# The complexity of variational retrieval of liquid cloud properties

**Kerstin Ebell[1]**, U. Löhnert[1], E. Orlandi[1], S. Crewell[1]

[1] *Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany*
*kebell@meteo.uni-koeln.de*

HD(CP)²
High definition clouds and precipitation for advancing climate prediction

## 1) Introduction

- in order to derive the atmospheric state as completely as possible, the combination of multiple wavelength active and passive remote sensing instruments is necessary
- extended version of the Integrated Profiling Technique (IPT; Löhnert et al., 2008) to also retrieve profiles of effective radius (REF; see Fig. 1)

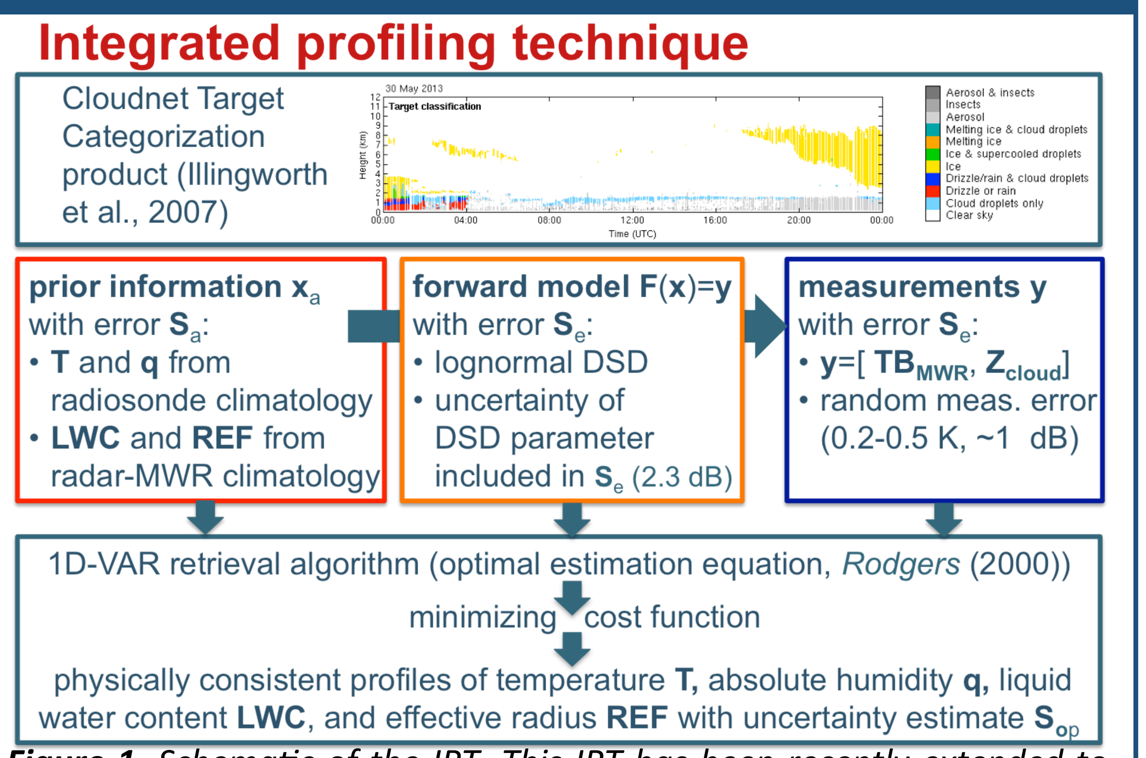



*Figure 1. Schematic of the IPT. This IPT has been recently extended to also retrieve profiles of droplet effective radius (REF) including updated prior information on LWC and REF and a new forward model for Z.*

## 2) Synthetic data study: retrieval performance

- 30 May 2013, 08-16 UTC (see Fig.1): create LWC and REF profiles („truth") based on observed LWP and Z values (Frisch et al. 1998; 2002) → simulate $\mathbf{TB_{MWR}}$ and $\mathbf{Z_{cloud}}$ „observations" → IPT → compare retrieved LWC & REF profiles to „truth"

