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Passive ground-based remote sensing using microwave radiometers

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ITALY

Contributions from:

Ed Westwater, Stick Ware, Steve Reising, Christian Matzler, Vinia Mattioli, Warren Wiscombe,...

Microwave radiometry in a nutshell

- Intro: why MW radiometry?
- Basic concepts
- From radiance to geophysical parameters
- Very brief history
- Typical applications
- Cutting-edge research
- Conclusions

Why microwave radiometers?

- Passive: natural emission of the atmosphere
- Robust and all-weather instruments
- Well-understood theory
- Accurate geophysical measurements
- Ready for Data Assimilation in NWP

Basic concepts of radiometry

- Measurement of thermal emission from:
  - Gases
    - in MW mainly oxygen and water vapor
  - Hydrometeors
    - in MW ice contribution is negligible
    - in MW scattering in negligible

- The measured quantity is Radiance (R)
  - Rd is converted to brightness temperature (Tb)
    - Planck's Law
  - Intuitive units [K]

- Tb are processed to estimate atmospheric variables
  - Ill-posed problem (solution in not unique/stable)
  - Need for a priori knowledge to constrain the solution
  - Variety of inversion methods
    - Regression
    - Neural Network
    - Optimal estimation
    - Variational (1DVAR)

Basic concepts of radiometry

- IR radiometry (wavelength ~4-15 μm):
  - High accuracy (ε_{Tb} ~ 0.1 K)
  - Clouds are opaque (unless very thin)
    - Clear sky: OK
    - Otherwise: information on cloud base

- MW radiometry (wavelength ~1 cm):
  - Good accuracy (ε_{Tb} ~ 0.3 K)
  - Can penetrate clouds
    - Liquid Water Path (LWP) estimates
  - Rain may be a problem
    - Mitigation solutions
      - hydrophobic coating, blowers
  - All weather

What can MW radiometers provide?

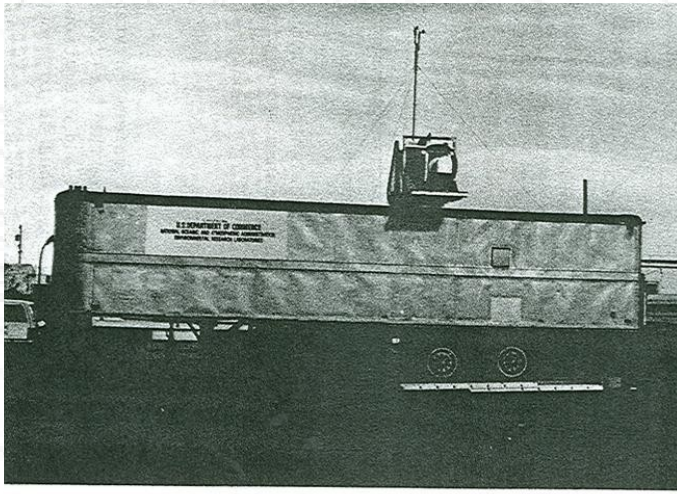
- Highly accurate measurements of integrated contents:
  - integrated water vapor (IWV)
  - liquid water path (LWP)

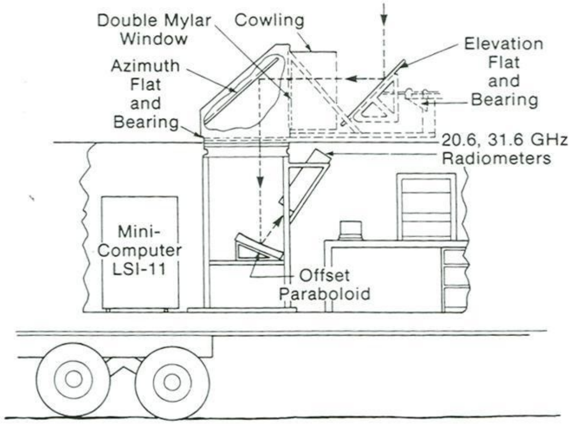
- Low resolution vertical profiles:
  - temperature profiles
    - higher resolution in the PBL
  - water vapor density profiles
  - liquid water content profiles (controversial)

- Measurements are ideal for:
  - data assimilation
  - combination with active instruments (radar/lidar)

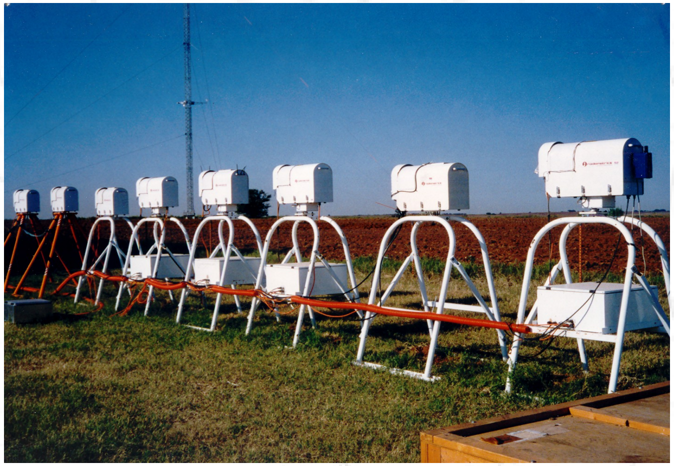
Very Brief History

- First experiments in 1960s





- Commercial units in 1980s



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In summary

- GB MW radiometry is a mature technique:
  - More than 40 years of experiments
  - More than 10 years of operational observations

- Commercial off-the-shelf units:
  - Specs:
    - 1-35 channels
    - 20-60 GHz range (λ~0.5-1 cm)
    - Azimuth and zenith scanning
  - Products:
    - IWV, LWP
    - T(z), WV(z), LW(z)
  - Reduced (competion-induced) cost:
    - ~100-150 keuro

Atmospheric Microwave Emission

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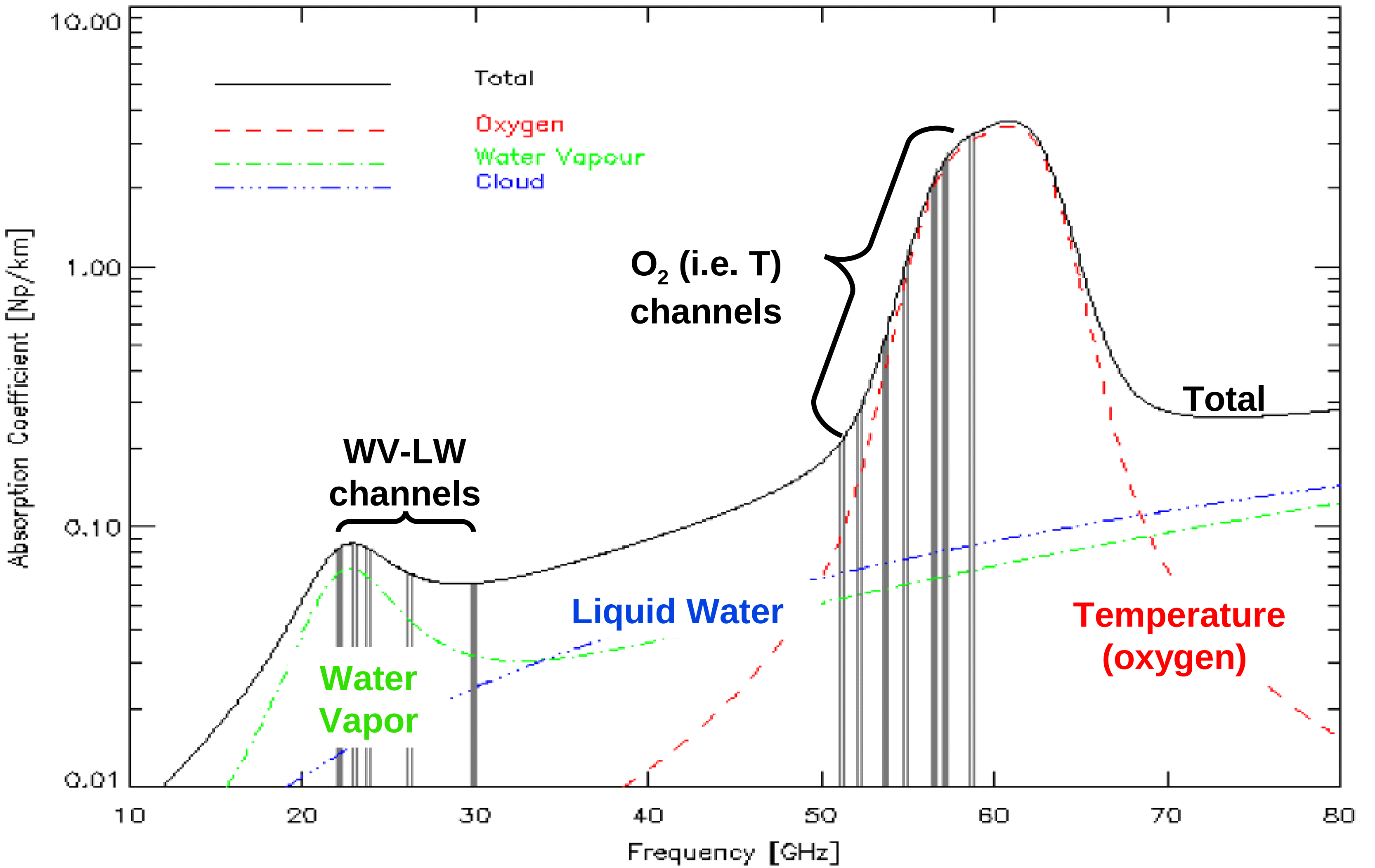

