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FIRST RESULTS FROM A SEMICONDUCTOR BASED 94-GHZ FM-CW DOPPLER RADAR CLOUD PROFILER

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1 INTRODUCTION

A new 94-GHz FM-CW Doppler radar cloud profiler for dual purpose use (ground based / airborne) is operated by the Institute for Tropospheric Research in Leipzig, Germany. The generation of transmitted power is based exclusively on semiconductor elements. Therefore, the radar front end can be directly connected to the airplane power supply in its airborne setup. In the ground based set up the complete radar system fits an $19''$ rack of 12 HU with an additional radom.

First measurement and a coarse calibration by comparing radar spectra to data from a ground based rain gauge will be performed and presented on the conference poster. Plans for first field measurements will be presented, and an outlook to possible enhancements and upgrades of the radar will be given.

2 RADAR SYSTEM

Due to the future airborne operation, some basic restrictions concerning system weight, size, and the necessary power supply had to be considered for the new radar. These requirements were achieved by using semiconductor devices for transmitted power generation. Since semiconductor devices are well suited for continuous moderate power generation, the radar is operated in FM-CW (Frequency Modulated Continuous Wave) mode (Strauch (1976)). A prototype of this kind of radar is described by Klugmann and Judaschke (1996). The front end is very robust and durable. An important aspect contributing to the low system weight is that the radar front end can be connected directly to a 28 V airplane power supply. The modular design allows easy upgrading of individual components of the radar system.

A block diagram of the radar front end is shown in Figure 1. It is a monostatic system with an average transmitted power of $P_{\mathrm{t}} \approx 350\,\mathrm{mW}$. The isolation between transmitting and receiving branch, obtained by a circulator and the additional application of an vector modulator, is $G_{\mathrm{i}} \leq -50\,\mathrm{dB}$. The high purity frequency modulated base signal of 4 to 4.3 GHz is generated by a voltage controlled YIG oscillator. After passing a low pass filter (LPF), a part of this signal is directed to the final mixer for the second intermediate frequency (2nd IF) by a power divider. The other part is used for upward conversion to 94 GHz in a mixer by means of a part of the signal of a stabilized InP Gunn oscillator. The upward converted signal phase locks an InP Gunn oscillator, which signal then is used to phase lock a high power oscillator of two cavity stabilized IMPATT diodes. Due to these measures, the signal after the IMPATT oscillator features a signal purity of $-70\,\mathrm{dBc\,Hz^{-1}}$ at a frequency offset of 100 kHz to the transmitting frequency. Part of the signal is branched off as input for a vector modulator enhancing the isolation between transmitting and receiving branch. The main

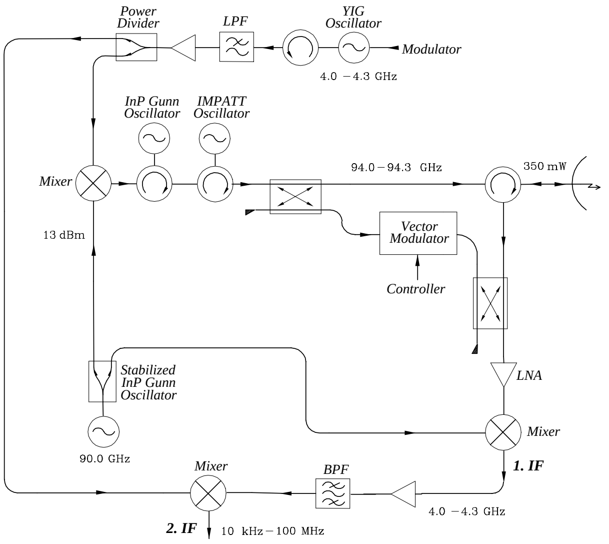

Figure 1: Block diagram of the radar front end.

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part of the signal is transmitted into the atmosphere by a Cassegrain antenna of antenna gain $G \approx 52\,\mathrm{dB}$ (aperture diameter $D_\mathrm{a} \approx 50\,\mathrm{cm}$).

The received signal is directed to the receiving branch by a circulator. This circulator, and the additional vector modulator, which phase shifts and amplifies the transmitted signal to generate destructive interference with the cross talk signal, provide the isolation of $G_\mathrm{i} \leq -50\,\mathrm{dB}$. The low-noise amplifier (LNA) indicated after the vector modulator is optional. This LNA can be used to increase the systems signal-noise ratio, if the contribution of its noise to the total system noise is in the order of the mixer noise.

