ACCURACY OF THE ENGINEERING CALIBRATION OF WEATHER RADARS

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1. INTRODUCTION

The calibration of weather radars is an ongoing issue since radars are used to measure precipitation. There are two fundamentally different approaches: the meteorological calibration and the engineering calibration. The meteorological calibration tries to correlate the signal received by the weather radar with an independent meteorological sensor with a different principle of measurement. The engineering calibration is based on the meteorological radar equation which relates the fundamental parameters of the radar to the reflectivity of the precipitation. Although it seems as if the engineering calibration is still the most used method to calibrate a weather radar only a few publications are addressing this important aspect of weather radar operation. The most important reference is probably [1]. However although uncertainty figures were provided in various papers their origins were not addressed. This paper provides an analysis of the uncertainty of the reflectivity measurement of a radar of which its parameters are individually calibrated. The origin of the contributing uncertainties is discussed.

2. ENGINEERING CALIBRATION

The engineering calibration is based on the meteorological radar equation **Eq. 1** There are two possibilities to perform an engineering calibration: The end-to-end calibration and the parameter calibration. The end-to-end calibration requires a target with a calibrated radar cross section. This target must be fixed at a known distance in the far-field of the radar antenna. The fixture must not disturb the cross section and the environment must exhibit a very low cross section in order to reduce the signal power received through the side lobes. A tethered sphere is normally used for this calibration. The standard radar equation must be used to calculate the radar constant which must then be converted to the meteorological radar constant. However this method is too elaborate for operational weather radar calibration. **Eq. 1** is derived from the equation provided in [2] with a few modifications. The radome attenuation is added and the wavelength is replaced by the frequency using $f = c/\lambda$. All parameters are listed in **Table 1**.

$$Z_E = \underbrace{\underbrace{\frac{2^{10}\ln(2)c}{\pi^3|K_W|^2}}_{C_P}\underbrace{\frac{L_{RD}^2}{G_A^2\theta^2}}_{C_{ANT}}\underbrace{\frac{1}{P_{TX}\tau f^2}}_{C_{TX}}\underbrace{\frac{L_{MF}}{G_{RX}}}_{C_{RX}}}_{C_R} L_P^2 P r^2 \qquad \textbf{Eq. 1}$$

	Antenna
G_A:	Gain
θ:	-3 dB Beam Width
L_{RD}	Radome Losses
C_{ANT}	Antenna Constant
	Physical Constants
c:	$c = 2.9978 \cdot 10^8$ m/s
$\|K_W\|^2$	$\|K_W\|^2 = 0.93$
C_P	Physical Constants Factor

	Transmitter
P_{TX}:	Peak Power
τ:	-3 dB Pulse Width
f	Frequency
C_{TX}	Transmitter Constant
	Receiver
G_{RX}	Gain
L_{MF}	Matched Filter Losses
C_{RX}	Receiver Constant

	Measurement
Z_E	Reflectivity
L_P	Propagation Losses
r:	Range
P	Received Signal Power

Table 1: Parameters of the Meteorological Radar Equation

3. TRANSCEIVER CALIBRATION

The parameter calibration described below is based on the radar model depicted in Fig. 1. The most accurate calibration of the transmitter power level is the measurement of the average power P_{TX_av}. Since the power is measured at port 3 of the reference coupler the modulus of the coupling attenuation $|S_{31}|$ must be considered. The power meter will show the measured power $P_{TX\_av\_meas}$. The peak power can be calculated from the pulse repetition frequency f_{PRF} and the pulse width τ.

The receiver calibration method presupposes that the receiver features a linear transfer characteristic which is normally the case for modern weather radars with digital receivers. In order to measure the receive gain a test signal with the power P_{Cal} is injected into port 3. By choosing the gain $G_{RX} = 1$ the signal level P_{Dig} indicated by the data system is referred to port 2 the reference coupler. Based on these measurements gain and peak power are now represented by **Eq. 2**.