Applications

- Established applications
  - IWV and LWP
    - Absorption model and wave propagation studies
    - Radiosonde validation and correction (dry bias)
    - Climatology
  - T(z), WV(z), LW(z)
    - Meteo
      - Nowcasting
      - NWP Data Assimilation
    - Aviation support
      - icing detection
      - convection

NWP requirements

Table 1-1 User requirements of temperature and humidity profiles for Regional NWP – minimum, breakthrough and maximum thresholds

NWP Regional	Temperature (K) Boundary Layer			Temperature (K) Lower Troposphere			Relative Humidity (%) Lower Troposphere			Integrated Water Vapour (kg/m^2)		
	Min.	Brk.	Max.	Min.	Brk.	Max.	Min.	Brk.	Max.	Min.	Brk.	Max.
Accuracy	1.5		0.5	1.5		0.5	10		5	5		1
Vertical Resolution (km)	0.5	0.3	0.01	2	1	0.1	2	1	0.1	N/A	N/A	N/A
Horizontal Resolution (km)	50	10	1	200	30	3	200	30	3	100		10
Observing Cycle (hr)	3	1	0.166	12	3	0.5	12	3	0.5	1		0.5
Delay in Availability (hr)	3		0.083	5		0.25	5		0.25	0.5		0.1

[After Hewison, 2006]

MW radiometer profiler performances

- Multi channels
  - 20-24 GHz - several channels for IWV and WV(z) sensing
  - 24-34 GHz - several channels for LWP and LW(z) sensing
  - 50-60 GHz - several channels for T(z) sensing

Radiometer-radiosonde statistics

- Accuracy
  - ~ 0.3 K in Tb
  - ~ 1.0 mm in IWV
  - ~ 0.02 mm in LWP
  - ~ 0.5-2.0 K in T(z)
  - ~ 0.2-1.0 g/m^3 in WV(z)

radiosonde representativeness error

[After Güldner and Spänkuch, JAOT, 2003

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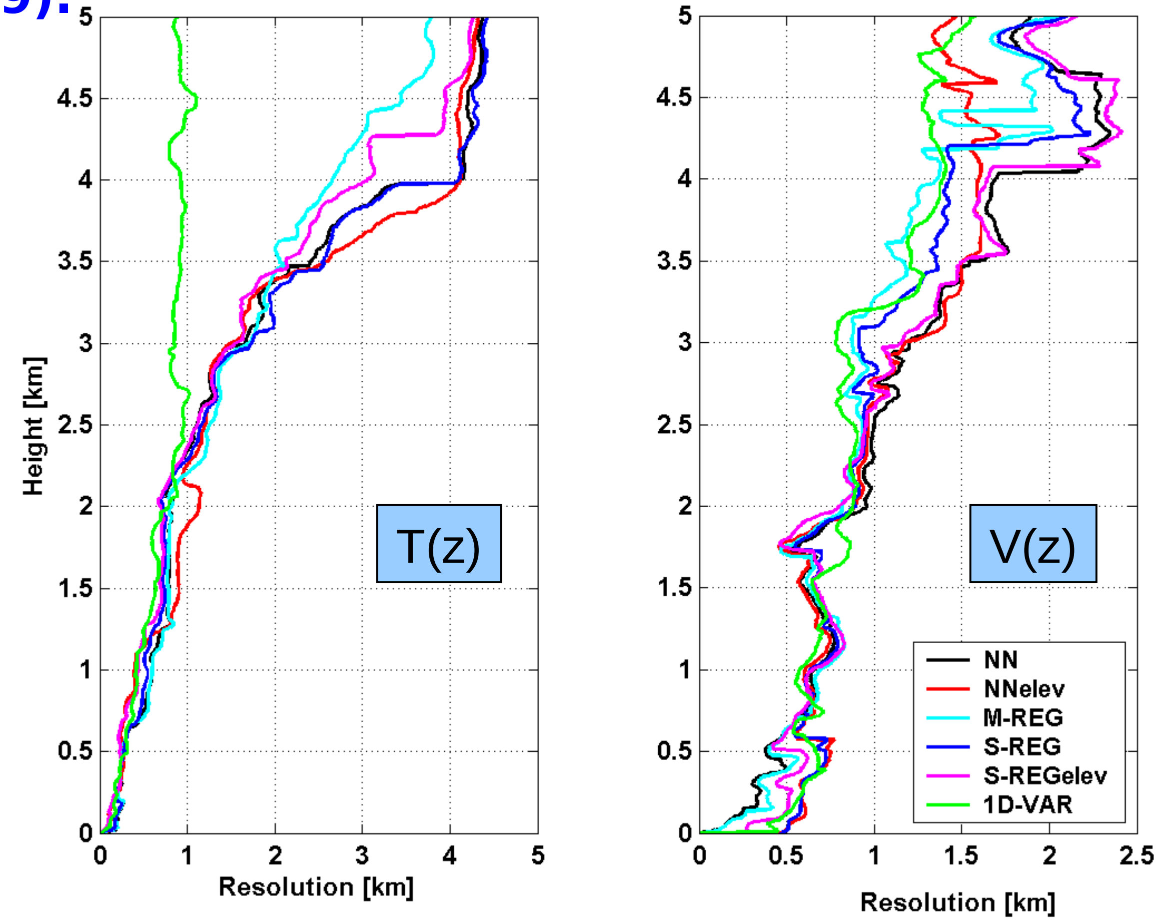
MW radiometer profiler performances

Vertical resolution
("inter-level error covariance method" (Smith et al., 1999).



COST720 Temperature, hUmidity and Cloud profiling (TUC) Campaign Payerne (CH)

[Cimini et al., 2006]

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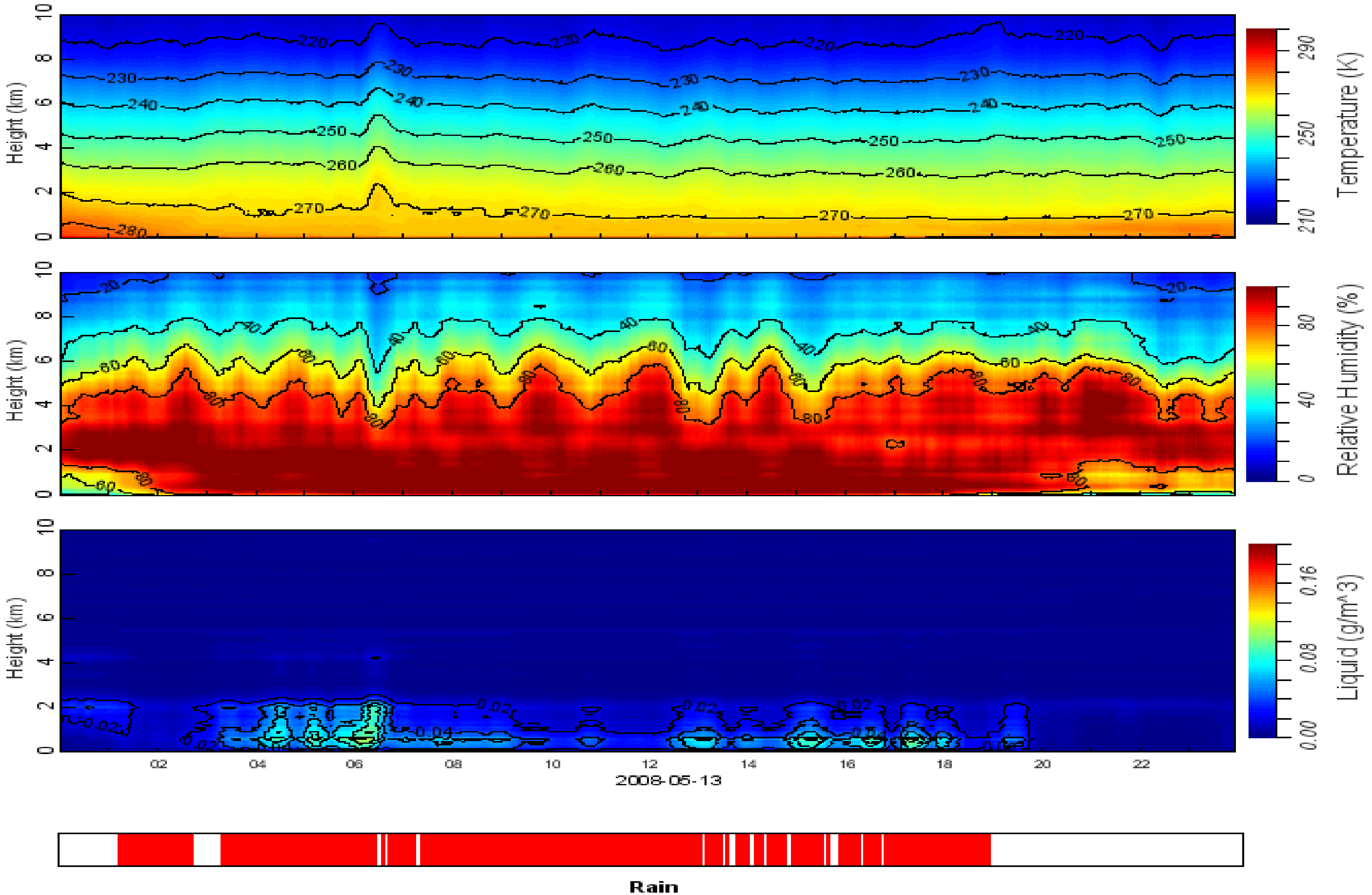
Continuous profiling (24/7)



