The GKSS 95-GHz cloud radar: experimental and theoretical studies in support of a spaceborne cloud radar mission.

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Introduction

In the frame of its activities in the research area of clouds and radiation the Institute of Atmospheric Physics of GKSS has recently purchased a 95-GHz (3.2 mm) cloud radar. The GKSS radar can contribute in several ways to studies supporting a satellite mission. In a stand alone mode, cloud layer and reflectivity statistics for target clouds of the mission could be obtained as well as phase and particle information retrieved from multi-parameter measurements based on polarimetric and Doppler information. High resolution measurements would provide data sets for integration length and range gate resolution studies. In future, the radar could be integrated into a net of instruments providing ground truth for the spaceborne sensors.

The participation of the GKSS radar in field experiments devoted to sensor synergy and algorithm tests is scheduled. Here the European CARL and MIDRAD projects have to be mentioned, the objectives of both activities has been introduced elsewhere during the workshop. In the following we introduce the GKSS radar by a system description and some examples of measurements. In addition, results of a theoretical study for a spaceborne cloud radar concerning sampling and minimum sensitivity aspects using a high resolution three-dimensional global climate model data set will be presented.

System description

The pulsed-Doppler radar is fully polarimetric and has a peak power of 1.7 kW. The system has been taken into operation in summer 1996. Since its capabilities cover those of a planned spaceborne system, the radar is well suited for preparatory studies for such a mission. Pulse repetition frequency (up to 80 kHz), number and location of range gates, pulse width and pulse polarisation are software selectable and allow for a range resolution between 7.5 m and 75 m up to a range of 15 km. The beamwidth of the center-fed Cassegrain antenna of 0.17° leads to a range cell diameter of 30 m at a distance of 10 km. Table 1 provides the main specifications of the radar. A typical pulse sequence for polarimetric measurements is sketched in Figure 1.

Table 1: Main specifications of the GKSS cloud radar.

Frequency	95 GHz (W band)
Peak power (EIA)	1.7 kW
Duty Cycle	1.2 % max
Pulse repetition frequency	50 Hz - 80 kHz
Pulse width	50 - 2000 ns
Antenna diameter	1.2 m
Beamwidth	0.17°
Antenna gain	60 dB
Transmit Polarization	H or V
Receive Polarisation	H and V
Cross-polarization isolation	26 dB
Dynamic range	70 dB
Output channels	$\log(\|h\|^2)$, $\log(\|v\|^2)$, I_h, Q_h, I_v, Q_v *

* $|v|^2$ and $|h|^2$ are received power in the vertical and horizontal receiver channel; I and Q are in-phase and quadrature components of the signal phase.

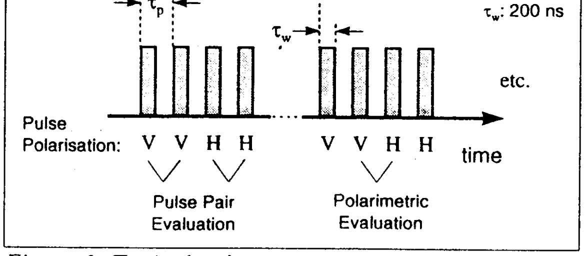

Figure 1: Typical pulse sequence as used for polarimetric measurements.

The real-time data products include polarimetric quantities (ZDR, LDR, ρ) and the first three moments of the Doppler spectrum (total power, mean velocity, velocity variance) derived by the pulse pair algorithm or a 64 point FFT full spectrum analysis. The minimum sensitivity at an altitude of 1 km is about -40 dBZ and at 10 km about -30 dBZ. The GKSS radar is currently used for a variety of studies related to the structure and properties of layer clouds (e.g. Quante et al., 1996; Danne et al., 1997). Its high temporal and spatial resolution allows detailed observations of cloud boundaries as well as of the internal structure of the clouds.

Measurement examples

Here two typical measurement episodes are shown in order to illustrate the type of results which can be expected from the cloud radar.
More examples can be found on our web page: *http://w3.gkss.de/englishRadar/miracle.html.*

Cloud layers and mesoscale structure of clouds: Extended stratiform clouds occurring in multiple layers are the most interesting targets with respect to the planned satellite mission. At mid-latitudes such clouds are often connected to passing frontal systems. Figure 2 shows typical clouds approaching with a warm front passing Geesthacht on September 11, 1996. The internally structured thin cloud layer of the first 30 minutes develops into a thicker cloud with pronounced structure on the mesoscale. Three detached cloud layers can be seen during the last 30 minutes presented in figure 2.