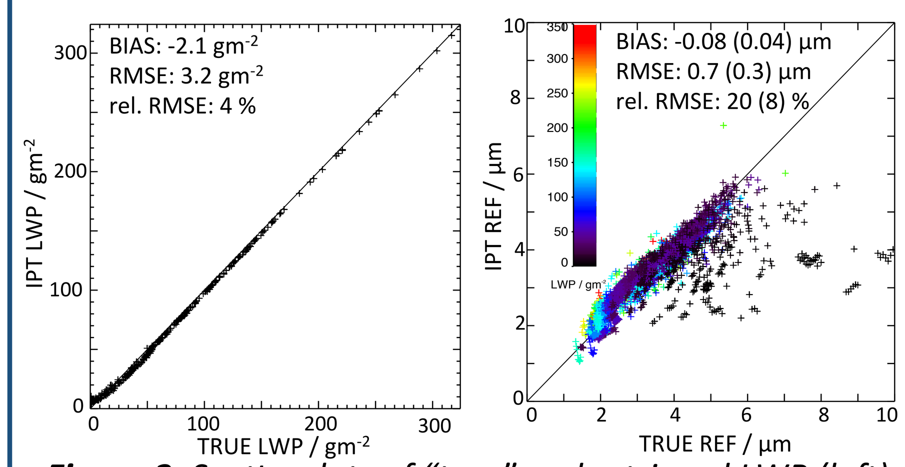



*Figure 2. Scatterplots of "true" and retrieved LWP (left) and REF (right) between 8 and 16 UTC on May 30, 2013 at JOYCE. Values in () for profiles with LWP>10 gm⁻² only.*

| IPT statistics 2013/05/30 8-16 UTC (synthetic data) | |
|---|---|
| **converged profiles** | 97 % |
| **theoretical retrieval uncertainties (mean±stddev)** | |
| LWC | 52±23% |
| REF | 17±6% |
| **degrees of freedom for signal (normalized by # cloud layers)** | |
| LWC | 30±6% |
| REF | 31±6% |

- true LWP and REF values generally very well reproduced
- only when LWP very small (<10 gm$^{-2}$), large erros in retrieved REF

## 3) Synthetic data study: retrieval sensitivities

- focus on profile at 11 UTC: cloud thickness 374 m (13 bins), LWP=65 gm$^{-2}$ → sensitivity studies

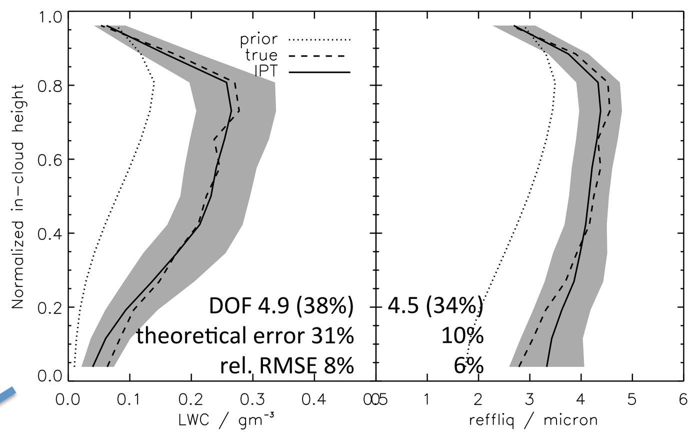



*Figure 3. True, prior and retrieved LWC (left) and REF (right) profiles for a liquid cloud with 374 m thickness and a LWP of 65 gm⁻². 1-sigma IPT uncertainty as shaded area. In this study, $S_e$ only includes measurement noise.*