13 May 2008 rainstorm at Boulder, Colorado.

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Azimuth and elevation scanning

ASMUWARA

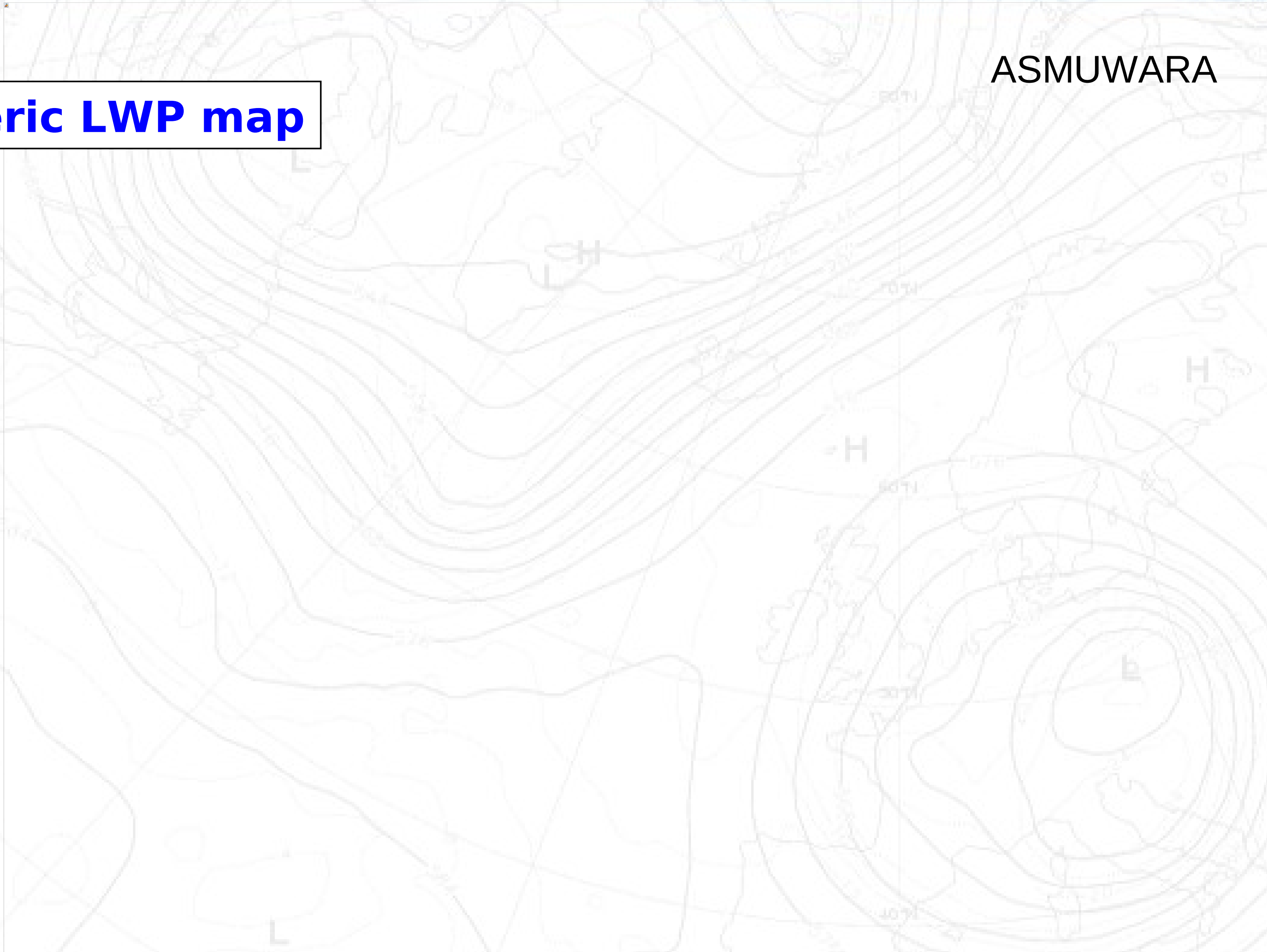
Hemispheric IWV map

[After Martin et al. 2003]

Azimuth and elevation scanning

Hemispheric LWP map

ASMUWARA



[After Martin et al. 2003]

What is the value of MWR profiler for meteorology and NWP ?

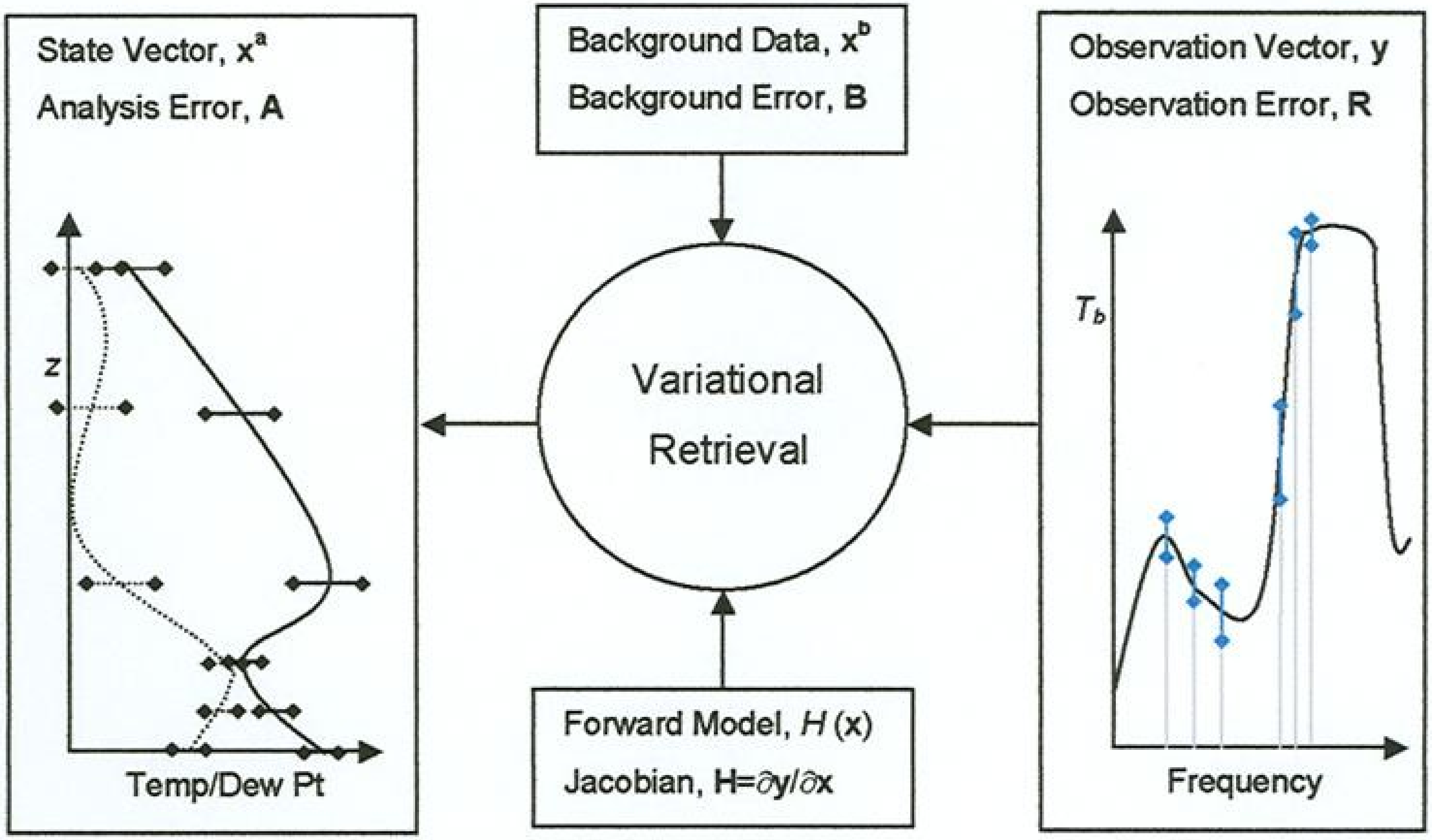
- Short term forecast skill may be poor due to a lack of timely data, particularly in the lower troposphere where severe weather originates
- Timely, accurate atmospheric temperature and humidity data are readily available from MW profilers, providing automated upper air observations without human intervention (unattended)
- Fresh radiometer data can feed weather forecast tools and indices developed for radiosondes
- Cloud liquid profile data are also readily available. Liquid profiles are needed to identify opportunity for weather modification and to monitor and forecast visibility and aircraft icing hazard (such as fog).

