SENSOR SYNERGY ALGORITHMS: DEVELOPMENT AND VALIDATION

André van Lammeren*, Dave Donovan and Hannelore Bloemink

Royal Netherlands Meteorological Institute (KNMI), The Netherlands

1. INTRODUCTION

Climate model output plays an important role in present policy making discussions. The representation of clouds and of their impact on radiative transfer remains one of the greatest sources of uncertainty in present day climate models. The IPCC'95 report states: ".. the most urgent problem requiring attention to determine the rate and magnitude of climate change and sea level rise are the factors controlling the distribution of clouds and their radiative characteristics ..." (IPCC, 95). To improve the representation, of clouds in models, better parameterizations of clouds are needed, both of the macrophysics and dynamics (cloud cover, cloud structure and turbulence) and of the microphysics (droplet spectra, distinction between ice and water, role of condensation nuclei and precipitation formation). In addition, the relation between the micro- and macro properties of clouds and radiative transfer has to be clarified.

In this paper an overview is given of the recent work in the development and validation of sensor synergy algorithms. The methods are extensively described in other publications and will not be repeated in full detail in this paper.

In this paper data from the CLARA and CLARE'98 campaigns are used. The CLARA campaigns focused on microphysics, their relation with the macro properties of clouds and their importance for routine observations of clouds by satellite and ground based remote sensing. Advanced ground based remote sensing techniques like radar and lidar, as well as satellites play a crucial role in monitoring of clouds. The algorithms which are used to derive physical parameters from these measurements (e.g. liquid water path, extinction profiles, total optical depth, albedo) are based on several crude assumptions about the micro-physical properties of the cloud and the relation between these properties and the measured (macro-physical) properties. The CLARA data set offers the opportunity for validation of the different remote sensing techniques with in situ measurements. Furthermore, the excellent collocation of the remote sensing instruments made it possible to develop sensor synergy algorithms. The CLARA campaigns took place in April, August and November 1996. In total more than 7 weeks of continuous, collocated lidar/radar observations were taken. The aircraft measurements were taken during 15 flights, with over 40 flight hours.

ESA initiated the CLARE'98 campaign organised in Chilbolton (UK). Again a set of collocated ground based remote sensing instruments were operated for several weeks. At the same time airborne lidar/radar data was taken (ARAT and Falcon aircraft) simultaneously with in situ observations from the C130 aircraft.

In section 2 of this paper recent work on the retrieval of cloud parameters for water clouds are discussed. Lidar/Radar retrievals of particle size and Ice Water Content (IWC) for ice clouds are discussed in section 3. Concluding remarks are presented in section 4.

2. WATER CLOUDS

2.1 Droplet Concentration

A new method was developed and tested to retrieve cloud droplet concentration from combining microwave radiometer, lidar and radar observations. It relies on the observation of cloud size (radar), liquid water path (microwave radiometer) and optical extinction near the cloud base (lidar). Aircraft observations were used to validate the result.

* Corresponding author address: André van Lammeren, Royal Netherlands Meteorological Institute., P.O. Box 201, 3730 AE De Bilt, The Netherlands; e-mail: lammeren@knmi.nl

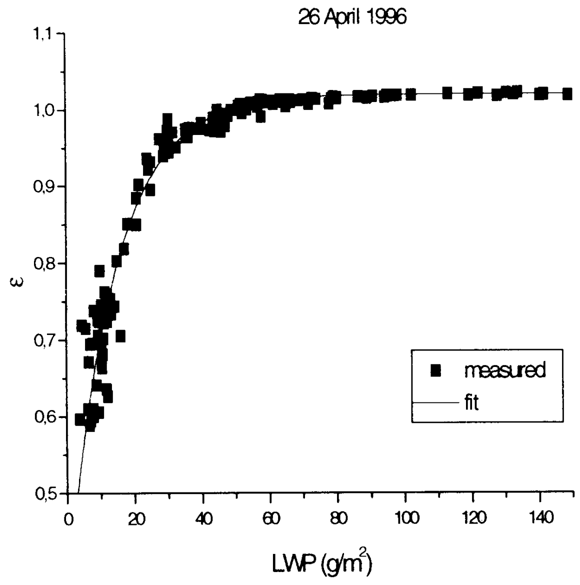

Fig. 1: Experimental results for the case of 26 April. Also shown is the fit to the data.

