplifier).

<table>
<thead>
<tr>
<th>Input level (dBm)</th>
<th>Level at $f_1$</th>
<th>Level at $f_2$</th>
<th>Level at $f_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-31</td>
<td>-50.8/-61.3</td>
<td>-47.6/-57.1</td>
<td>-46.3/-55.2</td>
</tr>
<tr>
<td>-22</td>
<td>-42.5/-53.3</td>
<td>-39.8/-49.4</td>
<td>-38.0/-47.8</td>
</tr>
<tr>
<td>-16</td>
<td>-37.9/-49.1</td>
<td>-34.5/-44.5</td>
<td>-31.9/-42.6</td>
</tr>
<tr>
<td>-11</td>
<td>-34.5/-46.5</td>
<td>-31.3/-41.7</td>
<td>-29.0/-40.0</td>
</tr>
</tbody>
</table>

Signal levels typically encountered in radar-receiver calibration are extremely hard to accurately measure. In our case, the -36 dBm output of the reference source was too low for the diode detectors. If modulated with shorter than about 200-300 ns pulses, it would have been outside the practical capabilities of all available spectrum analyzers, too. Even if the analyzer had – and some units do have – a bandwidth in excess of 10 MHz, the noise floor came too close. In our best case, we had a detection S/N of only some 15 dB with 10 MHz resolution bandwidth and -36 dBm input power, when the pulse width was 300 ns. An extrapolated (as analyzers A and C had 3 MHz maximum resolution bandwidths) worst-case level was higher than -25 dBm. An external amplifier, together with suitable attenuators, could give some relief, but generally only for a high-level measurement. Many amplifiers would fool further sensitivity recordings by their excessive output noise. Diodes will often work as biased noise detectors if very high gains are needed. Also, some diodes, such as our sample E, very rapidly go outside the square-law region, as shown in the calibration chart of Figure 10. Thus, any waveform analysis in the time domain becomes impossible.

5. References


4. “Fundamentals of RF and Microwave Power Measurements,” Agilent/Hewlett Packard Application Note AN 64-1A, p/n 5965-6630E.


7. Rohde & Schwarz Power Measurement Application Note.