Applications

- On-going research
  - 1DVAR and Data Assimilation
    - 1DVAR retrievals have been recently demonstrated for ground-based MW radiometers
  - 3D Tomography
    - Tomographic approach is being demonstrated for WV(z) and LW(z)
  - Low IWV and LWP sensing
    - Use of millimeter and submillimeter wavelengths

1-Dimention Variational Retrieval (1DVAR)

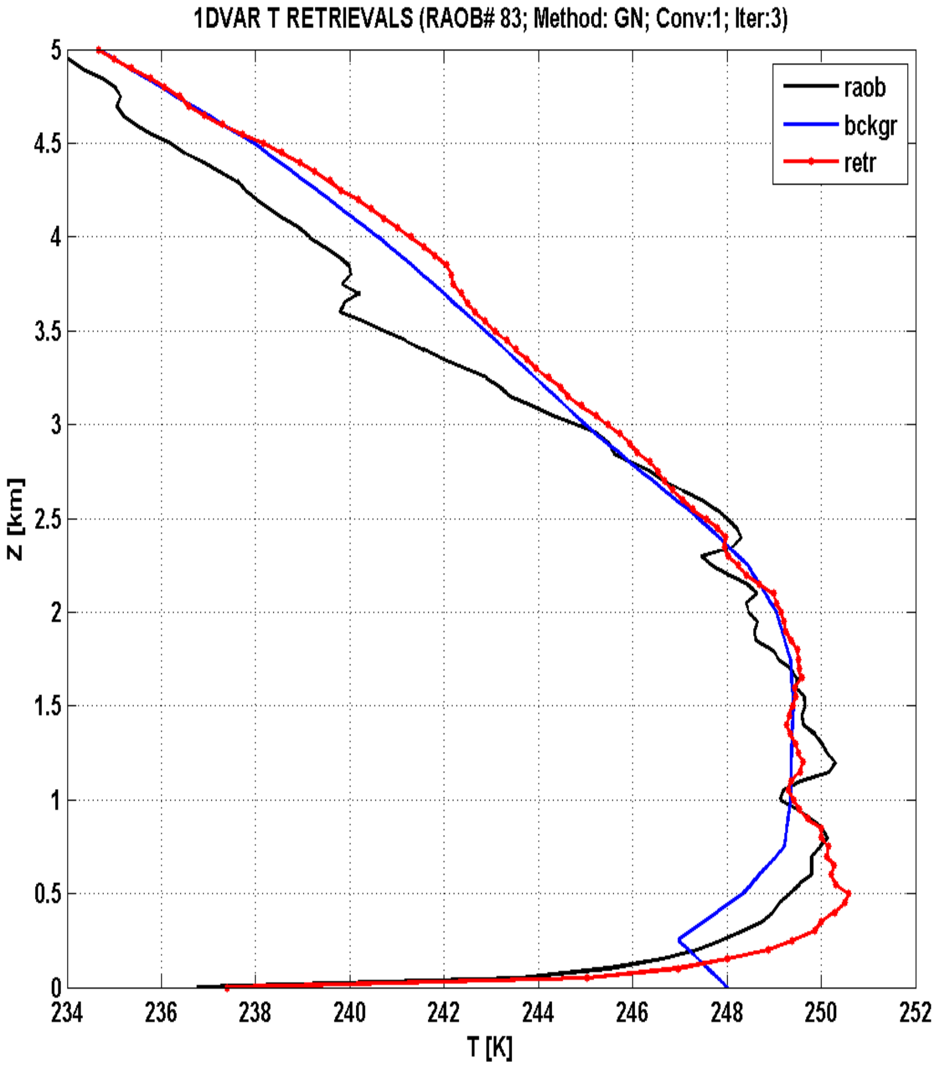
[After Hewison, 2006]



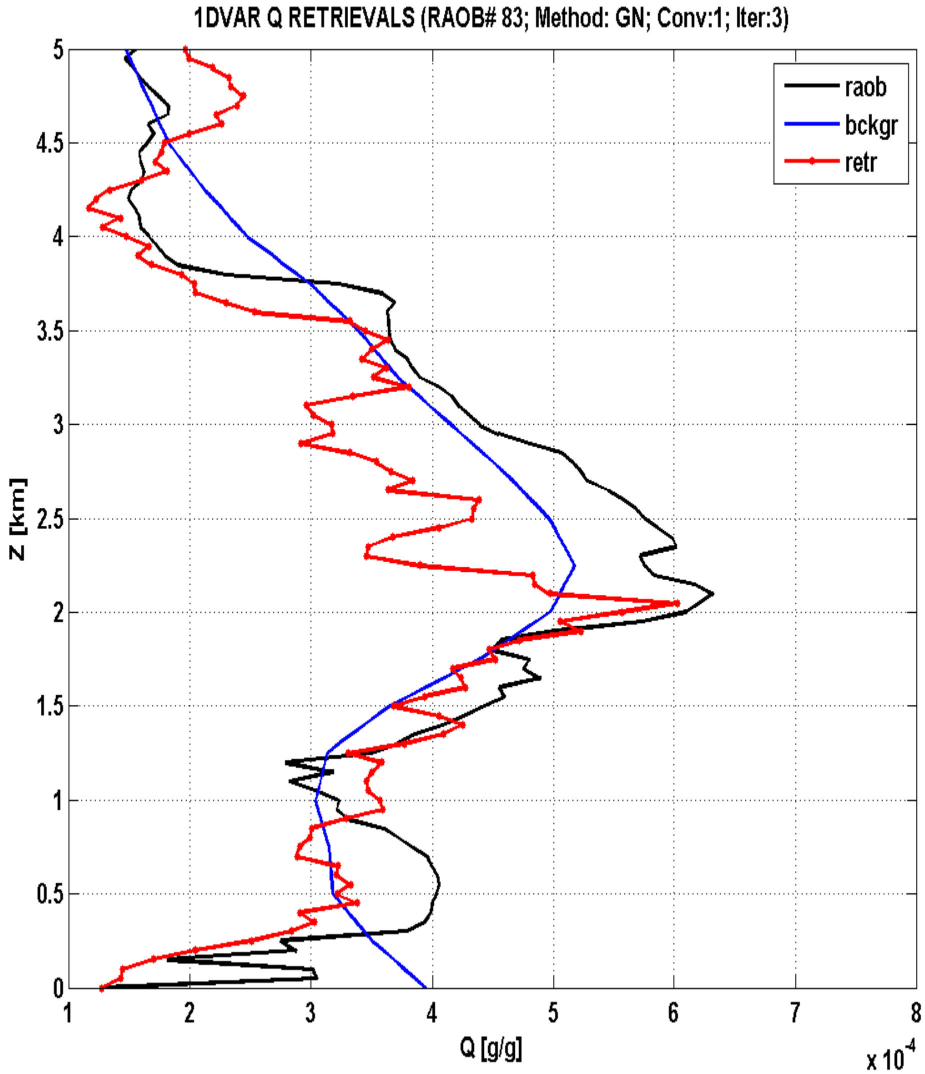
- 1DVAR retrievals have been recently demonstrated for ground-based MW radiometers
  - Hewison 2007, Lonhert et al. 2008, Cimini et al. 2009