The agreement between in situ and remote sensing observations is reasonable. Results of this study are published by Boers et al. (2000).

2.2 Liquid Water Path (LWP) and Emissivity

IR emissivity is a measure for the opacity of a cloud in the IR. The IR emissivity of a cloud is defined as the ratio of the radiation emitted by the cloud and the radiation emitted by a black body at the cloud base, and is an important parameter in the radiation balance. The radiation from the cloud can be determined from the IR radiometer data. The lidar can provide the cloud base altitude, and black body radiation from that altitude can be calculated by using the temperature profile measured by the radio sondes.

Cloud liquid water can be derived from microwave radiometer data. When this is compared with the IR emissivity, a clear relation between the two is found in the case of water clouds. This relation is different from the relation between the optical depth and cloud liquid water, because of the different scattering properties of cloud particles in the visible and the IR.

In general, for visible wavelengths, the asymptotic value of 2 is used for Q_{ext} , leading to the well-known relation between LWP and τ:

$$\tau = \frac{3}{2}\frac{LWP}{\rho_w r_{eff}}, \qquad (1)$$

However, it is clear that such an approximation cannot be applied to a water cloud in the IR. Instead, we propose a linear relation between Q_{ext} and r : $Q_{ext}(r)=C\cdot r$. Although such an assumption was mentioned in general in Platt (1976), to our knowledge it has not been applied directly to Q_{ext} for specific wavelengths. This will be a reasonable approximation for particles of up to about 10 μm. Note that this applies to the real particle radius r, and not to the effective particle radius R_{eff}.

Using this approximation results in

$$\tau_{IR} = C\frac{3}{4}LWP / \rho_w . \qquad (2)$$

In other words, for water clouds, the optical depth in the IR depends solely on the cloud liquid water, and not on the particle sizes or the particle size distribution, as long as the cloud particles are smaller than about 10 μm.

The IR emissivity, ε, of a cloud can be determined using the IR sky temperature, and the temperature at the cloud base, along the lines of the LIRAD method (Platt (1973)):

$$\varepsilon = \frac{R_{cloud}}{R_{cloudbase}}. \qquad (3)$$

Here, R_{cloud} is the observed radiance in the spectral range of the IR radiometer and $R_{cloudbase}$ is the radiance in the spectral range of the IR radiometer from an opaque cloud at the height of the cloud base measured by the lidar, and with a temperature as derived from the radio sonde.

One case from CLARA is presented here. On April 26, 1996 between 6:00-14:00 UTC a thin layer of strato cumulus is present at about 1.3 km altitude, which disappears after 8:30 UTC. Figure 1 shows the results of ε vs LWP for the case of 26 April. Only points where ε can be determined are plotted.

The result from the fit to all available date is identical to observations on other days. There is also an excellent agreement between these experimental results and the constants derived from the approximation of $Q_{ext}(r) = C \cdot r$. Furthermore, the value of the fitting parameter is also in agreement with the results published by Stephens (1978). More information on this algorithm can be found in Bloemink et al. (1999)

3. ICE CLOUDS

In principle, combined lidar and radar cloud soundings are capable of providing detailed height resolved information of the effective sizes of cloud particles. However, accounting for extinction at the lidar wavelength in an appropriate manner can be problematic. A procedure for estimating cloud effective particle radius and water content profiles has recently been developed. The procedure accounts for extinction in a self-consistent manner and has many advantages over conventional lidar or radar only procedures. The technique has been applied to a number of CLARA and CLARE'98 cases and two examples are presented here.