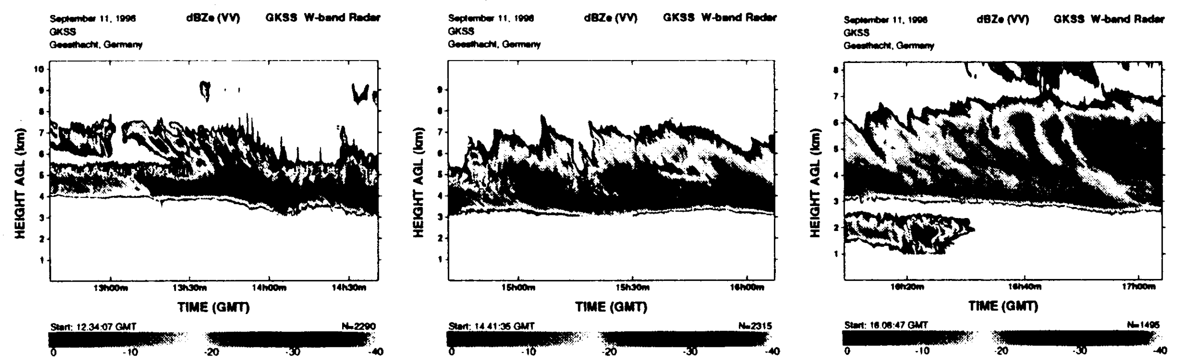

Figure 2: Mid- and high level stratiform clouds in conjunction with an extended warm front passing Geesthacht between 13:00 and 17:00 UTC on September 11, 1996. The clouds show a pronounced internal structure with fall streaks on different scales as well as the development of multiple layers. The images present successive time-height sections of the radar reflectivity factor in dBZ$_e$.

Cloud boundaries are intensively under investigation, their location determines the energy distribution within the atmosphere as well as surface energy budget. In figure 3 an example of combined measurements with the GKSS lidar BELINDA (Weitkamp et al., 1998) is shown for an elevated ice cloud. Distinct differences in the location of the cloud base can be seen, which are due to a few larger particles falling into the cloud base region causing a considerable radar return but no detectable lidar backscatter signal. For high level clouds dominated by fall streakes radar cloud bases are often biased by falling crystals. Systematic evaluations of similar measurments for all types of layer clouds are planned.

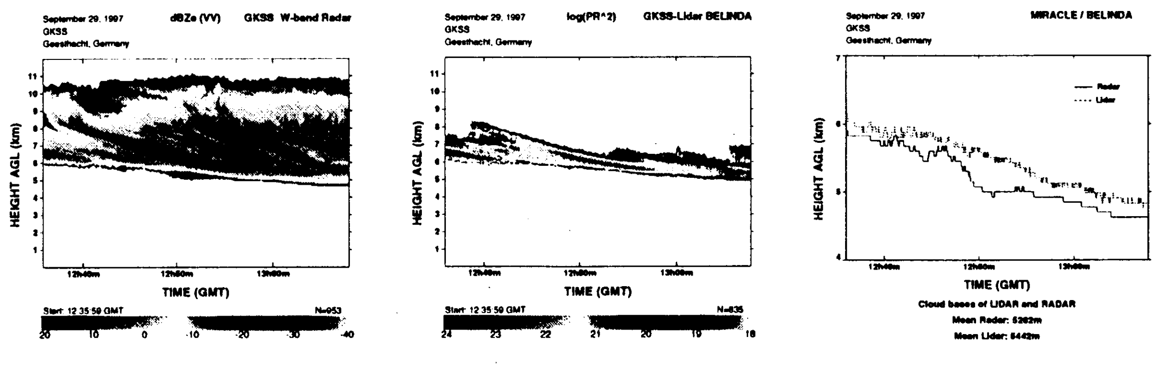

Figure 3: Radar reflectivity factor (left), lidar backscatter intensity (middle), and location of cloud base (right) for a segment of a high-level cloud layer observed simultaneously by the 95 GHz radar and a 720 nm lidar (BELINDA) on September 29, 1997.

Assessment of requirements for a proposed space-borne cloud profiling radar

Here we briefly summarize a theoretical study evaluating the potential of a future space-borne 94 GHz cloud profiling radar (CPR). This study has been carried out under ESA contract. An overview is given in Lemke et al. (1998), a detailed description can be found in Lemke et al. (1997).

Based on data from a high resolution (≈1°x1°) general circulation model (ECHAM4) run, which has been driven by measured sea surface temperatures, three-dimensional global cloud data sets have been generated and used as input data for a cloud radar simulation tool. The plausibility of the modeled cloud data sets (geographical cloud distribution, cloud water contents etc.) has been verified against available satellite and ground observer climatologies and typical microphysical data from aircraft experiments.

To assess the required sensitivity for a CPR, a criterion for radiatively important clouds (RIC) was defined. A RIC would change the outgoing long wave radiation, the short wave radiation budget or the atmospheric heating by more than a defined threshold and therefore needed to be detected by a CPR (Atlas et al., 1995).

Various sets of satellite orbit parameters and cloud radar characteristics (close to those of preliminary engineering studies; IGPO 10, 1994) have been used to sample the input data in several simulation scenarios employing a comprehensive radar model. The effect of the minimum detectable signal, integration length and orbit on parameters like cloud cover, cloud top and base heights, cloud thickness, number of cloud layers in the data set sampled by the satellite radar have been studied extensively.

Results

Considering an ideal sampling but taking into account attenuation due to atmospheric gases and upper layer clouds, the threshold effect has been investigated by analysis of the input data set.