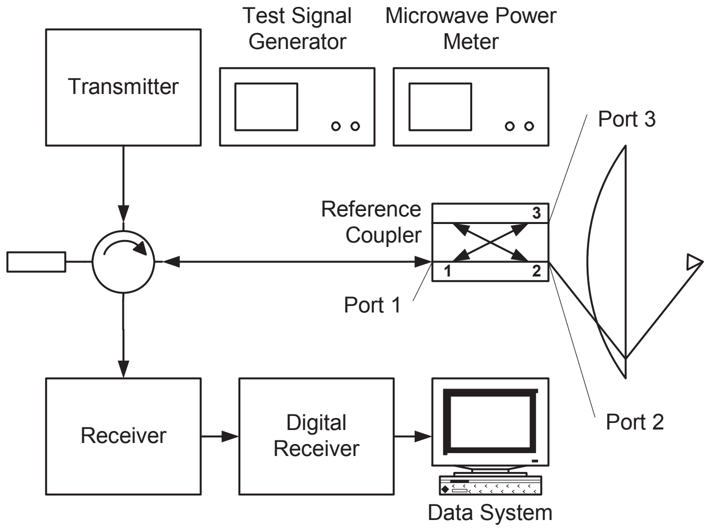

Fig. 1: Radar Model

$$G_{RX} = \frac{P_{Dig}}{\left|S_{31}\right| P_{Cal}} \quad ; \quad P_{TX} = \frac{P_{TX\_av\_meas}}{\left|S_{31}\right| f_{PRF}\,\tau} \tag*{Eq. 2}$$

These representations for gain and peak power are applied to re-write **Eq. 1**:

$$C_R = C_P \frac{L_{RD}^2}{G_A^2 \theta^2} \frac{f_{PRF}}{P_{TX\_av\_meas}\, f^2} \frac{\left|S_{31}\right|^2 P_{Cal} L_{MF}}{P_{Dig}} \tag*{Eq. 3}$$

4. CALIBRATION UNCERTAINTY

The relative error of the radar calibration can be expressed as the combined uncertainty of the measurements of the parameters of **Eq. 3**. The analysis of the combined uncertainty is performed according to [3]. The concept of this approach is also explained in The result is provided with **Eq. 4**.

$$\frac{\sigma_{CR}}{C_R} = \sqrt{\begin{aligned} &\left(2\frac{\sigma_{GA}}{G_A} + 2\frac{\sigma_\theta}{\theta}\right)^2 + \left(2\frac{\sigma_{LRD}}{L_{RD}}\right)^2 + \left(\frac{\sigma_{fPRF}}{f_{PRF}}\right)^2 + \left(\frac{\sigma_{PTXavmess}}{P_{TX,av,mess}}\right)^2 + \left(2\frac{\sigma_f}{f}\right)^2 + \ldots \\ &\ldots + \left(2\frac{\sigma_{S31}}{\left|S_{31}\right|}\right)^2 + \left(\frac{\sigma_{PKal}}{P_{Kal}}\right)^2 + \left(\frac{\sigma_{PDig}}{P_{Dig}}\right)^2 + \left(\frac{\sigma_{LMF}}{L_{MF}}\right)^2 + \left(\frac{\sigma_{DRX}}{D_{RX}}\right)^2 + \left(\frac{\sigma_{DTX}}{D_{TX}}\right)^2 \end{aligned}} \tag*{Eq. 4}$$

Since the gain G_A and the beam width θ of the antenna are correlated, the sum of their relative uncertainties must be squared, assuming a correlation coefficient of 1. All other parameters can be regarded as uncorrelated. Two terms have been added in order to account for deviations from the linear transfer function over the dynamic range. The receiver linearity is considered by σ_{DRX}/D_{RX} and the linearity of the interpulse transmitter peak power measurement channel is represented by σ_{DTX}/D_{TX}.