### Sensitivity to $S_a$ and $S_e$

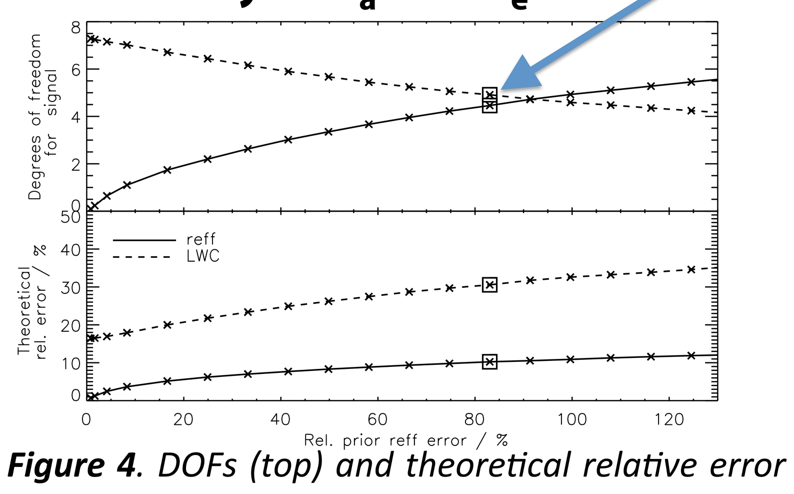



*Figure 4. DOFs (top) and theoretical relative error (bottom) for REF (solid line) and LWC (dashed line) as a function of the prior REF uncertainty.*

*Table 1. DOFs and theoretical retrieval error (in %) for REF and LWC for different variances in $S_e$. Last column: same measurement noise as in first column + radar forward model uncertainty of 2.3 dB (standard IPT configuration).*

| | TB: $(0.2)^2$-$(0.5)^2$ K$^2$, Z: $(1)^2$ dB$^2$ *1x* | *2x* | *3x* | +$(2.3)^2$ dB$^2$ (standard IPT configuration) |
|---|---|---|---|---|
| **LWC** | | | | |
| DOF | 4.91 | 4.07 | 3.52 | 3.76 |
| theor. unc. (%) | 31 | 38 | 45 | 36 |
| **REF** | | | | |
| DOF | 4.46 | 3.83 | 3.33 | 3.57 |
| theor. unc. (%) | 10 | 13 | 16 | 13 |

### Effect of measurement offsets and inappropriate forward model assumptions

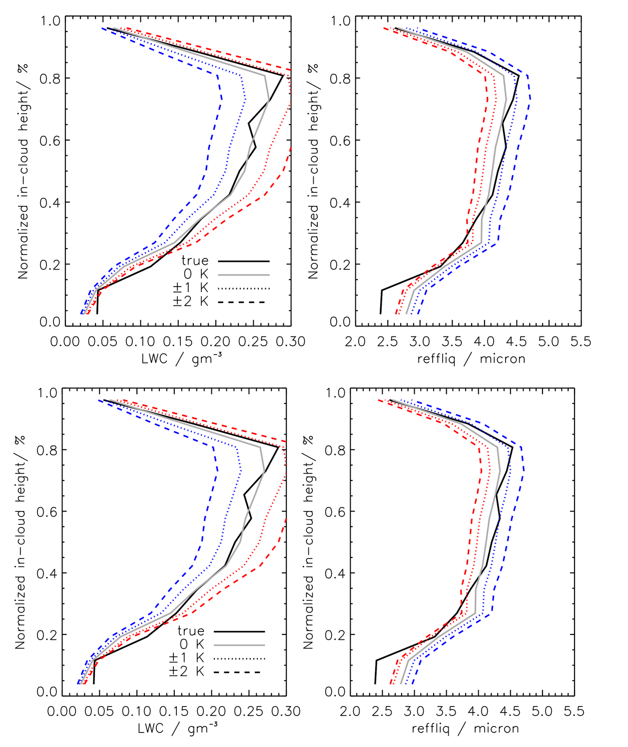



*Figure 5. Retrieved and true LWC (left) and REF (right) profiles for synthetic study on May 30, 2013, 11:00 UTC, for different biases in Z (top) and TB at 31.4 GHz (bottom). Positive (negative) bias values in red (blue). For the corresponding relative RMSE of the LWC and REF profiles see tables (right).*

