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Calibration of radar profilers by a rotating corner reflector

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Abstract. Two portable mono-static FM-CW Doppler radar profiler systems at 24 GHz and 94 GHz, respectively, have been calibrated using a continuously rotating corner reflector. The front-ends of both radars apply semiconductors for the generation of the transmitted power P_t exclusively. The portable 24 GHz profiler's aim is to record and investigate precipitation close to the ground. The 94 GHz profiler was developed for cloud investigation from the ground and from a research aircraft.

The calibrations showed that the 24 GHz rain profiler is sensitive enough to fulfill its purpose. That finding is supported by Doppler backscatter spectra recorded in rain. The 94 GHz profiler, however, lacks the required sensitivity due to severe system noise problems. This diagnose is confirmed by the results from operating the 94 GHz radar profiler to date. Both radar systems will undergo major design revisions to gain higher system sensitivities.

1 Introduction

Calibration for received power of radar systems aimed at clouds and precipitation serves various purposes. Prior to setting up a radar system for operation, calibration results can give a valuable insight into the sensitivity of the system. During operation, the calibration for received power is necessary to achieve correct values for hydrometeor parameters like drop size distribution, liquid water content and rain rate.

Two portable mono-static FM-CW Doppler radar profiler systems at 24 GHz and 94 GHz, respectively, have been calibrated using a continuously rotating corner reflector. The portable 24 GHz profiler's aim is to record and investigate precipitation close to the ground. The 94 GHz profiler was developed for cloud investigation from the ground and from a research aircraft.

The Digital Signal Processing (DSP) parts of both radar systems had to be calibrated. The purpose of this calibration is to assign a received backscatter power from radar targets (i.e. hydrometeors) to a given value in DSP units in the recorded Doppler backscatter spectra. This was achieved using a continuously rotating corner reflector of given size and distance.

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2 Theoretical Background

From Gossard and Strauch (1983) it can be derived that the fraction of received power P_r to transmitted power P_t of a radar system is given by

$$\frac{P_r}{P_t} = \frac{G_s G_t G_r \lambda^2}{(4\pi)^3 R^4}\sigma \qquad (1)$$

with G_s denoting the system gain due to losses and amplifiers, G_t and G_r the gain of transmitting and receiving antenna ($G_t = G_r$ for a monostatic radar), λ the transmitted wavelength, R the distance between radar and target, and σ the scattering cross section of the target. On the other hand the DSP part of the radar system delivers backscatter spectra that are given in arbitrary DSP units X_{DSP}. These are connected to the fraction given in Eq. (1) by

$$K_{DSP} X_{DSP} = P_r/(G_s P_t) \qquad (2)$$

where K_{DSP} denotes a calibration constant.

The calibration procedure was performed using a continuously rotating corner reflector. The set-up is sketched in Fig. 1. The corner reflector was moving circular in a way that it faced the radar permanently. The optional partial beam block shielded the reflector from the radar beam during backward motion (away from the radar). A typical result of this procedure can be viewed in Fig. 2. The displayed Doppler radar backscatter spectrum was recorded with the 24 GHz radar precipitation profiler using the partial beam block. A simulated spectrum (without partial beam block) is denoted by the dotted line.

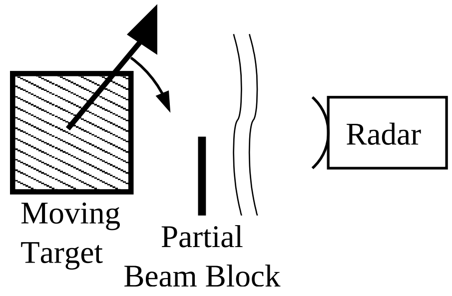

Fig. 1. Set-up of calibration.

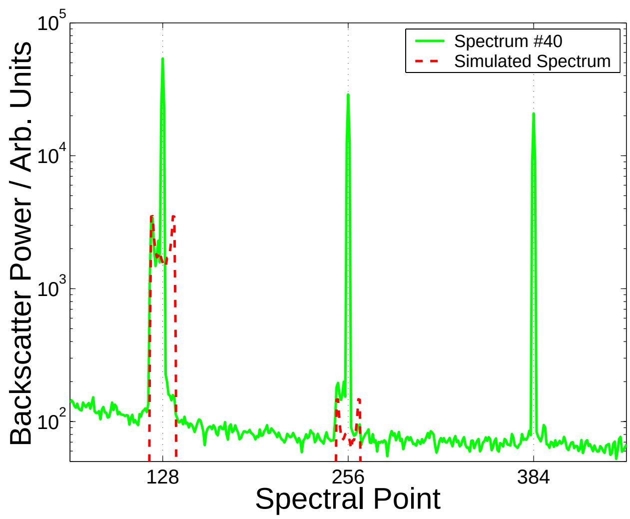

Fig. 2. Backscatter spectrum from rotating corner reflector recorded with the 24 GHz Doppler radar precipitation profiler.