Then the received signal is converted down to 4 GHz by the mixer of the first intermediate frequency (1^st IF) by means of the remaining part of the stabilized InP Gunn oscillator's signal. The resulting signal is band pass filtered (BPF) and fed into a second mixer for conversion to the second intermediate frequency (2^nd IF). This mixer's noise number is specified by the manufacturer to be $N_\mathrm{n} < 7\,\mathrm{dB}$, its conversion loss is $G_\mathrm{s} \approx -7\,\mathrm{dB}$.

The signal processing system features a DSP board based on TI's C6700 Digital Signal Processor, and carries a mezzanine board holding a 4 channel / 14 bit ADC able to record $10\,\mathrm{MSamples}/s$ in each channel and a 14 bit 7.5 MHz DAC.

In the ground based set up the complete radar system (front end, DSP system, and power supply) fits an $19''$ rack of 12 HU (approx. $500 \times 600 \times 700\,\mathrm{mm}^3$) with an additional radom. It is portable by a single person and only needs a standard power connector and an optional network connection for operation.

3 PERFORMANCE

The minimal detectable radar reflectivity Z_thre is calculated by

$$Z_\mathrm{thre}(R_0) = \frac{P_\mathrm{n}}{P_\mathrm{t}} \cdot \frac{512 \cdot \ln 2 \cdot \lambda^2}{\pi G G_\mathrm{s} \left|K\right|^2} \cdot \frac{R_0^2}{\Delta R} \cdot \left(1 + F^4\right) \quad (1)$$

Here P_t denotes the transmitted signal power, and G is the antenna gain. The system power gain as described by Doviac and Zrnić (1993) is given by G_s, radar wavelength is denoted by λ, target distance by R_0, and range resolution by ΔR. The term

$$F^4 \equiv \left(\frac{G\lambda}{8\pi R_0}\right)^2 \quad (2)$$

invented by Lataitis et al. (1998) accounts for a near field correction relevant for targets close to the radar, from the dielectric constant ε of water the factor

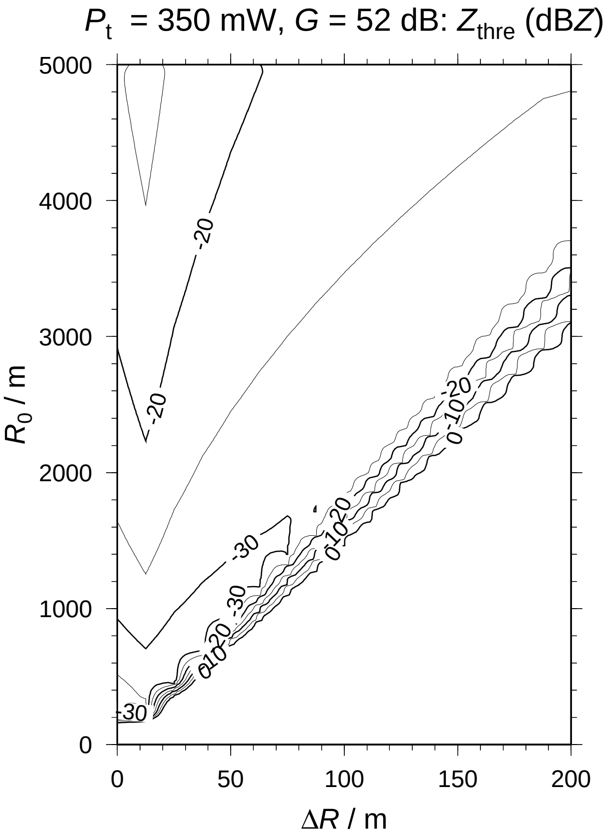

Figure 2: Minimum detectable radar reflectivity Z_thre regarding system noise and transmitter phase noise cross talk.

$$\left|\frac{\varepsilon(\lambda) - 1}{\varepsilon(\lambda) + 2}\right|^2 \equiv \left|K(\lambda)\right|^2; \; \left|K(3.2\,\mathrm{mm})\right|^2 \approx 0.82 \quad (3)$$

is calculated. The sensitivity of a monostatic FM-CW Doppler radar is determined by system noise and cross talk from transmitting into receiving branch, which combines to the overall noise power

$$P_\mathrm{n} = \left(k_\mathrm{B} T_\mathrm{n} + S_{P_\mathrm{c}}\right) \cdot B_\mathrm{D} \qquad \left(B_\mathrm{D} = \frac{2\Delta v}{\lambda}\right). \quad (4)$$