3.1 The algorithm

The lidar/radar algorithm that is employed here is the same as that described in Donovan et al. (1999). A schematic view of the inversion procedure (including multiple scattering effects) is outlined in Fig. 2. In the algorithm the parameter R'_{eff} is defined as:

$$R'_{eff} = [< r^6 > / < r^2 >]^{1/4} \quad (4)$$

In the case of to the case of randomly orientated ice crystals the definition has to be altered. Since the lidar extinction will mainly depend on the cross-sectional area of the particles and the radar reflectivity will mainly depend on the square of the mass of the particles we model ice clouds using distributions of equivalent R'_{eff} spheres:

$$R'_{eff} = \left[\frac{9}{16\pi} \frac{< (M(D)/\rho_i)^2 >}{< Ac(D) >} \right]^{1/4} \quad (5)$$

where, D is the maximum ice crystal dimension, M is the ice crystal mass, ρ_i is the density of solid ice and Ac is the cross-sectional area of the particles. For spherical particles Eqn.(5) is equal to Eq (4).

Multiple scattering has been accounted for in an approximate fashion using the formalism described in Eloranta (1998). To a large degree, the contribution of multiply scattered light to the observed lidar signal depends on the angular width of the forward scattering lobe of the cloud article's phase function compared with the field-of-view of the lidar receiver. The width of the forward scattering lobe is, in turn, related to the cross-sectional area of the cloud particles. In general, the larger the particles are the narrower the forward scattering lobe is.

If multiple scattering is ignored, then the retrieved extinction will be lower than the true extinction. Simulations made using both a Monte-Carlo model and the approximate model of Eloranta have shown that for the measurements of ice-clouds made using the CT-75K lidar this effect is generally expected to be below 10-20 % since the field of view of this instrument is less than 0.6 mrads. For the airborne LEANDRE lidar, with a 3.5 mrad fov, the measured extinction will be only about half the true extinction.

To account for multiple scattering effects, first an inversion is performed assuming no multiple scattering, then the retrieved extinction profile and particle sizes are used to estimate the multiple scattering contribution (to 3rd or 4th order). To do this, the angular width of the forward scattering peak is estimated using the derived lidar/radar effective radius R'_{eff} (Donovan et al. (1999)) profile together with diffraction theory. Once the multiple scattering contribution has been estimated as a function of range from the lidar the single scattered power can be estimated. When this is done, an inversion is performed on the estimated single-scatter only signal. The multiple scattering contribution is then re-estimated as before and another inversion is then performed. The process is then repeated until the estimated single-scatter power only profile has converged.

In effect, the inversion procedure performs a number of different Klett-type inversions each with a different boundary value and then chooses the boundary value which gives the

