6.3.5 Definition of instruments and algorithms for GCOS – WP5.

Work-package objectives:

To define the optimum combination of instruments for inferring cloud properties which combines the most accurate retrievals with a design which is reliable and easy to operate by a non-expert.

The overall requirement is to detect all clouds with an optical depth above 0.05 with instruments having a vertical resolution of 60m in a sample time of 30seconds. The instruments should be able to operate in all weathers and be left unattended for several days at a time.

Below we highlight three major findings of this work package.

1. An economic combination of a cloud radar with a simple ceilometer and low cost radiometer is sufficient to fulfil the specification.
2. An economic approach is to use low power FM/CW mm wave cloud radars and/or an X-band pulsed cloud radar.
3. Relaxation of radiometer specification is possible so that it can tolerate slow 5K drifs in the accuracy of the derived brightness temperatures.

Our recommendation to industry are in summary:

1. The mix of instruments with the specification in major findings 1.
2. Examine the economics of low power FM/CW mm wave cloud radars in comparison with an X-band pulsed cloud radar (major finding 2.)
3. Explore the costs of manufacturing a dual wavelength microwave radiometer with the relaxed specification (major finding 3).
4. We estimate that if the total cost of the cloud station can be reduced to the order of 250,000 euro then there is the expectation that each National Met Services may purchase several. Typical costs could be the order of 120,000 euro for the radar, 30,000 for the ceilometer and 100,0000 for the radiometers.

1. An economic combination of a cloud radar with a simple ceilometer and low cost radiometer.

The mix of instruments which is able to provide data for the algorithms developed in WP3 comprise a Dopplerised cloud radar, a simple ceilometer and a pair of microwave radiometers operating near the water vapour absorption line at 22GHz and in the region of high sensitivity to liquid clouds near to 3GHz. The radar signal is proportional to the sixth power of the particle size so it is not sufficiently sensitive to detect the small water droplets present in some low level liquid water clouds. So the radar is designed to detect all ice clouds whereas the lidar detects those water clouds which the cloud radar cannot sense and the radiometers supply the liquid water path which using cloud base and top from the lidar and radar can be used to derive a profile of liquid water content.

Specification of the cloud radar to detect ice clouds and ice water content.
As demonstrated below this requires a sensitivity to detect echoes of -55dBZ at a range of 1km with 60m resolution and a dwell time of 30seconds. Analysis of coincident radar and sensitive lidar data at Palaiseau is presented in Figure 1. This research level lidar is able to detect molecular backscatter and so can infer the optical depth of the thin ice clouds and compare with the ability of the radar with two sensitivity levels to detect these clouds. The average optical depth of the clouds missed with a radar having sensitivities of -45 and -55dBZ at 1km is 0.02 and 0.003 respectively. The requirement is to detect all clouds with optical depths of > 0.05. Examination of the pdfs reveals that -55dBZ at 1km is required to achieve this. Ice water content can then be deduced from the radar reflectivity (Z) and the model temperature or Z and the Doppler velocity (see algorithms in WP3 breakthroughs 9, 10 11). Doppler accuracy should be to 0.1m/s or better.