The calibration procedure yields the calibration constant K_{DSP} introduced earlier. To achieve this, the backscatter cross section

$$\sigma_{\mathrm{CR}} = \frac{4\pi}{12\lambda^2} l^4 \qquad (3)$$

of a trihedral corner reflector (l: length of sides) has to be inserted into Eq. (1). By summing up the individual powers $X_{\mathrm{DSP},i}$ in the backscatter spectrum, $X_{\mathrm{DSP}}=\sum_i X_{\mathrm{DSP},i}$ can be calculated. Knowledge of the radar system parameters $G_{\mathrm{t}}=G_{\mathrm{r}}$ and λ as well as of the distance R between reflector and radar allows to calculate the calibration constant K_{DSP}.

Retrieving the system sensitivity from the calculated calibration constant K_{DSP} requires knowledge about the radar system noise power P_{n}. Roughly spoken, a signal can be detected in the Doppler backscatter spectrum when $P_{\mathrm{r}}>P_{\mathrm{thre}}=:P_{\mathrm{n}}$, where P_{thre} is defined as threshold power. On the other hand, the power P_{r} of a radar signal backscattered from beam filling hydrometeor targets like clouds or precipitation can be derived from Gossard and Strauch (1983) for an Gaussian radiation pattern to be

$$\frac{P_{\mathrm{r}}}{P_{\mathrm{t}}} = 0.0354 \cdot \frac{G_{\mathrm{s}} G_{\mathrm{r}} \pi^4 |K|^2}{4\lambda^2} \frac{\Delta R}{R^2} Z \qquad (4)$$

where ΔR is the range resolution of the radar profiler, $|K|^2=:\left|\frac{m^2-1}{m^2+2}\right|$ depends on the complex refractivity m. The radar reflectivity factor Z is defined by $Z=:\sum_i N_i D_i^6$, where D_i is the droplet diameter and N_i the number concentration of droplets in the i^{th} size bin. Substituting Eq. (2) into Eq. (4) leads to the formula

$$K_{\mathrm{DSP}} X_{\mathrm{DSP}} = 0.0354 \cdot \frac{G_{\mathrm{r}} \pi^4 |K|^2}{4\lambda^2} \frac{\Delta R}{R^2} Z \qquad (5)$$

that connects the recorded values of X_{DSP} with the radar reflectivity Z of the target hydrometeors.

The goal is to calculate the threshold radar reflectivity Z_{thre}, which is the smallest detectable value of Z at a given distance R for the selected operation parameters of the radar system. For this purpose, $X_{\mathrm{thre}}=:\sum_j X_{\mathrm{n},j}$, where the summation j runs over all spectral bins that contain the Doppler radar backscatter signal, has to be inserted into Eq. (5). This allows calculation of Z_{thre}.

If the relation between P_{r} and X_{DSP} could be accessed directly, e.g. by applying a signal or noise source of known power, the described proceeding would allow to calculate the radar constant K_{Rad}.

This constant connects the Power P_{r} received by the radar to the radar reflectivity Z of the investigated hydrometeors according to the formula $P_{\mathrm{r}}=K_{\mathrm{Rad}} \cdot G_{\mathrm{s}} \Delta R/R^2 \cdot Z$. The radar constant combines geometric and technical parameters of the radar system, e.g. P_{t}, λ or antenna gain G. Only the system gain G_{s}, the range resolution ΔR and the distance R between radar and investigated scattering target are given explicitly, since these are no constants.

3 Radar Systems

The front-ends of both radars apply semiconductors for the generation of the transmitted power P_{t} exclusively and apply a monostatic antenna setup. Both radar systems apply the FM-CW Doppler principle introduced by Strauch (1976). The signal processing systems of both radar profilers are set up using the Matlab development environment.

The precipitation profiler is a compact semiconductor based Doppler radar profiler operated at 24 GHz. It is easy to set-up and operate and fits literally into a briefcase. It's aim is to record and investigate precipitation in the planetary boundary layer close to the ground.