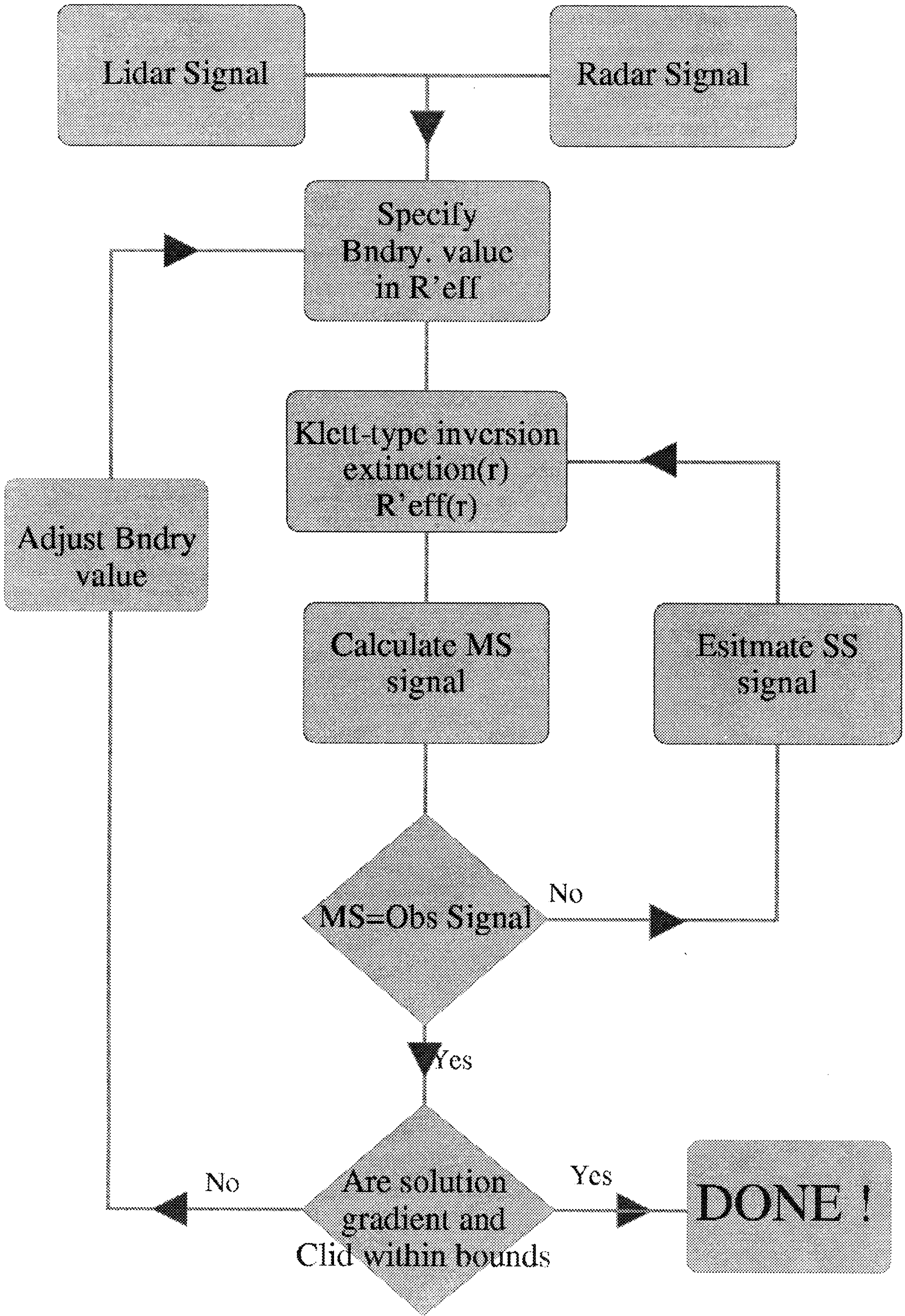

Fig. 2 Schematic representation of the lidar/radar inversion algorithm. For further explanation see text.

smoothest retrieved R'_{eff} profile which corresponds to a feasible value of the lidar calibration constant, C_{lid}.

3.2 April 18, 1996 (CLARA)
Results of the retrieval for April 18th, 1996 are shown in Fig. 3. During this time period, co-located microwave radiometer observations showed that little liquid water was present over Delft so that the lidar and radar were observing an ice cloud. Here the normalization altitude was about 4.5 km.

Figures 3a and 3b show the lidar signals and the radar reflectivity (respectively) from 20:00 to 24:00 hrs UTC on April 18, 1996. The retrieved R'_{eff} field is shown in Fig. 3c while the estimated ice-water content field is shown in Fig. 3d. The ice water content was estimated assuming a gamma-type distribution in D with γ equal to 5 and also assuming that the particles were randomly orientated ice complex-polycrystals (Mitchell et al. (1996)).