The frequency bandwidth B_D is determined by the vertical velocity range Δv, over which the cloud droplets are distributed due to fall velocity and turbulent vertical wind. The spectral cross talk power S_{P_c} is calculated by

$$S_{P_\mathrm{c}}(f) \equiv \frac{\mathrm{d}P_\mathrm{c}(f)}{\mathrm{d}f} = G_\mathrm{i} \cdot \frac{P_\mathrm{t}}{\sqrt{\pi}\sigma_f} \cdot \mathrm{e}^{-\left(\frac{f}{\sigma_f}\right)}, \quad (5)$$

with σ_f denoting the e^{-1}-width of the transmitted signal's probability density function (PDF). A received signal from a target of radial velocity v at a distance R_0 according to Strauch (1976) shows up in the backscatter spectrum at the frequency

$$f_r(R_0) = k \cdot f_s + \frac{2v}{c} \cdot f_0; \ \left(k = \mathrm{round}\left(\frac{R_0}{\Delta R}\right)\right). \quad (6)$$

Here f_0 denotes the radar base frequency, and f_s describes the repetition frequency of the frequency modulation cycle (sweep frequency) determined by the desired unambiguous velocity range Δv_m:

$$f_s = \frac{2\Delta v_m}{c} \cdot f_0. \quad (7)$$

Neglecting the second term of Eq. (6) caused by the Doppler shift, a received signal from a given R_0 can be found at:

$$f_r(R_0) \approx \mathrm{round}\left(\frac{R_0}{\Delta R}\right) \cdot f_s. \quad (8)$$

Combining Eqs. (7) and (8), the achieved f_r can be inserted into Eq. (5) to evaluate Eq. (4). This result can be inserted into Eq. (1) to estimate Z_{thre} taking into account the cross talk.

Figure 2 shows a sensitivity estimation for the radar for $f_s = 6\,\mathrm{kHz}$ resulting in $\Delta v_m \approx 9.6\,\mathrm{m\,s^{-1}}$. It is assumed that $\Delta v \approx 2\,\mathrm{ms^{-1}}$. For a 94 GHz radar ($\lambda = 3.2\,\mathrm{mm}$) this leads to $B_D \approx 1250\,\mathrm{Hz}$.

4 MEASUREMENTS

The radar has shown to meet its design specifications. According to the sensitivity estimation presented in Fig. 2, the radar in its actual state should be able to detect weak drizzle and even boundary layer Stratus clouds. A coarse estimation of the radar's sensitivity can be made by comparing radar spectra in stratiform precipitation to data from a ground based rain gauge. The simplified relation

$$Z(R_0) = K_{\mathrm{rad}} \cdot \frac{R_0^2}{\Delta R} \cdot P_r \quad (9)$$

(P_r denoting the received power) is compared to an empirical expression according to Rogers and Yau (1994) relating rain rate R and Z:

$$Z = 200\,\frac{\mathrm{mm}^6}{\mathrm{m}^3} \cdot \left(\frac{R}{1\,\mathrm{mm\,h^{-1}}}\right)^{1.6}. \quad (10)$$

The radar constant K_{rad} is adjusted to generate the best match between the Z values derived from the lowest radar range gate applying Eq. (9) and the respective Z values calculated from the ground based rain gauge data by means of Eq. (10). Calibration measurements of this type as well as measurements from precipitation and boundary layer clouds will be presented on the conference poster.

5 CONCLUSION/OUTLOOK

A semiconductor based 94-GHz FM-CW Doppler radar profiler has been put into operation at the Institute for Tropospheric Research (IfT). The sensitivity in the actual state is estimated to be sufficient to detect weak drizzle and boundary layer Stratus clouds. First measurements and a coarse calibration will be presented at the conference poster. In fall 2001, the radar will take part in the BALTEX BBC field campaign in Cabauw, the Netherlands.

The radar system has been set up in a modular design. This allows successive enhancements to obtain higher sensitivity, e. g. application of an additional low-noise ($N_n \approx 7.5\,\mathrm{dB}$) amplifier with a gain of $G_a \approx 15\,\mathrm{dB}$, and increasing the transmitted power to $P_t \approx 1.6\,\mathrm{W}$. The long term goal is to mount the radar in a small airplane.

6 ACKNOWLEDGMENT

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