| Offset (dB) | rel. RMSE error (%) LWC | REF |
|---|---|---|
| 0 | 8 | 6 |
| 1 | 8 | 10 |
| -1 | 8 | 9 |
| 2 | 8 | 18 |
| -2 | 8 | 15 |
| 3 | 9 | 26 |
| -3 | 9 | 21 |

| Offset (K) at 23.04 GHz | 31.4 GHz | rel. RMSE error (%) LWC | REF |
|---|---|---|---|
| 0 | 0 | 8 | 6 |
| 0 | 1 | 13 | 7 |
| 0 | -1 | 16 | 7 |
| 0 | 2 | 24 | 9 |
| 0 | -2 | 27 | 10 |
| 2 | 0 | 12 | 6 |
| -2 | 0 | 9 | 6 |
| 2 | 2 | 18 | 7 |
| -2 | -2 | 21 | 8 |
| -2 | 2 | 30 | 10 |
| 2 | -2 | 33 | 13 |

How large is the retrieval error if the true DSD differs from the assumed one?
→ simulate TB and Z „observations" for typically observed DSD (lognormal, modified gamma) but assume lognormal DSD with fixed logarithmic spread (0.38) in retrieval

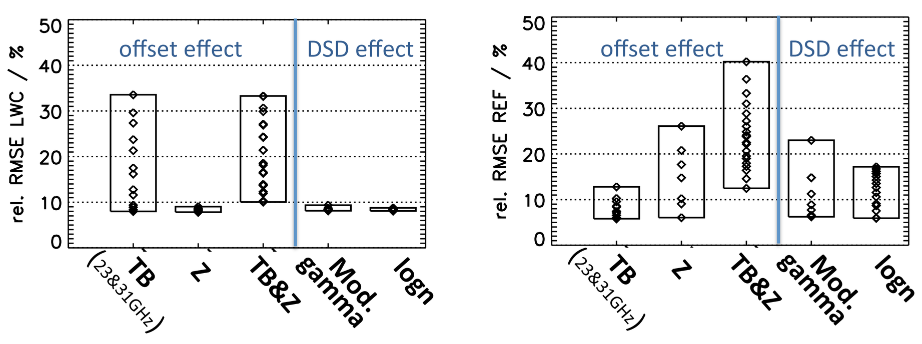
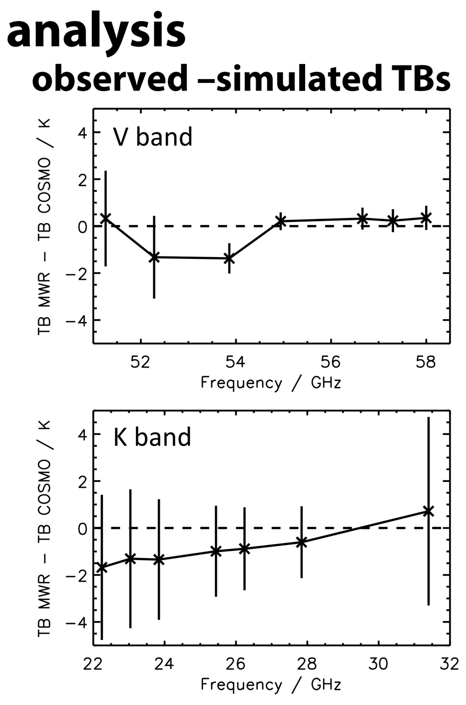



*Figure 6. Spread of rel. RMSE of LWC (left) and REF (right) due to potential measurement offset errors (see also Fig. 5) and differences in the assumed and true DSD.*