Examples of 1DVAR Retrievals during RHUBC

T(K)



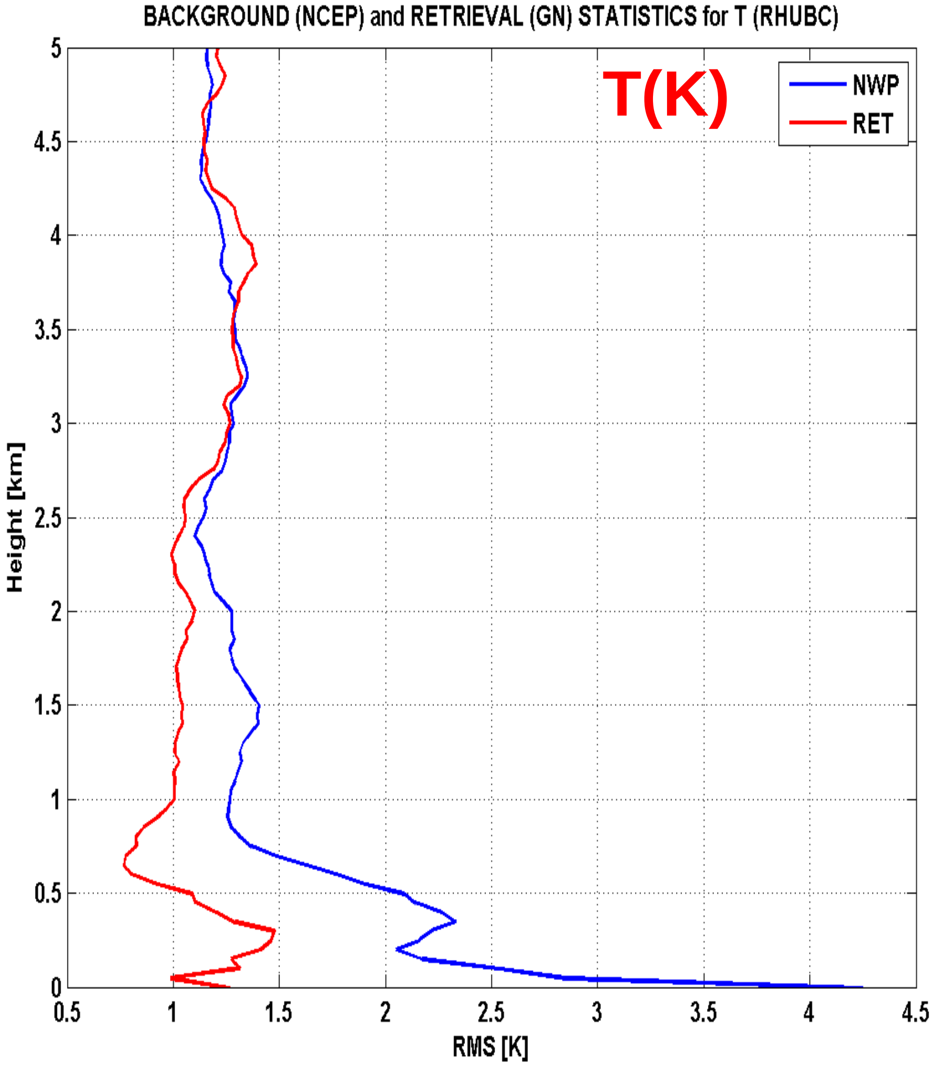
Q(g/g)

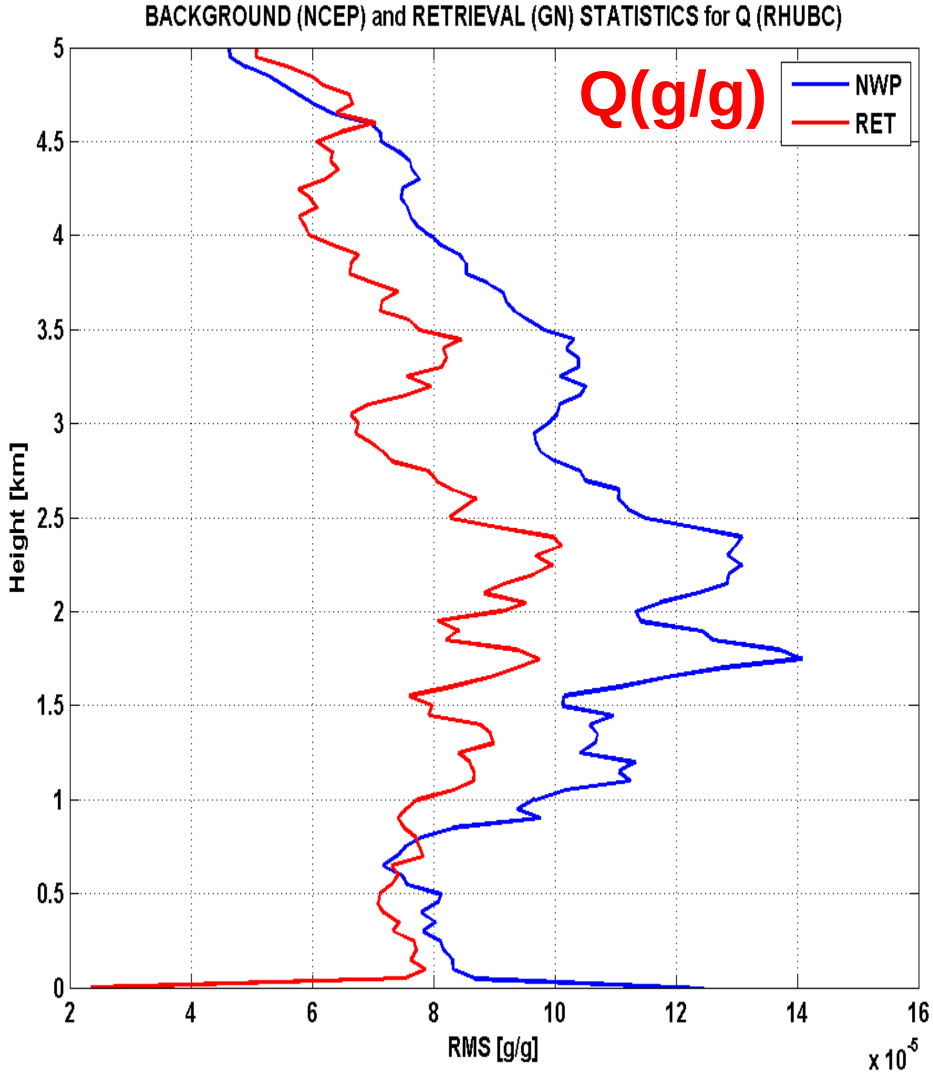


Statistics of 1D-VAR Retrievals during RHUBC

Convergence: 100% (T) and 98% (Q)

Consistency: 98% (T) and 60% (Q)



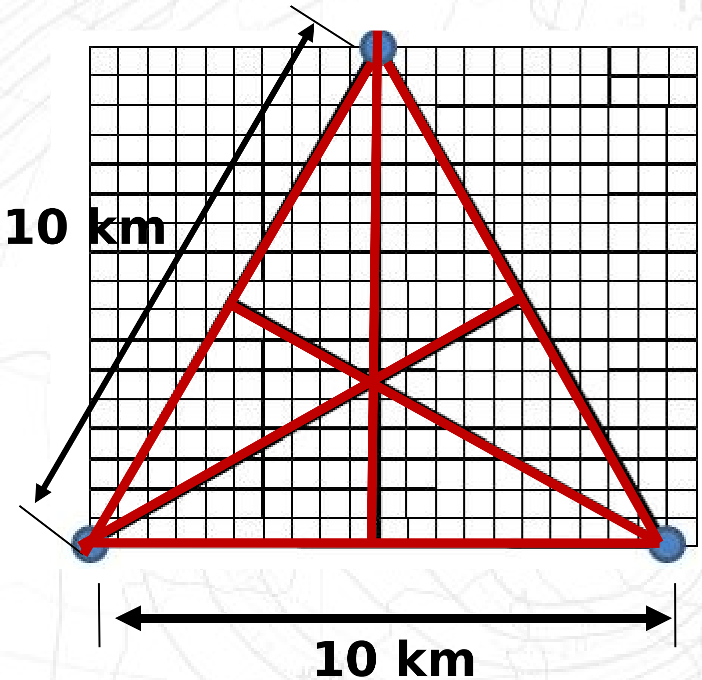


1-Dimention Variational Retrieval (1DVAR)

- Statistics of 1D-VAR retrievals show that this technique outperforms other retrieval methods
- The method is totally flexible and suitable for data assimilation in NWP models
- Observations are now ready to be assimilated into NWP