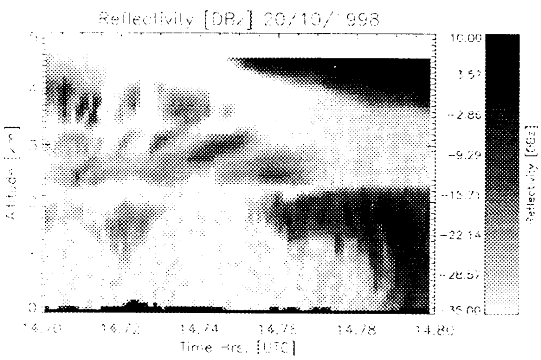

Fig 4. Observed radar reflectivity for the ARAT flight path, October 20, 1998

3.3 October 20, 1998 (CLARE'98)
During CLARE98, several flights of the UK meteorological office C-130 aircraft were conducted (Francis, 1999). The C-130 mounted several in-situ particle sizing instruments including 2D-C and 2D-P probes. These instruments are, in principle, capable of measuring the effective size of ice-crystals and to infer the ice-water content of the sampled cloudy volume.

On October 20th a near coincident flight path was flown by the French ARAT aircraft and the UKMO C-130. The ARAT carried the LEANDRE 532nm lidar along with the KESTREL 94 GHz Radar. Details of the two instruments can be found in Guyot et al., (1999a) and Guyot et al., (1999b). The observed radar reflectivity for this flight is shown in Fig. 4. Here a large cloud is visible in the top right portion of the figure.

The C-130 flights on this day show that layers of liquid water were often present over and around Chilbolton. However, little water was encountered during the coincident C-130 flight at 4.6 km. An inversion is conducted assuming only ice to be present.

A comparison between various cloud properties inferred from the 2D probe measurements and the lidar/radar inversion results is shown in Fig. 5. The lidar/radar results shown are for an altitude of 4.55 km which was the maximum height at which reliable data was obtained. The C-130 flew at an altitude of around 4.6 Km which is just slightly higher than the maximum height of the lidar/radar data but is within one range bin (the resolution of the lidar data was 60 meters) of the top of the lidar/radar data. Results for the two different ways of interpreting the 2D probe data are also shown. The lidar/radar IWC and R'_{eff} estimates shown here were generated using the complex polycrystal model of Mitchel et al. (1996). It should be noted that this model specifies a different mass-vs-area relationship than either of the two approaches used to interpret the 2D probe data.

Due to a difference in speed between the ARAT and the UKMO C-130 the distance between the two aircraft varied during the flight. The results of the comparison between the lidar/radar results and the in situ data of the data are plotted as a function of longitude (Fig. 5a) and time (Fig. 5b). From the R'_{eff} plot it is clear that a better agreement is obtained when the results are plotted as a function of longitude. This can be understood if the separation of the two aircraft is taken into account. If the results are plotted as a function of longitude, the aircraft are within approximately 300m of each other (Fig. 6a). When time is used as a coordinate, the separation between the two aircraft is 5 km at the start of the track and decreases to a few hundred meters at the end. This results