## 4) IPT application at the Jülich Observatory for Cloud Evolution JOYCE

### MWR offset analysis

*Figure 7. MWR TB bias and standard deviation (error bars) based on 120 clear sky cases between 2012/05/23 and 2013/08/02. Simulated TBs based on COSMO-DE.*



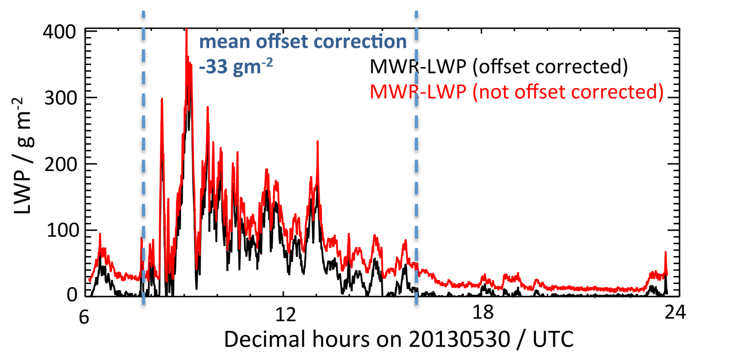




*Figure 8. Time series of MWR-LWP on May 30, 2013. Clear-sky offset-corrected LWP (black) and original LWP (red).*

### Retrieval performance

| IPT statistics 2013/05/30 8-16 UTC (real observations) | |
|---|---|
| **converged profiles** | 86 % |
| **theoretical retrieval uncertainties (mean±stddev)** | |
| LWC | 39±4% |
| REF | 16±2% |
| **degrees of freedom for signal** | |
| LWC | 28±5% |
| REF | 31±7% |

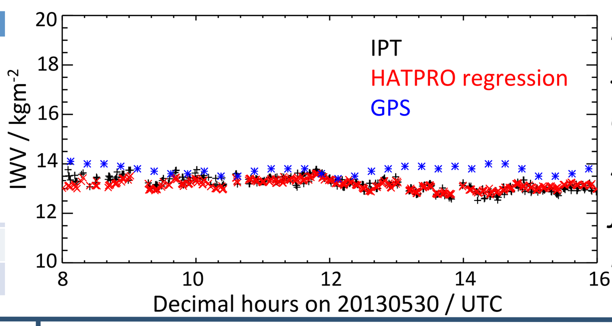



*Figure 9. Time series of IWV on May 30, 2013, for different retrieval methods.*

### Sensitivity to TB correction

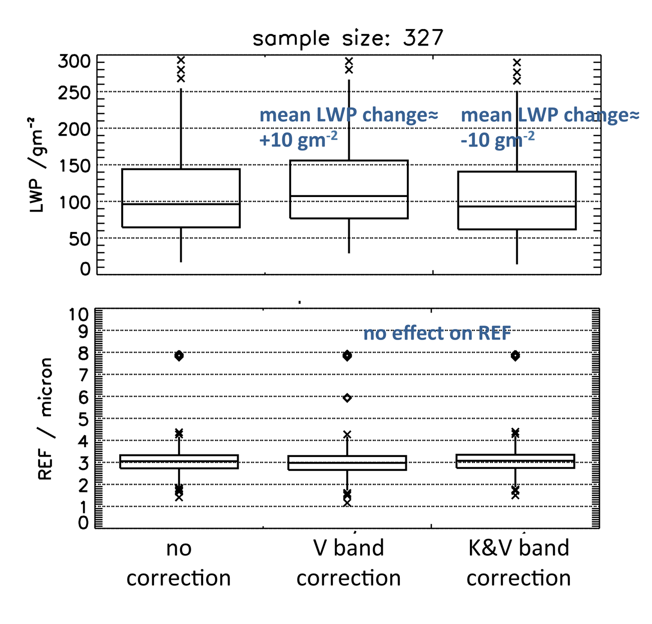



*Figure 10. Boxplots of retrieved LWP (top) and REF (bottom) on March 17, 2014, 8-16 UTC, for different TB corrections.*

