The complexity of a 1D-Var retrieval for temperature, humidity and warm clouds

O1 Supersites

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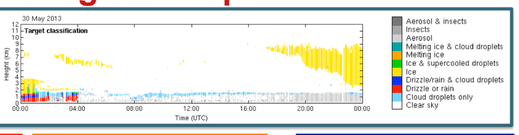
HD(CP)² High definition clouds and precipitation for advancing climate prediction

1) 1D-Var retrieval scheme

Integrated profiling technique

Cloudnet Target Categorization product (Illingworth et al., 2007)



prior information x_a with error S_a:
- **T** and **q** from radiosonde climatology
- **LWC** and **REF** from radar-MWR climatology

forward model F(x)=y with error S_e:
- lognormal DSD
- uncertainty of DSD parameter included in S_e (2.3 dB)

measurements y with error S_e:
- **y**=[TB_{MWR}, Z_{cloud}]
- random meas. error (0.2-0.5 K, ~1 dB)

1D-VAR retrieval algorithm (optimal estimation equation, *Rodgers* (2000))
minimizing cost function
physically consistent profiles of temperature **T,** absolute humidity **q,** liquid water content **LWC**, and effective radius **REF** with uncertainty estimate S_{op}

Figure 1. Schematic of the IPT. The 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.

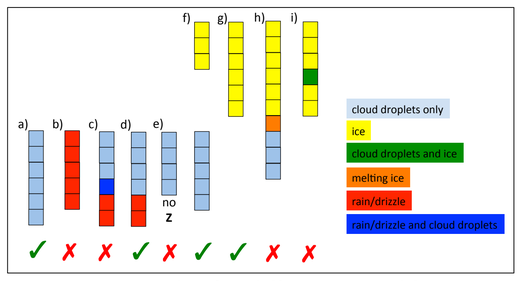


Figure 2. Examples for different possible Cloudnet cloud classifications in the atmospheric column where the IPT can and can not be applied .

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 TB_{MWR} and Z_{cloud} „observations“ → IPT LWC & REF → comparison to „truth“

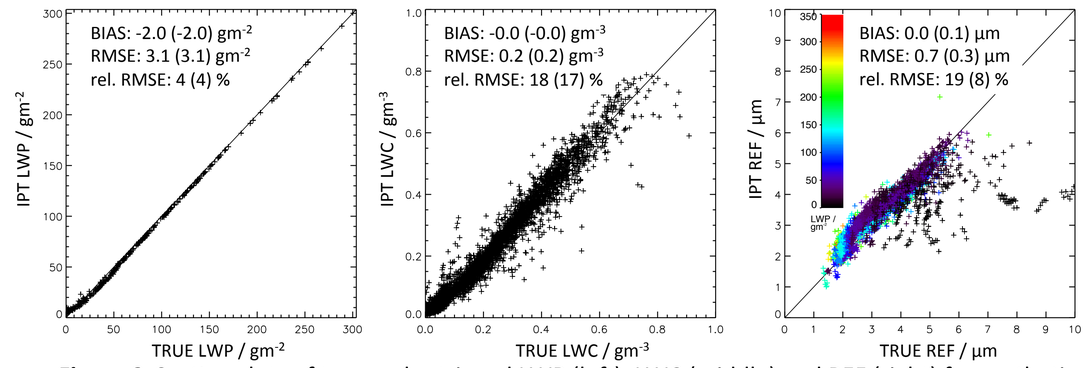


Figure 3. Scatter plots of true and retrieved LWP (left), LWC (middle) and REF (right) for synthetic case study on May 30, 2013 at JOYCE. *Values in () refer to profiles with LWP>10 gm^{-2}.*

3) Synthetic data study: error characterization and retrieval sensitivities

Theoretical retrieval error and degrees of freedom for signal

Table 1. IPT statistics for synthetic case on 30 May 2013, 8-16 UTC.

converged profiles	97 % (376 of 385)
theoretical retrieval uncertainties (mean±stddev)	
LWC	52±23%
REF	17±6%
degrees of freedom for signal (DOF) in profile of	
LWC (normalized by # cloud layers)	29±6%
REF (normalized by # cloud layers)	29±5%
temperature	2.3±0.01
absolute humidity	1.6±0.04

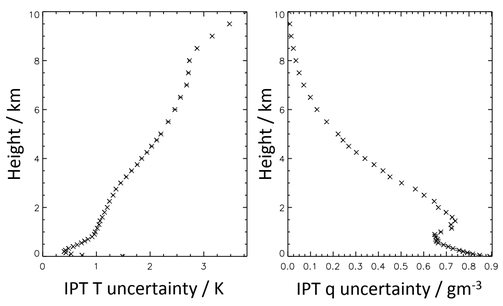


Figure 4. Theoretical retrieved temperature (left) and abs. humidity (right) error for synthetic case study on May 30, 2013 at JOYCE.

Are the retrieved profiles consistent with the measurements?