The 94 GHz profiler was developed for cloud investigation from the ground and from a research aircraft. The monostatic antenna setup that was chosen due to restricted space in the aircraft results in serious cross talk between transmitting and receiving branch. Some key system parameters can be found in the Table 1.

Table 1. Some system parameters of the calibrated radar profilers.

	24 GHz	94 GHz
P_t	5 mW	200 mW
G_t=G_r	17 dB	52 dB
3 dB width	15° / 30°	0.3°
ΔR_{min}	1.5 m	7.5 m
ΔR_{typ}	3 m	50 m
ranges (typ.)	8	32

Table 2. Sensitivity of the Doppler radar rain profiler with range resolution set to $\Delta R \approx 2.5$ m.

R/m	$Z_{thre}/10^3\,mm^6\,m^{-3}$	Z_{thre}/dBZ
2.5	.3	24.8
5.0	1.2	30.8
7.5	2.7	34.3
10.0	4.8	36.8
12.5	7.5	38.8

4 Results

A typical calibration Doppler backscatter spectrum recorded with the 24 GHz precipitation profiler is displayed in Fig. 2. A trihedral corner reflector of l=0.14 m was placed at R=16.95 m. The radar was operated at $\Delta R \approx 11.1$ m. Summing up the noise corrected power in the spectral bins showing backscatter signal from the corner reflector, the calibration constant was found to be $K_{DSP}=1.6 \cdot 10^{-6}$.

For the purpose of estimating Z_{thre}, which gives an insight into the radar system's sensitivity, a Doppler backscatter profile from rain was evaluated. This spectrum is displayed in Fig. 3. In this case the radar profiler was operated with $\Delta R \approx 2.5$ m. Regarding the noise floor and assuming that the maximum velocity spread of the backscatter spectrum is $\Delta v = 10\,ms^{-1}$ covering a frequency range of Δf=1.6 kHz, the sensitivity was found to be as listed in Table 2.

The calibrations showed that the 24 GHz rain profiler is sensitive enough to fulfill its purpose: It is able to record Doppler backscatter spectra from precipitation near ground (R<30 m) with a fine range resolution (1.5 m$\leq \Delta R \leq$5 m). That finding is supported by Doppler backscatter spectra recorded in rain.

Applying the same procedure to the 94 GHz cloud profiler revealed that it lacks the required sensitivity due to severe system noise problems. The system sensitivity is only sufficient to detect hail near ground (R<100 m) with range resolutions typically chosen for cloud investigation (25m$\leq \Delta R \leq$50 m). This diagnose is confirmed by the results from operating the 94 GHz radar profiler to date.

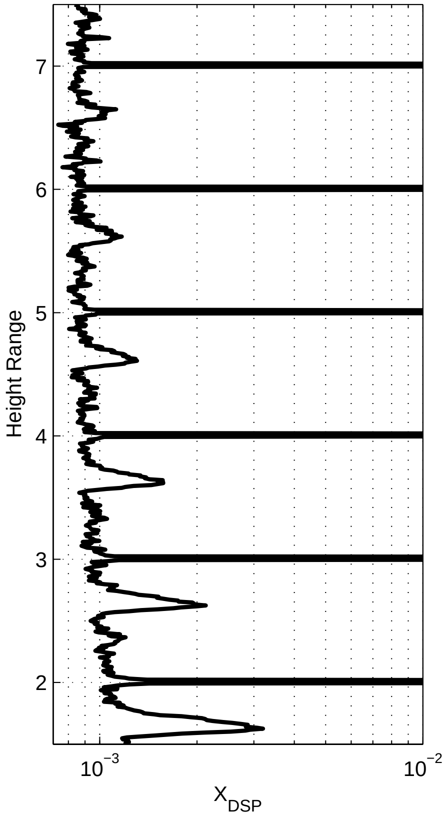

Fig. 3. Backscatter spectrum from rain with the 24 GHz Doppler radar cloud profiler.

5 Conclusions and Outlook

A 24 GHz precipitation profiler and a 94 GHz cloud profiler have been calibrated using a continuously rotating corner reflector. It was shown in detail that the compact precipitation profiler is sensitive enough to record and investigate moderate to heavy rain in the boundary layer close to the ground. The 94 GHz cloud profiler was found to lack the sensitivity required for it's field of application to date.

Both radar systems will undergo major design revisions to gain higher system sensitivities. The 24 GHz precipitation profiler also will become more compact by this re-design.

References

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