### How well do different warm cloud retrieval algorithms agree?

- comparison of IPT-LWC and REF to other commonly used retrieval methods:

**LS** (*Liao and Sassen*, 1994) **LS+FRISCH95** (*Frisch et al.*, 1995)

$$LWC = \left(\frac{N_0 Z_{cloud}}{3.6}\right)^{1/1.8} \qquad r_{eff} = \exp\left(\frac{5}{2}\sigma_x^2\right)\left(\frac{3LWC}{4\pi\rho_w N_d \exp\left(\frac{9}{2}\sigma_x^2\right)}\right)^{1/3}$$

**LS+MWR:**
LWC scaled with $LWP_{MWR}$ if $LWP_{MWR}$>$LWP_{LS94}$ N=100 cm$^{-3}$, $\sigma_x$=0.35, $N_d$=200 cm$^{-3}$

**FRISCH98** (*Frisch et al., 1998*) **FRISCH98+02** (*Frisch et al., 2002*)

$$LWC_i = \frac{LWP_{MWR} Z_i}{\sum_i Z_i^{1/2}\Delta z} \qquad r_{eff}(h) = \frac{Z^{1/6}(h)}{2LWP_{MWR}^{1/3}}\left(\frac{\rho\pi}{6}\right)^{1/3}\left(\sum_{i=1}^{m} Z^{1/2}(h_i)\Delta h\right)^{1/3}\exp\left(-2\sigma_x^2\right)$$

$\sigma_x$=0.38

**CHIU12** (*Chiu et al., 2012*)
transmittance based retrieval, zenith sunphotometer radiances
LUT($I_{440nm}$, $I_{870nm}$, $I_{1620nm}$) → reff and COT + uncertainties

$$LWP_{CHIU12} = \frac{5}{9}\rho_w \tau r_{eff}$$

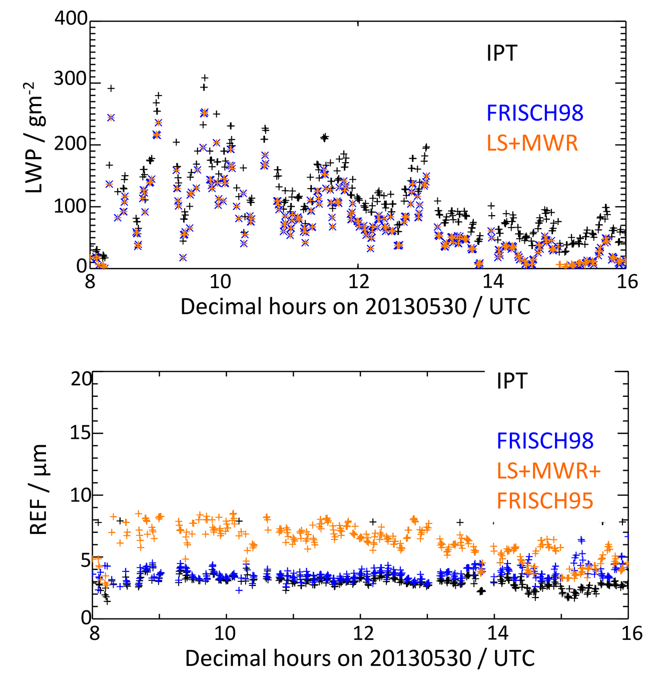



*Figure 11. Time series of LWP (top) and REF (bottom) on May 30, 2013, for different retrieval methods.*