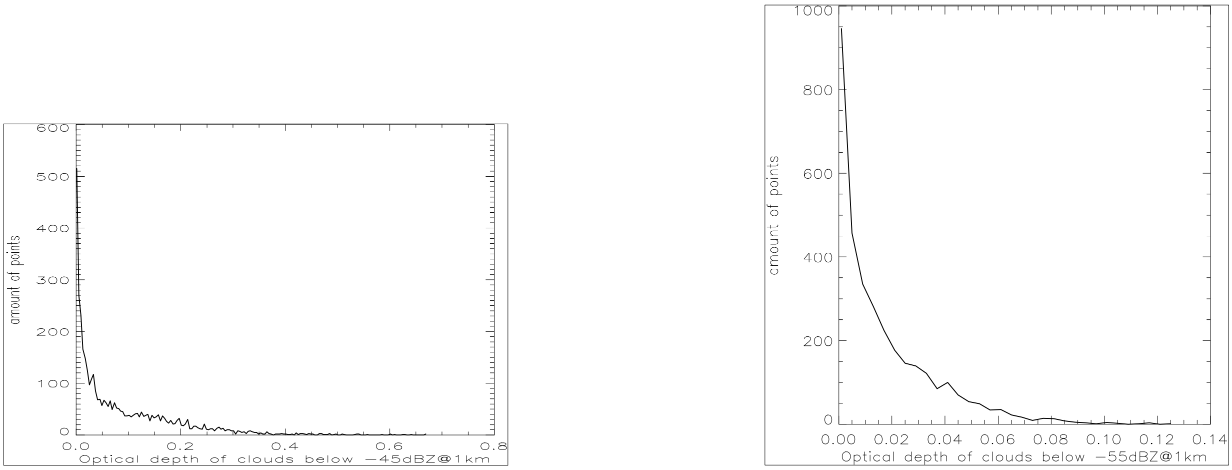


Figure 1: Optical depths of the clouds missed with a radar sensitivity of -45dBZ and -55dBZ at 1km height. -55dBZ is needed to detect virtually all clouds with an optical depth > 0.05.

Detection of low level water clouds. Figure 2 shows the fraction of stratocumulus clouds detected by the lidar which also give a detectable radar signal, and shows that even a sensitivity of -55dBZ at 1km will detect just 50% of stratocumulus clouds. We therefore conclude that it will be very difficult to design a radar which can detect all liquid water clouds and specify that the role of **the lidar** is to detect water clouds and as a consequence a simple cheap ceilometer will suffice. Note that a lidar alone is not sufficient because if low level water cloud is present the lidar signal is completely extinguished at low levels; a radar is essential to detect the high altitude ice clouds even when low level water clouds are present.

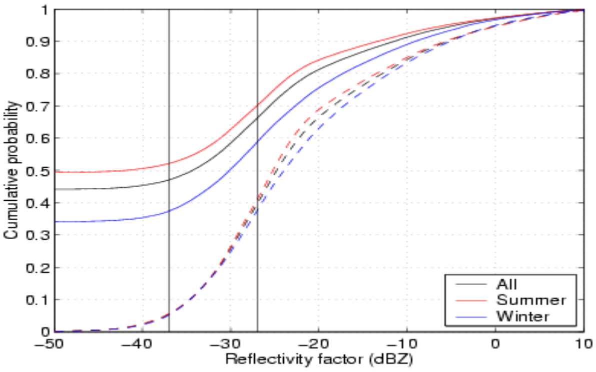


Figure 2. Analysis of one years stratocumulus clouds observations at Chilbolton showing the cumulative probability of detecting a liquid water cloud as a function of the radar sensitivity. All such water clouds are easily detected by the ceilometer, even though 50% are missed even at a sensitivity of -50dBZ.

Estimating cloud liquid water content This is difficult using radar and lidar backscatter, because any radar backscatter tends to be dominated by the occasional drizzle droplet which makes a negligible contribution to the liquid water content and the lidar detects such clouds but is rapidly extinguished. Accordingly we have developed an algorithm which does not rely on the quantitative values of the radar or lidar backscatter. Instead the lidar is used to detect cloud base and the cloud top is detected by the radar signal. Once cloud base and top are known, then the temperatures are taken from the operational model and the adiabatic liquid water profile and the total liquid water path computed. This is then compared with the observed liquid water path and the dilution of the cloud derived, and the true liquid water content derived by scaling the adiabatic liquid water profile by the dilution factor. In part 3 of this section we show how liquid water path can be accurately found from a pair of **microwave radiometers.**

2. Low power FM/CW mm wave radars and X-band pulsed cloud radars.

A Dopplerised cloud-radar with a sensitivity of -55dBZ at 1km for a 30second dwell can be implemented either at mm-wave as in the CloudNET or, potentially, at X-band. For mm-wave observations 35GHz is the preferred frequency. The technology is mature, and amplifier tubes operate at 35GHz for several years with only a small loss of power (Figure 3). In addition the attenuation due to oxygen, water vapour and liquid cloud water is relatively small. In contrast Figure 4 which shows the serious loss of power for the three 94GHz tubes used at Chilbolton and Paris during the project. (each costs about 100,00 Euro).