Figure 4 shows the monthly distribution of reflectivity as would be seen from a satellite device in case of ideal sampling. It follows that a radar with -30 dBZ threshold would detect 69% (75%) of the total three-dimensional cloud population in the summer (autumn) month. An improvement of the radar sensitivity to -40 dBZ would increase the detected fraction to 88% (92%). Considering only the distribution of RIC, approximately 85% could be observed at -30 dBZ and 95% at -40 dBZ, respectively.

As the radar is expected to provide information about the vertical structure, the cloud detection ability is assessed at different height bands according to the ISCCP classification. Results are shown in Table 2. Because of radar signal attenuation and their low reflectivities, the detection of low level clouds is most crucial: only 40% of the low level cloud population in July would be detected at a radar sensitivity of -30 dBZ. As 99% of low level clouds are identified as radiatively important, a threshold of -40 dBZ is desirable, increasing the detected fraction to 77%. For the upper levels, the situation is less critical: 81% of the mid- level and 74% of the high level clouds are detectable with at -30 dBZ threshold. At the middle level, 97% of the cloud volume is recognised as RIC, whereas at the high level merely 72% is judged to be of radiative importance. Analyses have also been carried out for different latitude bands representing different climate regimes. In the subtropical region, where maritime stratus clouds are dominant, observations are most difficult, as only 55% of the total cloud population has a radar reflectivity higher than -30 dBZ, but 85% exceeds a threshold of -40 dBZ.

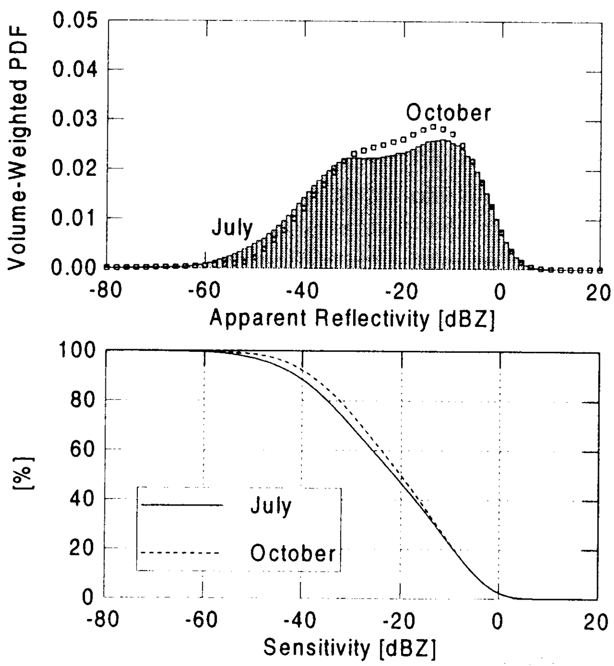

Figure 4: Upper panel: Normalized global monthly distribution of apparent (attenuated) reflectivity as derived from the input data sets for July and October. Lower panel: Cumulative sum for above distributions.

Table 2: Percentage of detected cloud volume at the three height bands for different sensitivity thresholds as obtained for ideal sampling (July input data set). Values in parentheses refer to RIC population.

threshold	low	mid-level	high
-20 dBZ	17% (17%)	63% (65%)	50% (69%)
-30 dBZ	40% (40%)	81% (81%)	74% (97%)
-40 dBZ	77% (77%)	94% (94%)	90% (100%)

The inaccuracy in detected cloud volume fraction at a certain sensitivity threshold due to erroneous derivation of radar reflectivity from cloud water content is equivalent to a modification in demanded sensitivity by about 5 to 7 dBZ in the considered sensitivity range.

To investigate the impact of sampling, two sun-synchronous orbits have been used in the simulations, mainly differing in their repeat cycles. It is found that the data subsets sampled below the satellite path are almost identical for the considered orbits and representative for the global data.

Based on first sampling studies of existing ground-based cloud radar data, it is recommended to use sufficient horizontal and vertical resolution, on the order of 10 to 20 km along-track and not more than 500 m in the vertical to obtain reliable cloud boundaries and to avoid an underestimation of IWP.

For a vertical resolution of 500 m, 12% of the global distribution of the grid mean cloud bases are found within the blind layer. As almost all low level clouds are radiatively important, a higher vertical resolution may be considered to reduce the loss due to the blind layer.

Conclusions

Presently, no satellite data product resolves the vertical cloud distribution with sufficient resolution to derive fluxes within the atmosphere and at the surface with the desired accuracy. Therefore, it is strongly recommended to include a cloud radar as a high priority candidate into the list of potential elements for an Earth radiation mission.

Obviously a better sensitivity limit than -30 dBZ would be desirable from the scientific point of view. However, for any threshold between -30 and -40 dBZ, the obtained 3D cloud distribution would be more comprehensive and more valuable than those presently available.

In the given height range, different polar orbits would provide similar cloud radar results, hence it is recommended that an optimised orbit should be selected on the basis of a synergy study for the total mission. Small angle scanning would not improve the ability to sample a representative subset of data.

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