5. UNCERTAINTY SPECIFICATIONS

The uncertainty of the specifications of the various parameters has to be provided by the manufactures or must be derived from the measurement process. For instance if a microwave power meter is used not only its inherent uncertainty but also the uncertainty introduced by the VSWR of the device-under-test must be considered. Unfortunately different ways to specify uncertainty are used. Therefore all specifications must be converted to the standard uncertainty. Premium measurement instruments are specified in terms of their expanded uncertainty k. If i.e. $k = 2$ is specified the uncertainty lies within the confidence interval 2σ. Some vendors specify maximum errors. These can be converted by assuming an expanded uncertainty with $k = 3$ (3σ). The uncertainty figure of an analog-to-digital converter given in **Eq. 5** is also important fort his analysis. R_{ADC} is the full-scale range and LSB is the least significant bit of the converter.

$$\frac{\sigma_{RADC}}{R_{ADC}} = \frac{LSB}{\sqrt{12}} \Big/ R_{ADC} \qquad \textbf{Eq. 5}$$

For the calculation of the standard deviation of the reflectivity measurement the range must be considered. The standard deviation of the range measurement is determined by the range resolution.

$$\frac{\sigma_{ZE}}{Z_E} = \sqrt{\left(\frac{\sigma_{CR}}{C_R}\right)^2 + \left(2\frac{\sigma_r}{r}\right)^2} \qquad \textbf{Eq. 6}$$

A typical standard deviation calculation budget for a weather radar is given in Table 2. Please note that the resulting standard deviation is significantly less than 1 dB.

Calculation of the Standard Deviation

Parameter	Type of Uncertainty				rel. Std. Dev.	Weight	Addend
	Type	Figure	lin. Figure	k			
Gain	abs. Error	0,3 dB	0,0715	3	0,0238	2	
Beam Width	abs. Error	0,03 Grad					
	abs. Figure	1 Grad	0,0300	3	0,0100	2	0,0046
Radome Losses	rel. Uncertainty	0,02 dB	0,0046	1	0,0046	2	0,0001
PRF	rel. Uncertainty		2,50E-05	3	0,0000	1	0,0000
Meas. Av. Power	rel. Uncertainty	0,08 dB	0,0186	1	0,0186	1	0,0003
Frequency	abs. Error	2000 kHz					
	abs. Figure	5640 MHz	0,0004	3	0,0001	2	0,0000
Coupl. Att.	rel. Uncertainty	0,2 dB	0,0471	1	0,0471	2	0,0089
meas. TSG Power	rel. Uncertainty	0,08 dB	0,0186	1	0,0186	1	0,0003
meas. Dig. Level	rel. Uncertainty		1,80E-05	1	0,0000	1	0,0000
Matched Filter Loss	rel. Uncertainty	0,2 dB	0,0471	1	0,0471	1	0,0022
Lin. Error RX	rel. Uncertainty	0,2 dB	0,0471	1	0,0471	1	0,0022
Lin. Error TX	rel. Uncertainty	0,05 dB	0,0116	1	0,0116	1	0,0001
		Rel. Std. Dev. of the Radar Constant					**0,1372**
		Rel. Std. Dev in dB					**0,5583**
Range	Resolution	25 m					
	abs. Figure	50 km	0,0005	1	0,0001	2	0,0000
Std. Dev. of the Reflectivity Measurement at the Range		**50 km**	**Total Rel. Std. Dev.**				**0,1372**
			Total Rel. Std. Dev. in dB				**0,5583**

Table 2: Std. Dev. Calculation Budget

6. REFERENCES

[1] P. Joe (Ed.), AMS Radar Calibration and Validation Specialty Meeting, Albuquerque, NM, 13-14 January 2001

[2] R. Doviak, D. Zrnic, Doppler Radar and Weather Observations, 2nd Ed. Academic Press, San Diego, 1993, p. 82

[3] ISO/IEC Guide 98-3:2008, Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), ISO/IEC 2008

[4] R. E. Rhinehart, Radar for Meteorologists, Rhinehart Publications, Columbia, OH, 2004