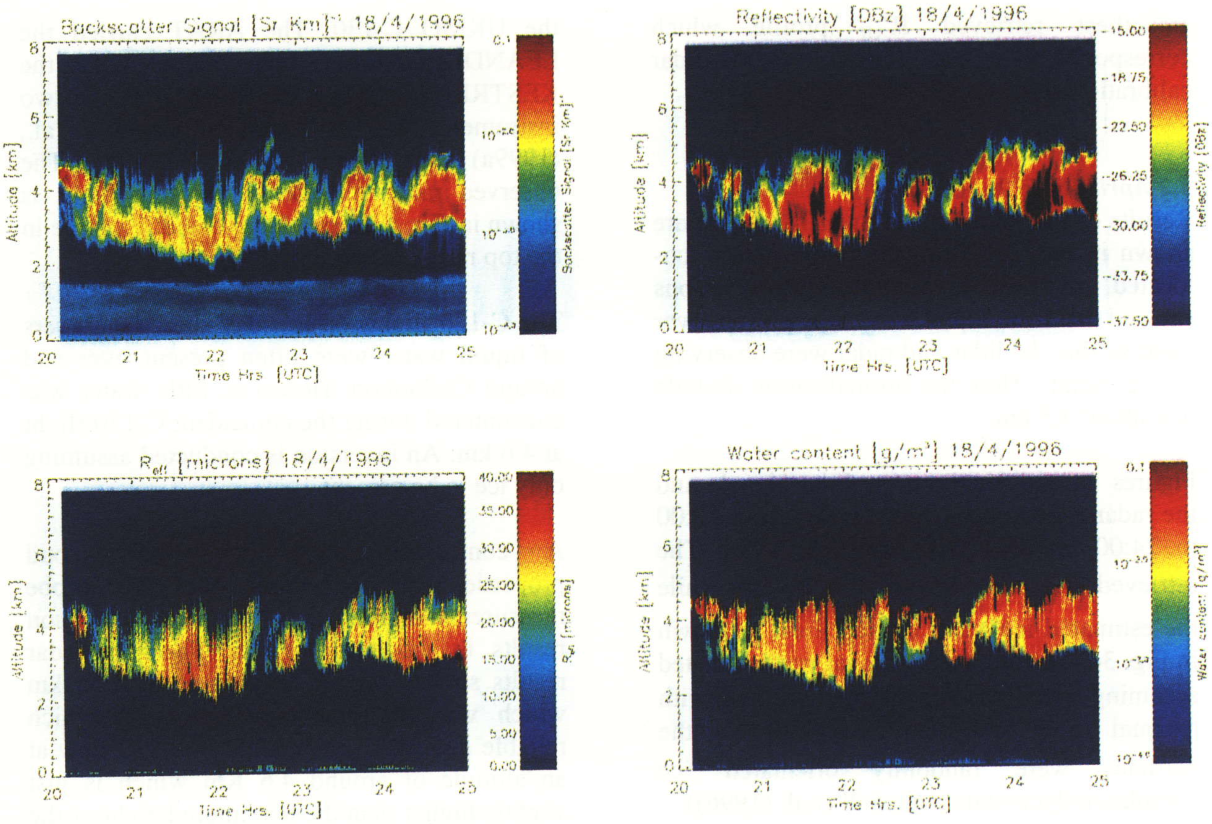

Fig 3 ***Observed and derived clud parameters for April 18, 1996. Upper panel: observed lidar backscatter (3a), and radar reflectivity (3b). Lower panel: derived effective radius, R'_{eff} (3c) and ice water content (3d)***