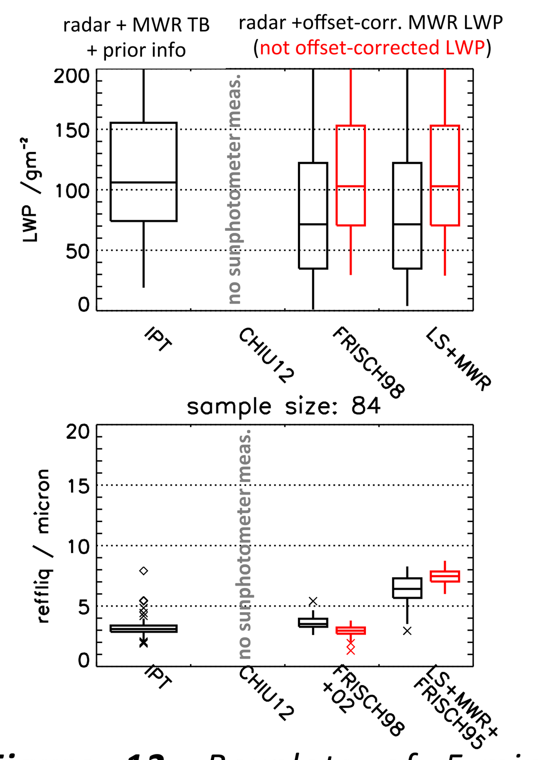
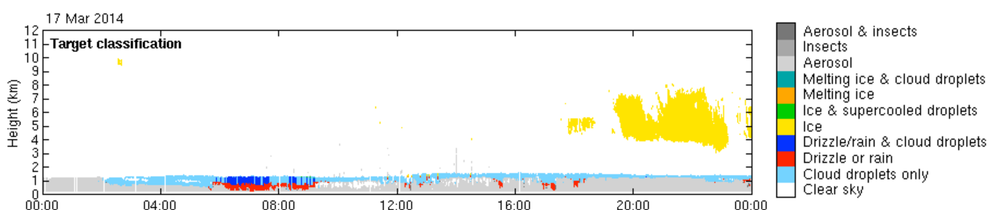



*Figure 12. Boxplots of 5-min averaged LWP (top) and REF (bottom) on May 30, 2013.*

*Figure 13. Cloudnet categorization on March 17, 2014, for JOYCE.*



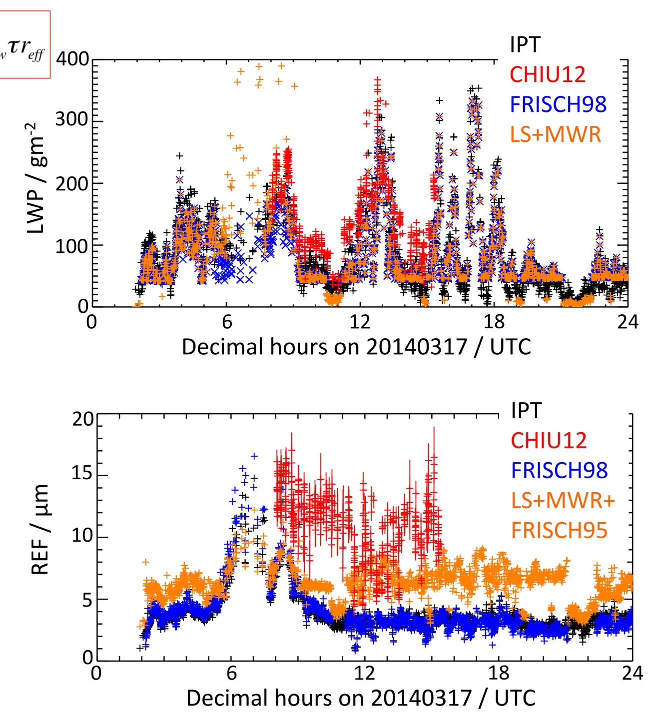




*Figure 14. Time series of LWP (top) and REF (bottom) on March 17, 2014, for different retrieval methods.*