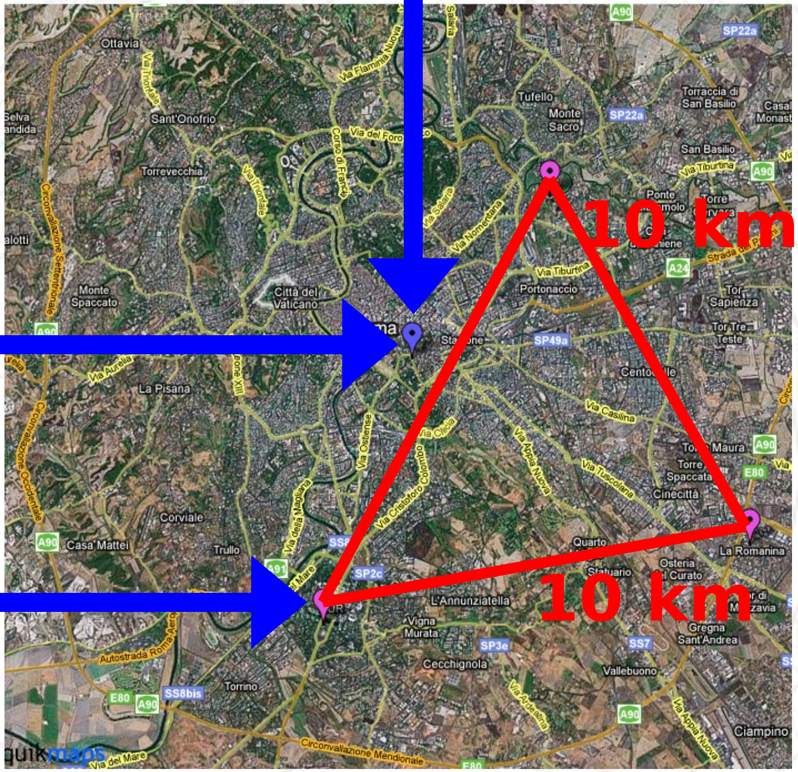
3-D WV tomography

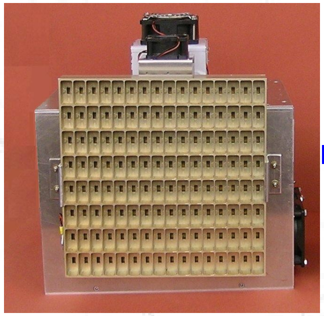
- Contribution from Microwave Systems Laboratory - Colorado State University (CSU), Fort Collins, CO
- 3-D Water Vapor retrieval (2D map + profile) using a network of 3 scanning Compact Microwave Radiometers (CMR)



Experimental Setup (Rome, Sept-Oct 2008)

- Three CMR in a 10 km triangle
- One 2-channel MWR
- Radiosondes
- High resolution NWP (1 km)