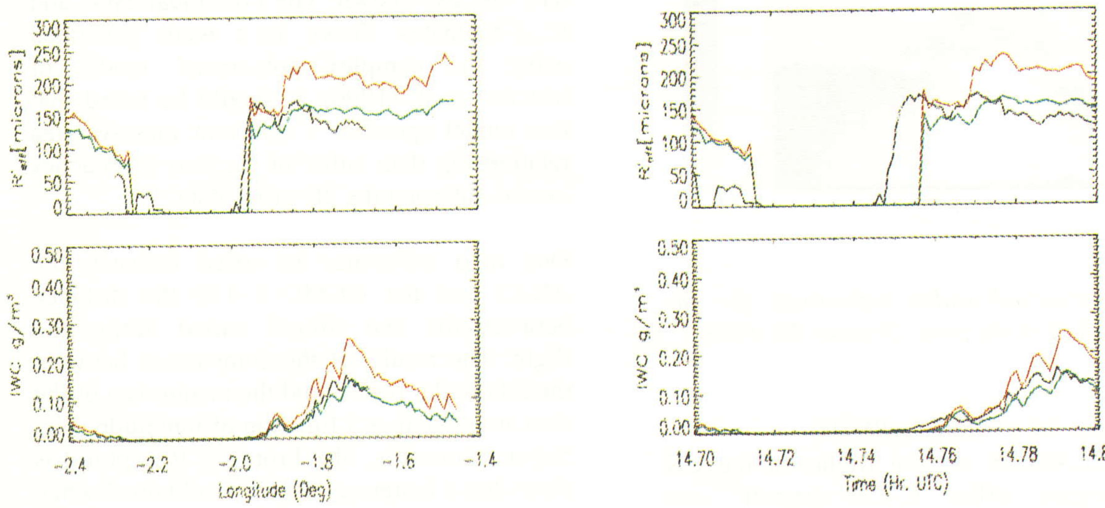

Fig 5 ***Comparison of lidar/radar results and 2D probe results for the ARAT/C-130 flight path. The black-solid lines show the results from the lidar/radar inversions at 4.55 km. The red lines show the results for the 2D probe data using the mass-vs-area relationship while the green lines show the results of the mass-vs-maximum average dimension relationship.***

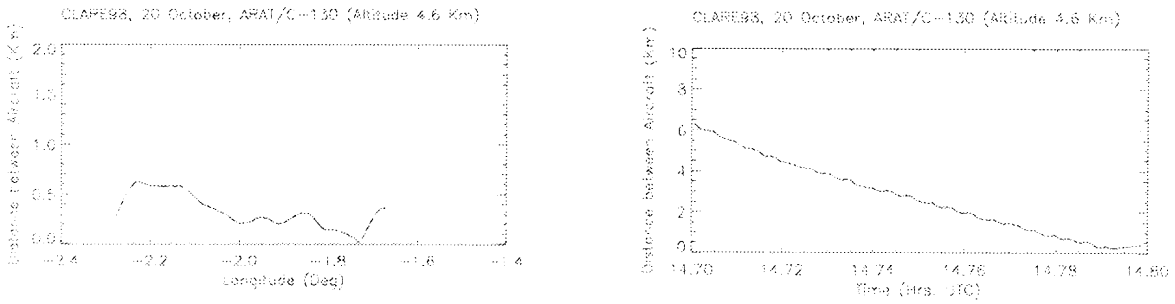

Fig. 6 Distance between the ARAT and C!#) aircraft as a function of longitude and time for October 20, 1998.

illustrates the importance of collocated observations. Separations of a few hundred meters are still not ideal. However, given the large extent and high apparent stability of the large ice cloud sampled here together with the horizontal resolution of the aircraft measurements (about 500-600 meters for the C-130 measurements) they may be considered adequate for useful comparison in this case.

The comparisons between the lidar/radar derived quantities and the 2D probe measurements are seen to be consistent within the uncertainty between the two methods for determining particle mass. In particular, the lidar/radar results for IWC appear to agree somewhat better for most of the flight path with the maximum dimension derived 2D probe estimates. The significance of this result is unclear at this point. A more rigorous comparison should be made which would incorporate the same mass-vs-area relationship in the lidar/radar retrievals as that used in the 2D probe estimates.

The agreement obtained between the remotely derived and in-situ derived cloud properties presented here is impressive, especially considering the diversity of the two approaches and the many possible sources of uncertainty inherent in both the lidar/radar retrieval process and the interpretation of the 2D probe images. It remains to be seen whether such agreement is to be commonly expected or is limited to certain special circumstances.

Further work should be performed to investigate the validity of the approximate treatment of non-spherical particle scattering implicitly used in the lidar/radar inversion process. As well, better characterisation of the nature of proper mass-vs-area relationships for ice crystals would benefit both the interpretation of 2D probe data as well as aid in the accurate inversion of combined lidar and radar data.

4. CONCLUDING REMARKS

The CLARA and CLARE'98 data set are valuable data sets for the development and validation of sensor synergy algorithms. Collocated lidar, radar and infrared radiometer data is. The presence of in-situ aircraft measurements and other remote sensing instruments allows for a detailed analysis of sensor synergy algorithms.