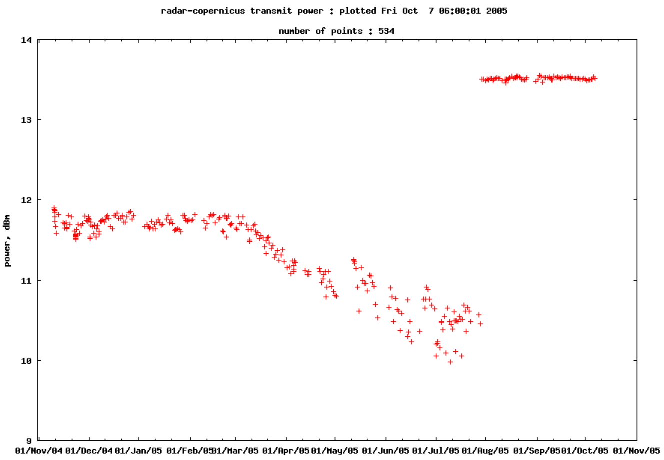


Fig 3–The small loss in power of the 35GHz one year at Chilbolton.

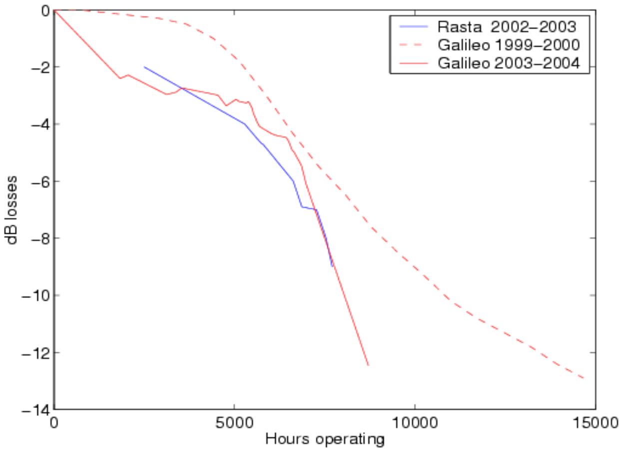
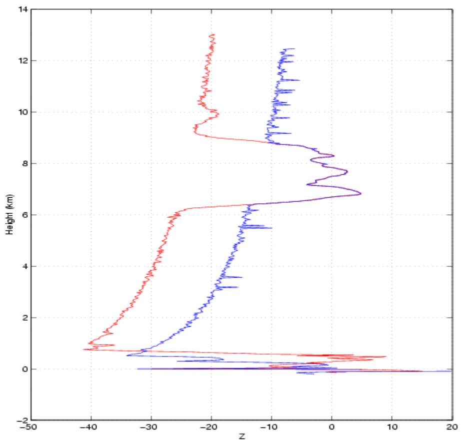


Fig 4 – Rapid decay of power by over 10dB of three 94GHZ amplifier tubes after just 8000hrs of operation (11 months).

Fig 5 and 6 below show that lower power radars with coded pulses have satisfactory performance. Tests comparing the reflectivities measured with the 8bit coded pulse and the single pulse mode for the 35GHz cloud radar at Chilbolton are show that there are minimal range sidelobes near high reflectivity targets.



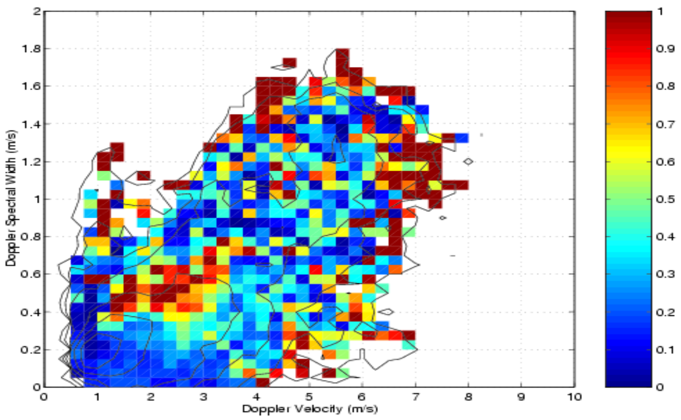


Fig 5: Comparison showing the 10dB extra sensitivity for the coded pulse (red) compared to the uncoded blue pulse, and the absence of range sidelobes for the coded pulse.

Fig 6. Analysis of range Z errors (in dB) introduced for the coded pulse compared to the uncoded one, as a function of the Doppler velocity and Doppler width of the target. Errors of 1dB can be introduced for high Doppler velocities and Doppler widths, but in this condition the attenuation of the precipitation is much larger than 1dB.