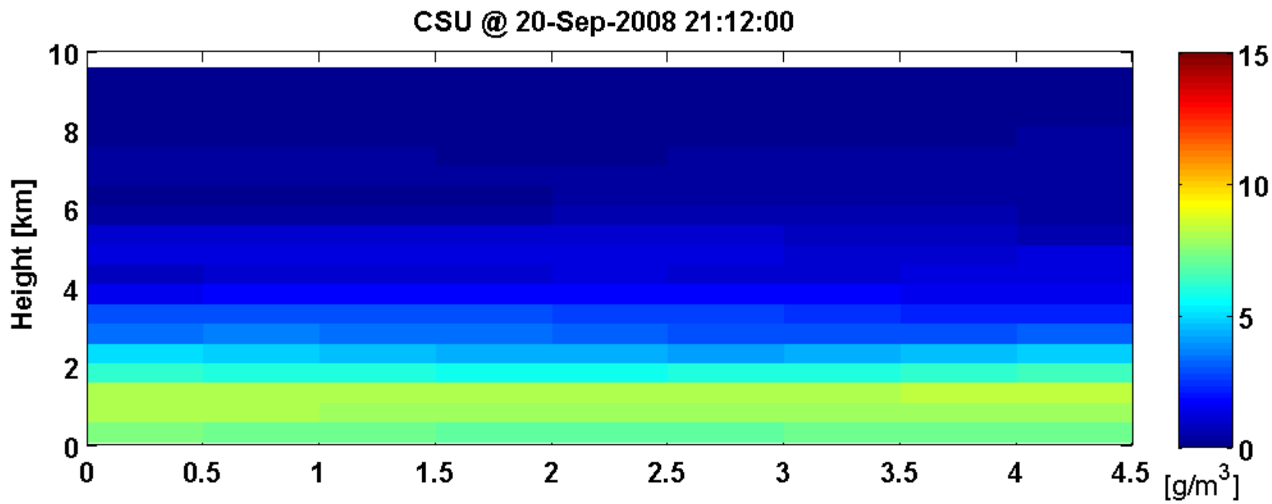




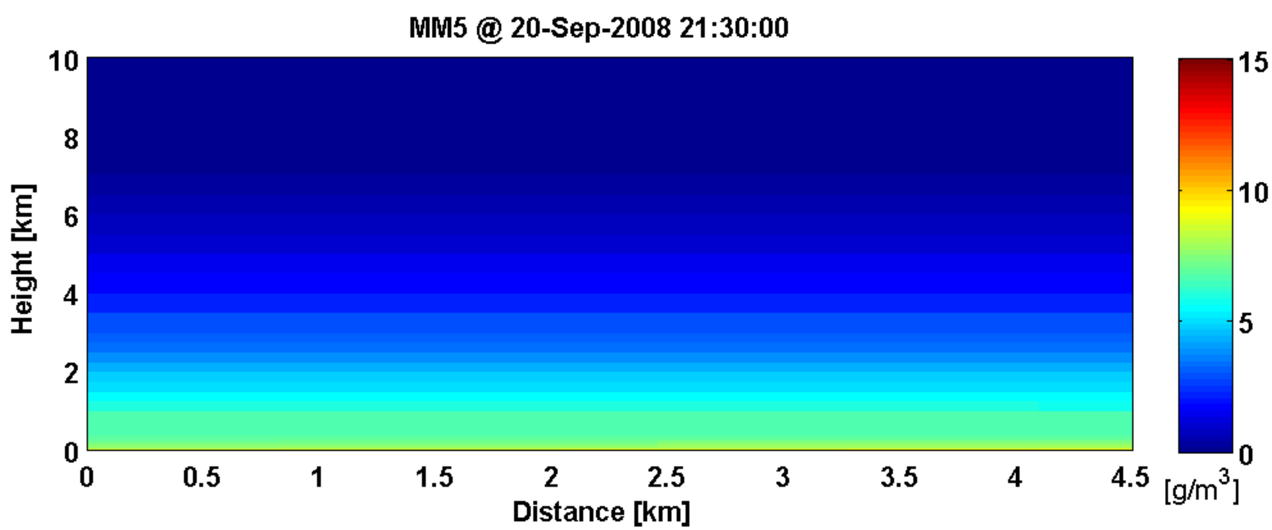
Preliminary Comparison with NWP

Water Vapor density profiles [g/m³] @ 20 Sep 21:30

- CMR



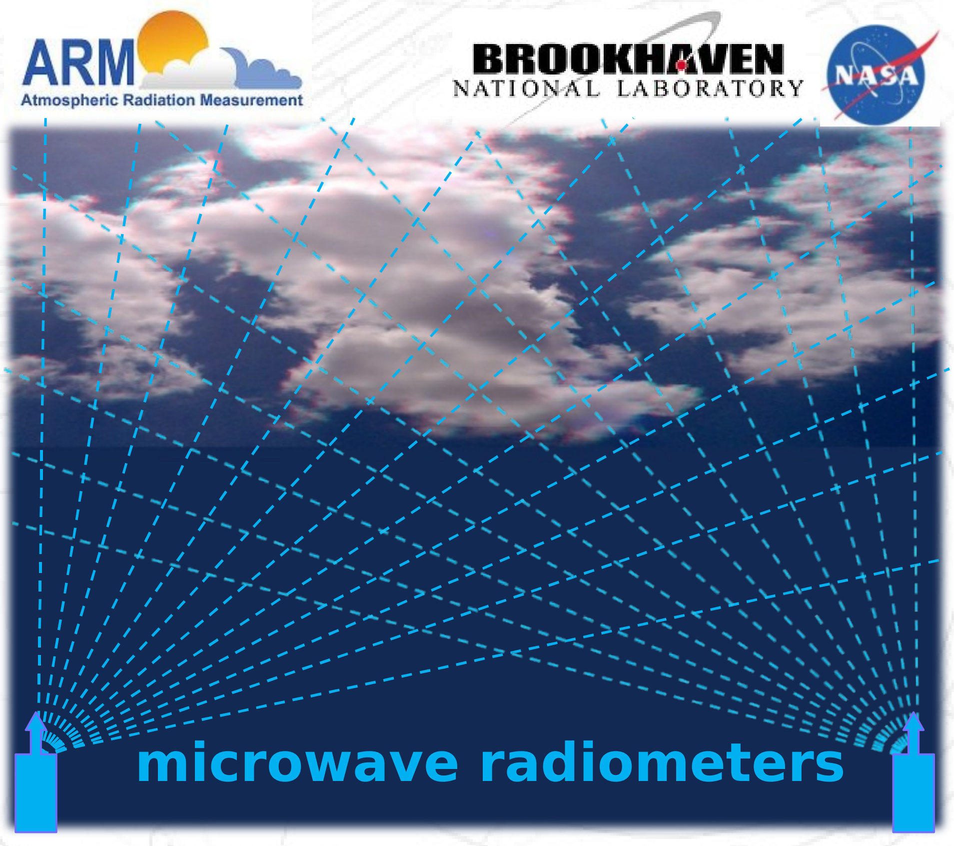
- MM5



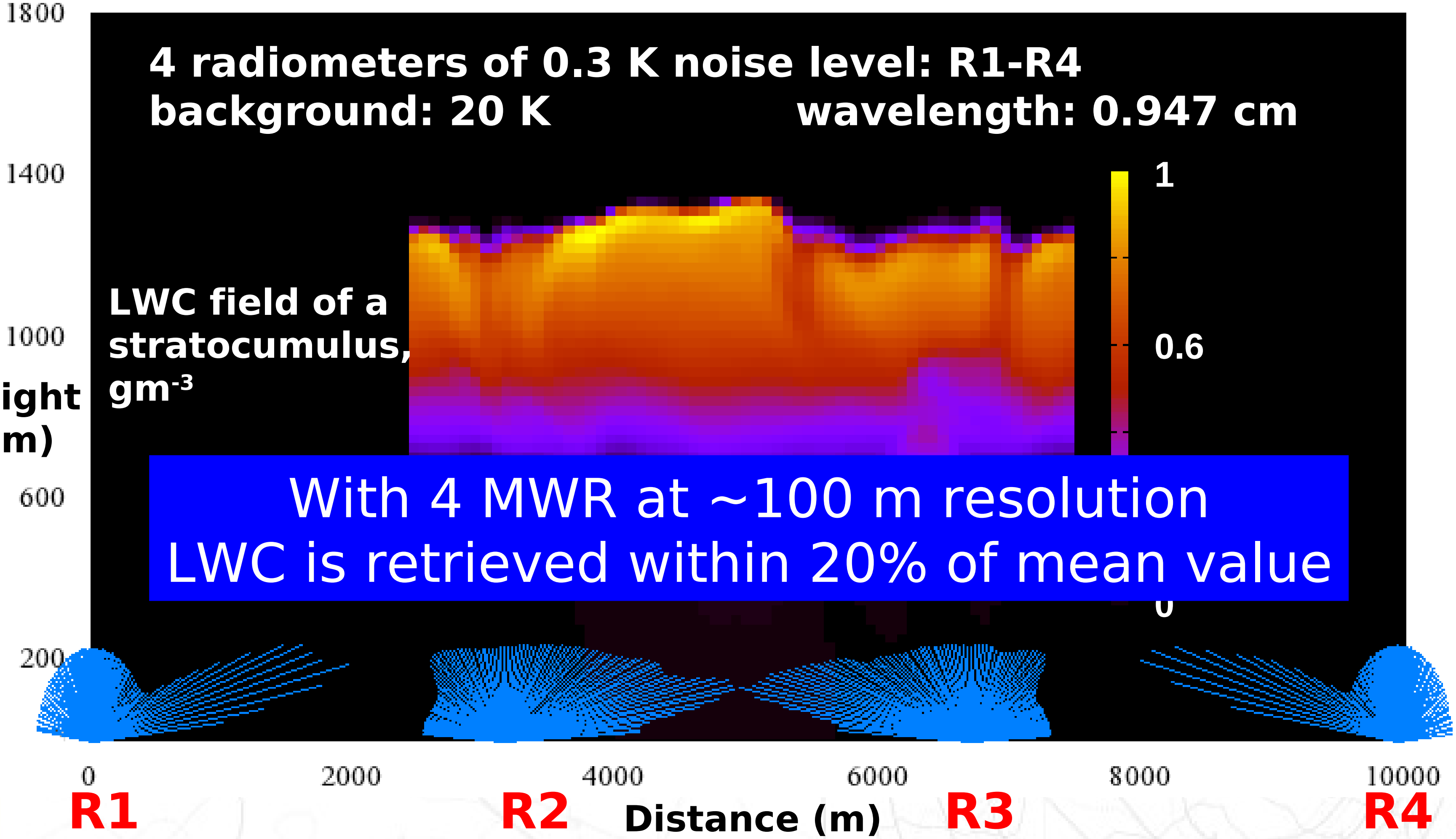
3-D Cloud Tomography

- Contribution from Atmospheric Radiation Measurement (ARM) Program scientists (Huang, Liu, and Wiscombe)

- Analysis on synthetic simulated data



3-D Cloud Tomography (synthetic data)



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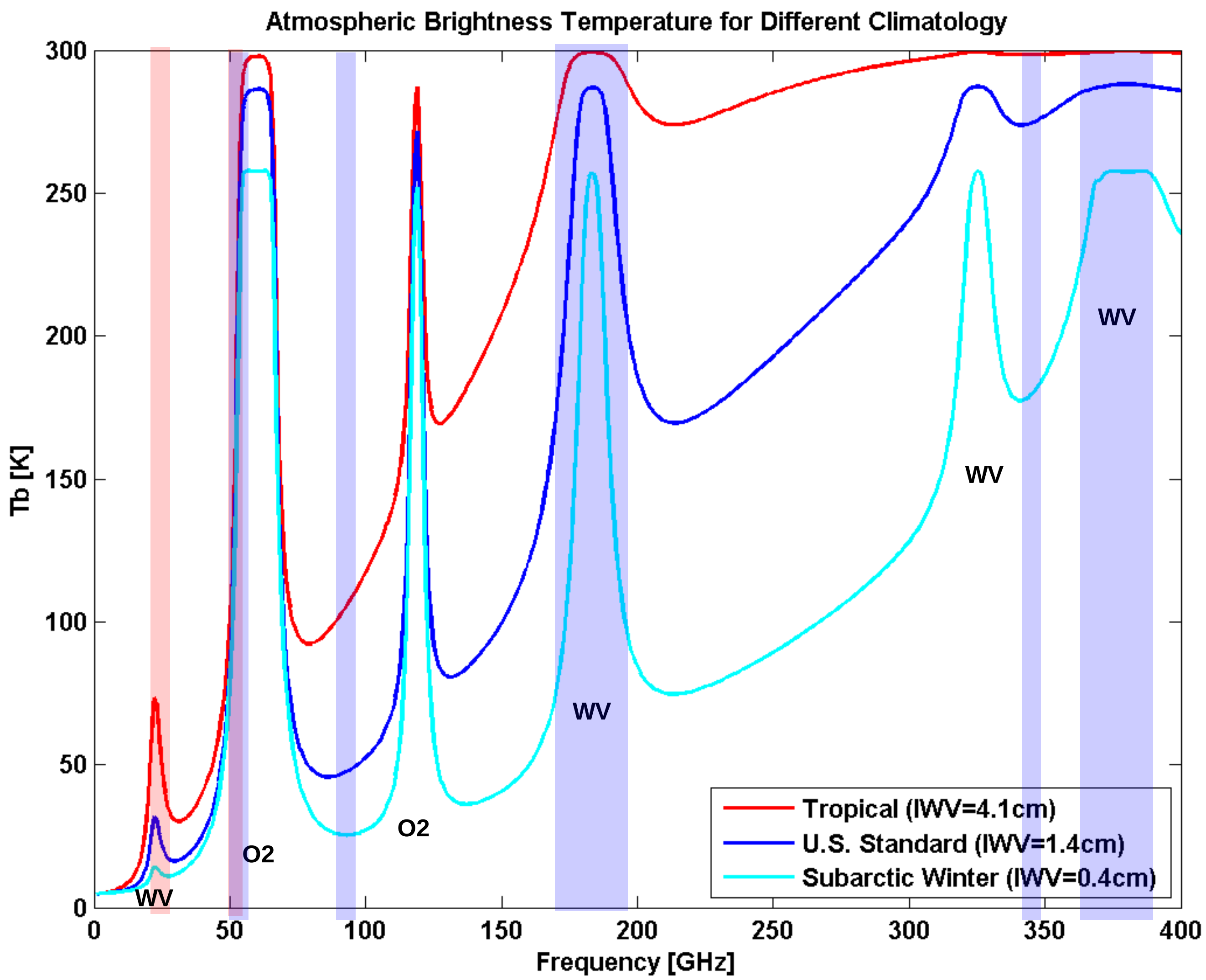
Measuring low IWV and LWP