For water clouds the emissivity calculated from observed IR cloud base temperature and cloud base heights can be used to estimate the LWP clouds for thin Sc-clouds. It is likely that this method could also be applied to space observations. One complicating factor will be the unknown temperature of the earth surface below the semi-transparent cloud.

A novel Lidar/Radar retrieval algorithm has been presented. Results from two case studies were shown. In general the algorithm has shown to be robust and the derived R'_{eff} and IWC are consistent with the in-situ observations made during CLARE'98. In the near future more work will be done on the validation of the algorithm.

For more information on the CLARA project, e.g. copy of the final report, copy of the

CLARA data-set or reprints of published papers, please contact the first author of this paper or visit the CLARA web-site (http://www.knmi.nl/CLARA).

REFERENCES

Boers, R., H. Russchenberg, J. Erkelens, V. Venema, A. van Lammeren, A. Apituley and S. Jongen, 2000: Ground-based remote sensing of stratocumulus cloud droplet concentration during CLARA-1996. J. Appl. Meteor., **39**, No. 2, pp 169-181

Bloemink, H., A. van Lammeren, A. Feijt and S. Jongen: Active-passive sensor synergy for cloud observations; IR cloud properties and cloud liquid water. Proceedings of the symposium on "Remote sensing of cloud parameters: retrieval and validation", Delft, The Netherlands, 21-22 October 1999, pp 113-117.

Donovan, D, A. van Lammeren: Combined lidar and radar cloud particle effective size retrievals made during CLARA. Submitted for publication in Phys. Chem. Earth.

Donovan, D.P., J. Goddard, H. Savageot and R.J. Hogan, 1999: Cloud effective radius and water contents inferred from combined lidar and radar observations during CLARE98, CLARE '98 Final workshop, 14-15 September 1999, Noordwijk The Netherlands. Proceedings are in Press.

Elorante, E.W., 1998: Practical model for the calculation of multiply scattered lidar returns. Appl. Opts, **37**, 2464-2472.

Guyot, A., J. Testud, O. Danne, M. Quante, and P. Francis, 1999a: Calibration of the University of Wyoming 95 GHz airborne radar during CLARE'98. CLARE '98 Final workshop, 14-15 September 1999, Noordwijk The Netherlands. Proceedings are in Press.

Guyot, A., J. Testud, J. Pelon, V. Trouillet, and P. Francis, 1999b: Synergy in ice clouds between airborne nadir pointing radar and lidar during CLARE'98. CLARE '98 Final workshop, 14-15 September 1999, Noordwijk The Netherlands. Proceedings are in Press.

Intrieri J.M., G.L. Stephens, W.L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle size using lidar and radar backscatter technique. J. Appl. Meteor., **32**, 1074-1082.

IPCC'95, Intergovernmental Panel on Climate Change, 1995: IPCC Second Assessment Report – Climate Change 1995, UNEP/WMO

Mitchell, D.L., A. Macke, and Y. Liu, 1996: Modeling Cirrus Clouds. Part II: Treatment of Radiative Properties, *J. Atmos. Sci.*, 53, 2967-2988 (1996).

Platt, C.M.R., 1973. *J.Atmos.Sci.* **30**, 1191-1294 (1973).

Platt, C.M.R.,1976. *Quart.J.R.Met.Soc.* **102**, 553-561 (1976).

Stephens, G.L., G.W. Paltridge and C.M.R. Platt, 1978. *J.Atmos.Sci.* **35**, 2133-2141 (1978).

ACKNOWLEDGEMENT

The authors would like to thank the participants to the CLARA and CLARE'98 campaigns for their contributions. Especially H. Russchenberg (CLARA radar), P. Francis and R. Hogan (C130 data), J. Testud (KESTREL radar) and J. Pelon (LEANDRE lidar).

The CLARA project is partly funded by the National Research Program on climate change and environmental protection in the Netherlands.

More information on the CLARA project can be found on internet:

http://www.knmi.nl/CLARA/