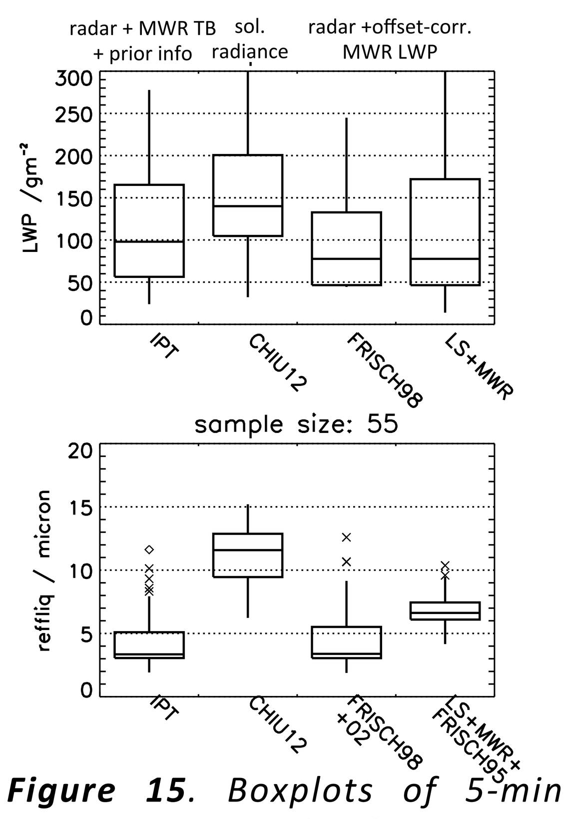



*Figure 15. Boxplots of 5-min averaged LWP (top) and REF (bottom) on March 17, 2014.*

***Acknowledgement:***
We thank **Christine Chiu** for providing the sunphotometer retrieval at JOYCE.

***References:***

**Chiu, J.C.** et al., Cloud droplet size and liquid water path retrievals from zenith radiance measurements: examples from the Atmospheric Radiation Measurement Program and the Aerosol Robotic Network, *Atmospheric Chemistry and Physics*, 10313–10329, 2012.
**Frisch, A.**, C. Fairall, and J. Snider, Measurement of stratus cloud and drizzle parameters in ASTEX with a Kα-Band doppler radar and a microwave radiometer, *Journal of the Atmospheric Sciences*, 52, 2788–2799, 1995.
**Frisch, A.**, G. Feingold, C. Fairall, T. Uttal, and J. Snider, On cloud radar and microwave radiometer measurements of stratus cloud liquid water profiles, *Journal of Geophysical Research*, 103, 23195–23197, 1998.
**Frisch, A.**, M. Shupe, I. Djalalova, G. Feingold, and M. Poellot, The retrieval of stratus cloud droplet effective radius with cloud radars, *Journal of Atmospheric and Oceanic Technology*, 19, 835–842, 2002.
**Illingworth, A. J.**, et al., CLOUDNET Continous evaluation of cloud profiles in seven operational models using ground-based observations, *Bulletin of the American Meteorological Society,* 88 (6), 883–898, 2007.
**Liao, L**. and K. Sassen, Investigation of relationships between Ka-band radar reflectivity and ice and liquid water contents, *Atmospheric Research*, 34, 231-248, 1994
**Löhnert, U.**, S. Crewell, O. Krasnov, E. O. O'Connor, and H. Russchenberg, Advances in continuously profiling the thermodynamic state of the boundary layer: integration of measurements and methods, *Journal of Atmospheric and Oceanic Technology*, 25, 1251-1266, 2008.
**Rodgers, C.**, Inverse methods for atmospheric spounding: theory and practice. 238p. World Scientifiy, 2000.

## 5) Conclusions

- IPT performs very well in idealized conditions
- accurate knowlegde of appropriate prior information (incl. uncertainties) crucial
- measurement offset errors can significantly increase the retrieval error (TB→LWC, Z→ REF)
- uncertainties in assumed DSD can cause REF errors of the same order of magnitude
- measurement offset correction crucial but quantification difficult
- IPT results consistent with Frisch et al. (1998, 2002) retrieval
- all radar-MWR methods provide a (too?) low REF