- X^2 test on $\delta\hat{\mathbf{y}} = \hat{\mathbf{y}} - \mathbf{y}$: $\delta\hat{\mathbf{y}}$ should be Gaussian distributed with zero mean and covariance $\mathbf{S}_{\delta\hat{\mathbf{y}}} = \mathbf{S}_e \left(\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_e\right)^{-1} \mathbf{S}_e$
- here: physically consistent solution in 98% of the converged cases (Fig. 5)

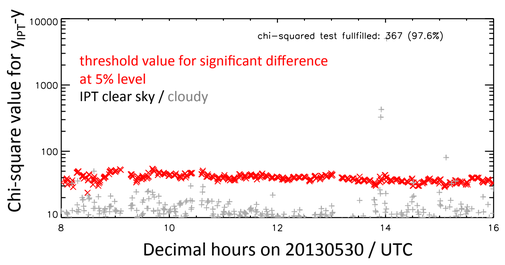


Figure 5. Time series of X^2 test on y_{IPT}-y for synthetic case study on May 30, 2013 at JOYCE.

Sensitivity to measurement noise

→ experiments with doubled TB and Z noise
→ experiment with correlated TB noise (correlations based on typical observed values)

	standard noise	2x TB noise	2x Z noise	correlated TB noise
DOF				
T	2.3	1.9	2.3	2.4
q	1.6	1.3	1.6	1.6
LWC (%)	29.0	28.4	28.8	29.0
REF (%)	28.8	28.7	28.6	28.8
IPT uncertainty				
LWC (gm^{-3})	0.06	0.07	0.06	0.06
REF (µm)	0.6	0.6	0.6	0.6

Table 2. DOF and theoretical retrieval uncertainty for REF and LWC for modified measurement error covariance matrices $\mathbf{S}_e$.

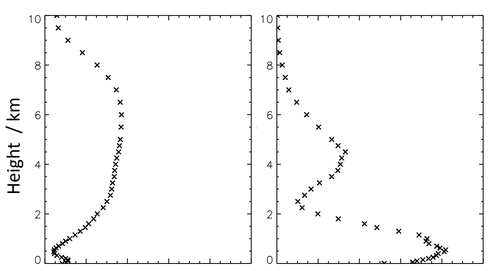


Figure 6. Differences in theoretical uncertainty for retrieved temperature (left) and abs. humidity (right) profiles if TB noise is doubled. Results for synthetic case study on May 30, 2013 at JOYCE.

Effect of inappropriate forward model assumptions

How large is the retrieval error if the true DSD differs from the assumed one?
→ simulate TB and Z„observations“ for typically observed DSDs but assume lognormal DSD (σ_x=0.38) in IPT

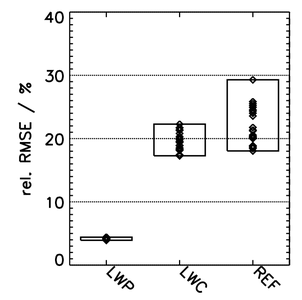


Figure 7. Spread of rel. RMSE of LWP, LWC and REF due to differences in the assumed (logn) and true DSD.

4) IPT application at JOYCE

- often large discrepancies between simulated and observed TBs (see example for liquid cloud cases 8 Oct 2013; Fig. 8) resulting in failure of X^2 test (Fig. 9a)

→ Are the MWR TBs biased?

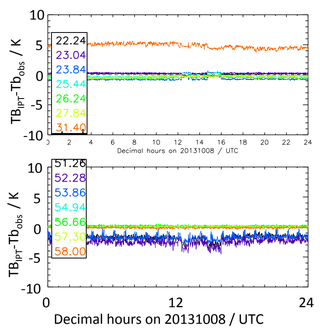


Figure 8. Time series of differences in simulated and observed TBs on Oct 8, 2013 at JOYCE. All MWR channels included.

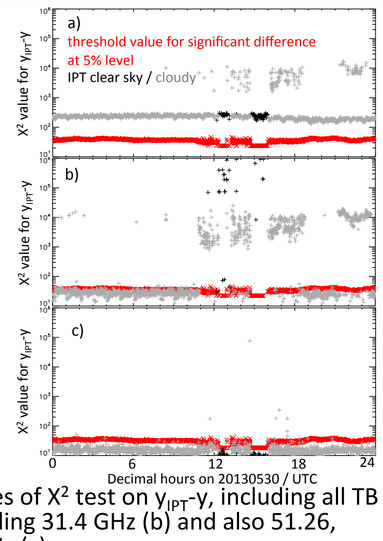


Figure 9. Time series of X^2 test on y_{IPT}-y, including all TB channels (a), excluding 31.4 GHz (b) and also 51.26, 52.28 and 53.86 GHz (c).

Identification of biased MWR TBs

- TBs of K- (22.24-31.4 GHz) and V-band (51.26-58.0 GHz) have typical clear-sky spectra (Fig. 10) → test if TB differences of two channels are in expected range

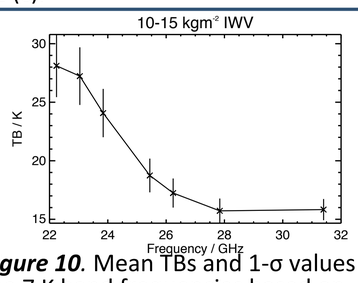


Figure 10. Mean TBs and 1-σ values of the 7 K band frequencies based on 7761 radiosonde forward calculations.