A potentially low cost alternative which should be further investigated is the use of a conventional pulsed radar at X-band. Components at X-band are relatively cheap and calculations show that a simple pulsed system transmitting 200kW pulses of length 0.4usecs with a 2m antenna should meet the sensitivity specification. One particular advantage of the use of X-band (3cm) concerns radome attenuation. In periods of even very light rain a wet radome can lead to a loss of about 7dB at mm wave frequencies so data taken during such events must be flagged as unreliable. This leads to difficulties when observations are compared with the model. In such rain radome attenuation at X-band is negligible.

3. Relaxation of the Radiometer specification.

Liquid water path (LWP) have been inferred for many years fby converting the observed brightness temperature to an optical depth, and then solving two simultaneous equations to give the LWP and VWP (vapour water path). Because the values of uncertainty over the mass absoprtion coefficients and instrument calibration drift, this can lead to values of LWP when no cloud is present and some negative values of LWP. The new technique (see WP3 breakthrough 5) identifies cloud free periods using the ceilometer, and forces LWP to zero by optimising the calibration offsets. This leads to much more accurae values of LWP and avoids the spurious negative values of liquid water. Most important from the instrument design point of view is that this retrieval is tolerant to offsets of up to 5K in the brightness temperatures.

Figure 6 (left hand side) shows the biases in LWP introduced by artificially adding an error of up to 5K in turn to the two brightness temperatures (Tb) measured by the radiometers using the conventional method of solving the two equation linking brightness temperatures to the liquid water apth and the water vapour path and shows that the 5K error results in errors of LWP of between 100 and -50 g m^{-2}, independent of the true value of the LWP. The middle panel describes the performance of a simple technique which involves a simple subtraction of the non zero LWP inferred before and after the cloudy period errors are reduced but are still too large. The right hand panel reveals that the new optimal adjustment brightness temperature measurements of up to 5K introduces errors of less than 2% in the inferred LWP. Current techniques require that Tb be measured to 0.5K. This entails frequent calibration using standard sources, and frequent tip curve calibrations whereby the radiometer is scanned in elevation radiometer and adjustments made so the inferred LWP is consistent. This is unnecessary when the required accuracy is relaxed to 5K and simplifies the instrument design. The only requirement is that the system calibration does not drift during periods of cloud cover.

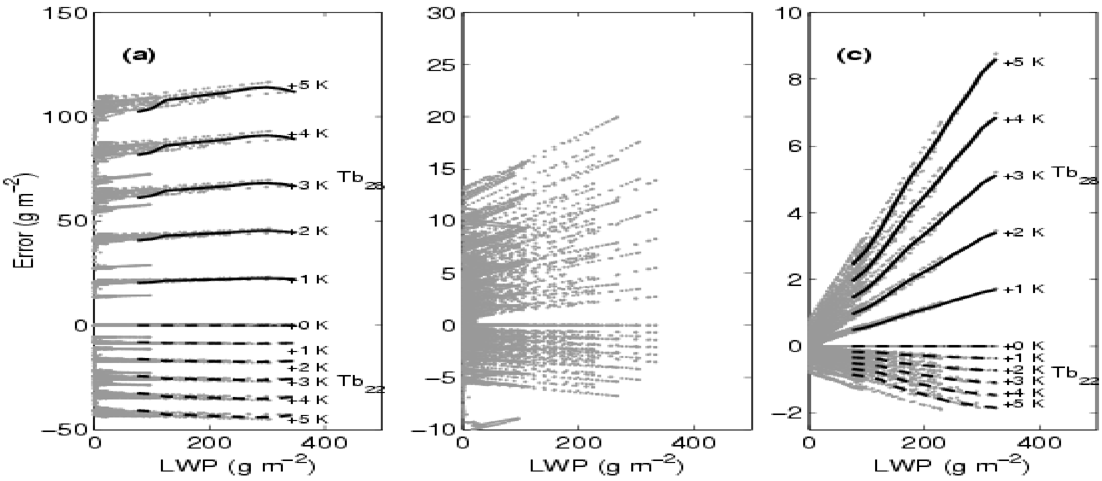


Figure 6 : Errors introduced into the inferred LWP by offsets in the observed brightness temperatures (RHS), using simple method of subtracted the no-cloud offset (center) and using the optimized calibration adjustment (LHS).

6.4. Conclusions including socio-economic relevance, strategic aspects and policy implications.

The correct representation of clouds is a key issue in models used to predict future global warming and for forecasting of high impact weather such as flash floods. The effect of clouds has to be parameterised and represented by just two prognostic variables in each of the grid boxes used to represent the atmosphere in the numerical model used for the forecast. In both climate and weather forecasting models the variables are typically the fraction of the grid box which contains clouds and the mean mass of cloud per unit volume of the grid box.

The unacceptable spread in predictions of future global warming is mainly due to difficulties in representing the clouds. Correct representation of clouds is also essential for short term weather forecasts. CloudNET has produced a data set of cloud profiles over several years at three ground based station in the UK, France and The Netherlands and compared them with the representation of the clouds within six forecasting mdoels run operationally over Europe. For the first time these observed cloud profiles can be used to evaluate the performance of the models, to identify where they work well and where there are shortcomings, and hence indicate where the cloud parameterisation schemes can be improved.

Because of the success of CloudNET the original scope of the work has been extended:
a) From the original three observing stations (Chilbolton, UK; Paris, France, Cabauw, NL) to include Lindenberg (Germany) and, after the recommendations of the GEWEX Cloud and Aerosol Profiling Group, to include the ARM stations of the USA Department of Energy located in Oklahoma, Alaska, together with those in the Western Tropical Pacific at Naru and Manaus.
b) From the four the original operational forecasting models of ECMWF, KNMI (Netherlands, MeteoFrance and the UK Met Office mesoscale model, to include three further models: the Lokal Modell of DWD (Germany), the RCA model of SMHI (Sweden), and the global version of the Met Office Model.

As a result of the success of CloudNET, Europe now has the infrastructure to:
a) Observe, on a continuous basis, profiles of cloud properties at four ground stations in Europe and four outside Europe, which are then converted into the cloud variables (with defined errors) used in climate and weather forecasting models and archived together with the output of seven operational forecast models for the grid box over the observing station in NetCDF format on a publicly accessible web site.
b) Compare the cloud variables derived from observations with the model representation and provide statistics of model performance including skill scores, updated monthly, of the ability of the models to represent clouds. These statistics available on the web site enable new cloud parameterisations implemented on the models to be rapidly evaluated. Climate models essentially use the same cloud parameterisations.
c) Manufacture at an economic cost cloud observing stations which could be deployed operationally.
d) Enable European scientists to exploit the above advances for the analysis of data from future space missions providing global profiles of cloud characteristics such as the NASA/Canadian CloudSAT cloud radar and the NASA/CNES cloud lidar to be launched in spring 2006, and the JAXA/ESA joint EarthCARE mission which will embark a Dopplerised cloud radar and lidar on the same satellite for launch in 2012.

The Meteorological Services involved in the CloudNET study, namely MeteoFrance, the Met office, KNMI, SMHI, DWD and ECMWF have expressed the wish that the ClodusNET infrastructure continue to operate. A considerable investment has been made setting up this structure, at a small fraction of this cost the obsevations and model data can continue to flow to the data centre at Reading and the statistics of model peformance continue to be provided. This enables the Met Services to receive a rapid appraisal of any new or modified cloud scheme in their model and impact on the forecast. A summary of some of the specific results of the evaluation of how the various models represent clouds was given on pages 32-45.

6.5. Dissemination and exploitation of the results.

The main customers of the CloudNET results are the National Weather Forecasting Centres, Climate Forecast Centres and ECMWF. Representatives of ECMWF, KNMI, MeteoFrance, SMHI and the Met office attended the final CloudNET seminar held in October 2005 at Beeskow, Germany. They find the information on how their models are representing clouds to be unique and very valuable and have expressed the wish that the CloudNET infrastructure continues to operate. All the results are published in the open literature.

One conclusion of the CloudNET project which has been communicated to out industrial partner has been the specification for a standard cloud observing station which would comprise a Dopplerised vertically pointing cloud radar, a ceilometer, and a pair of microwave radiometers. The specifications drawn up indicate that such a station could be manufactured for about 250,000 euro, and as such one could expect each National Met Service to purchase up to six to complement their existing automatic weather observing systems. Initially the use would be for model evaluation, but the national weather services are making plans to assimilate real time cloud data which would be obtained from such cloud observing stations into their models to improve the forecasts.