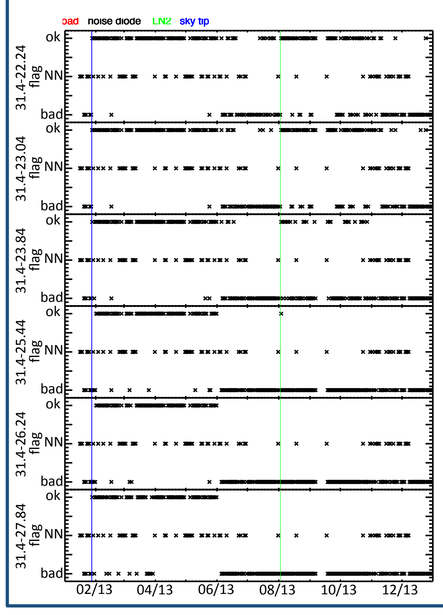


Figure 11. *Data flag of 31.4 GHz channel indicating if TB difference between 31.4 GHz and other freqeuency is within 2-σ*. Only days with at least 100 2-min clear sky cases are considered.

- 31.4 GHz: TB differences are not within *2*-σ starting from June 2013 (Fig. 11) → spectral inconsistency
- exclusion of 31.4 GHz improves retrieval performance (Fig. 9b)
- lowest 51.26-54.94 GHz channels show tendency not to be within 1-σ
- exclusion of 51.26-53.86 GHz can further stabilize retrieval (Fig. 9c)

5) IPT application at RAO

Data availability & impact of biased TBs

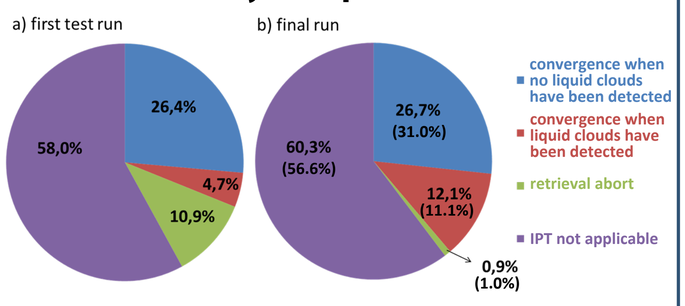


Figure 12. IPT data availablity for 2014 when all MWR frequencies are included (a) and when the most biased MWR channels in the V band (51.25, 52.28, 53.85 GHz) are excluded (b). Numbers given as percentage values with respect to the total number of 365*2880 possible profiles over the full year. Numbers in () for 2013.

- IPT data available 42% (2013) and 39% (2014) of time
- exclusion of likely biased channels significantly increases cloud case convergence rate from 4.7 to 12.1%
- in cases where IPT can be applied, convergence rate of 98%

Further quality checks

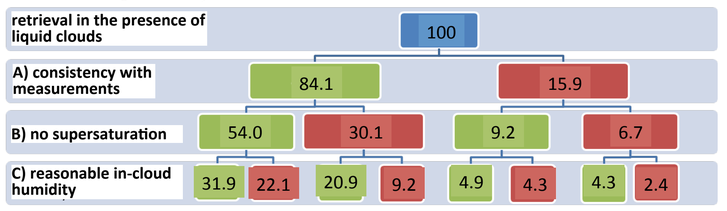


Figure 13. Data quality statistics of converged liquid cloud cases in 2013 (in %) regarding A) consistency with measurements (X^2 test on y_{IPT}-y), B) no unrealistic supersaturation in profile and C) realistic in-cloud humidity (RH > 95%). % values in green (red) boxes indicate good (bad) data.

- liquid cloud cases: results largely consistent with observations but often unrealistic supersaturation and too small in-cloud humidities → also due to lim. vertical information in T and q
- comparison to 282 radiosondes (2013):
  - 68.1% of X^2 tests on q_{IPT}-q_{sonde} passed
  - 31.9% of X^2 tests on T_{IPT}-T_{sonde} passed → too small retrieval uncertainties in T?
- comparison to IWV GPS (331,178 cases in 2013):
  - 80% of time IWV_{IPT} and IWV_{GPS} are within 2 kgm^{-2}

6) Conclusions & Outlook

- IPT performs very well in idealized conditions:
  - RMSE for LWC and REF ~20%
  - theoretical unc. for LWC and REF: 52 and 17%
  - physically consistent results
  - results sensitive to changes in TB noise but less to Z noise (due to relatively large forward model uncertainty in Z)
  - deviation of assumed DSD from true one may increase REF error up to 30%
- X^2 test on y_{IPT}-y essential quality check; also indicator for measurement problems
- bias free measurements crucial → detailed measurement analysis necessary
- applicability of IPT mainly limited by cloud conditions and instrument data availability
- reasonable agreement with independent data
- IPT data status at JOYCE & RAO: data for 2013 (also 2014 for RAO) currently processed and uploaded to data base soon