- Accurate measurements of low amounts of IWV and LWP are important
  - High occurrence
    - specially in polar and elevated regions
  - Large errors in radiative impact

- Conventional MWR show little sensitivity to low amounts of IWV and LWP
  - IWV < 5 mm
  - LWP < 0.05 mm

- Millimeter-wave (higher freq) radiometry offer enhanced sensitivity
  - Appealing for deployment in polar and elevated site

Atmospheric emission (Tb) in MW-MMW



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Tb response to IWV during clear-sky

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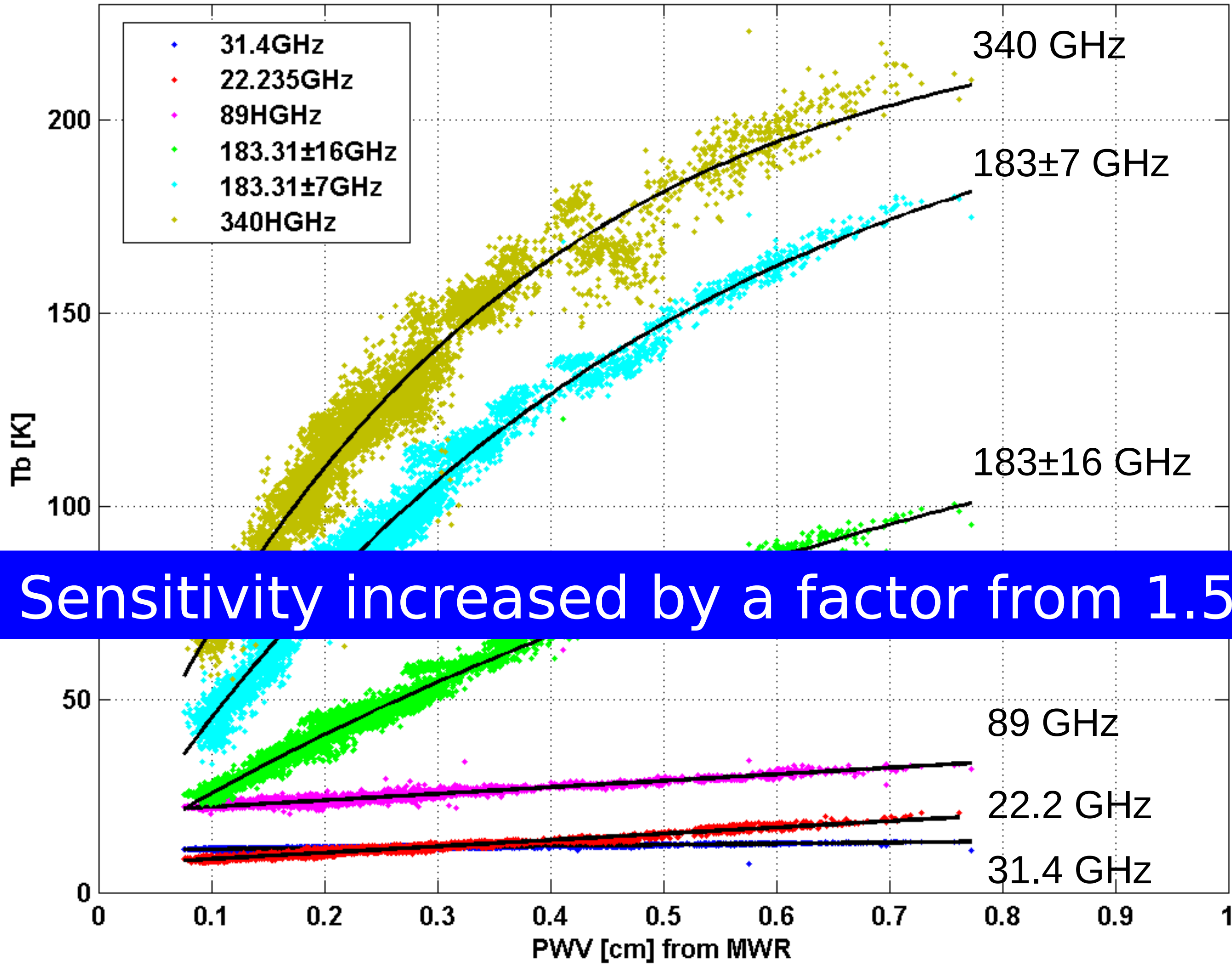

IWV Sensitivity increased by a factor from 1.5 to 33

[Cimini et al., 2007a; 2007b]

Tb response to LWP during cloudy sky

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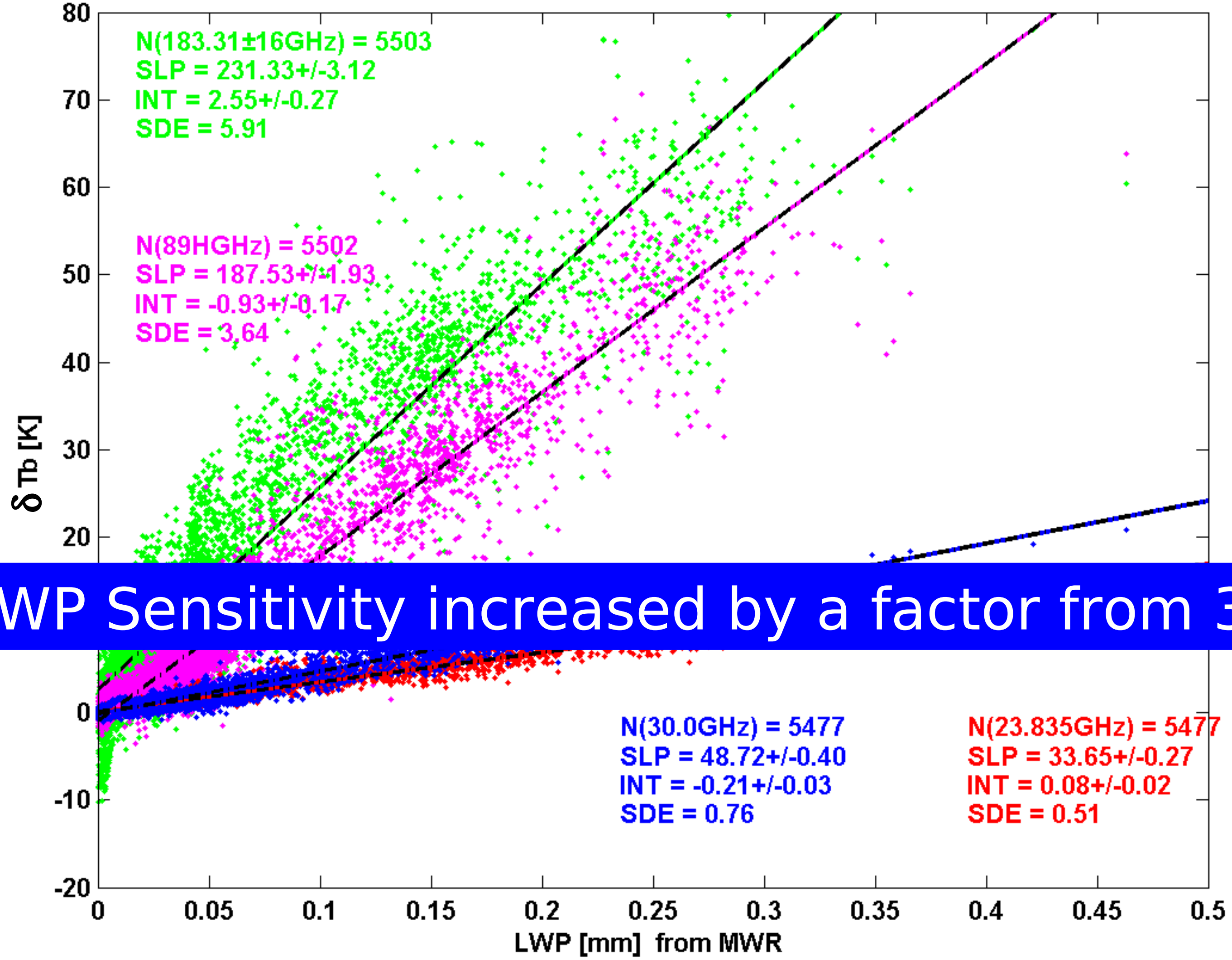
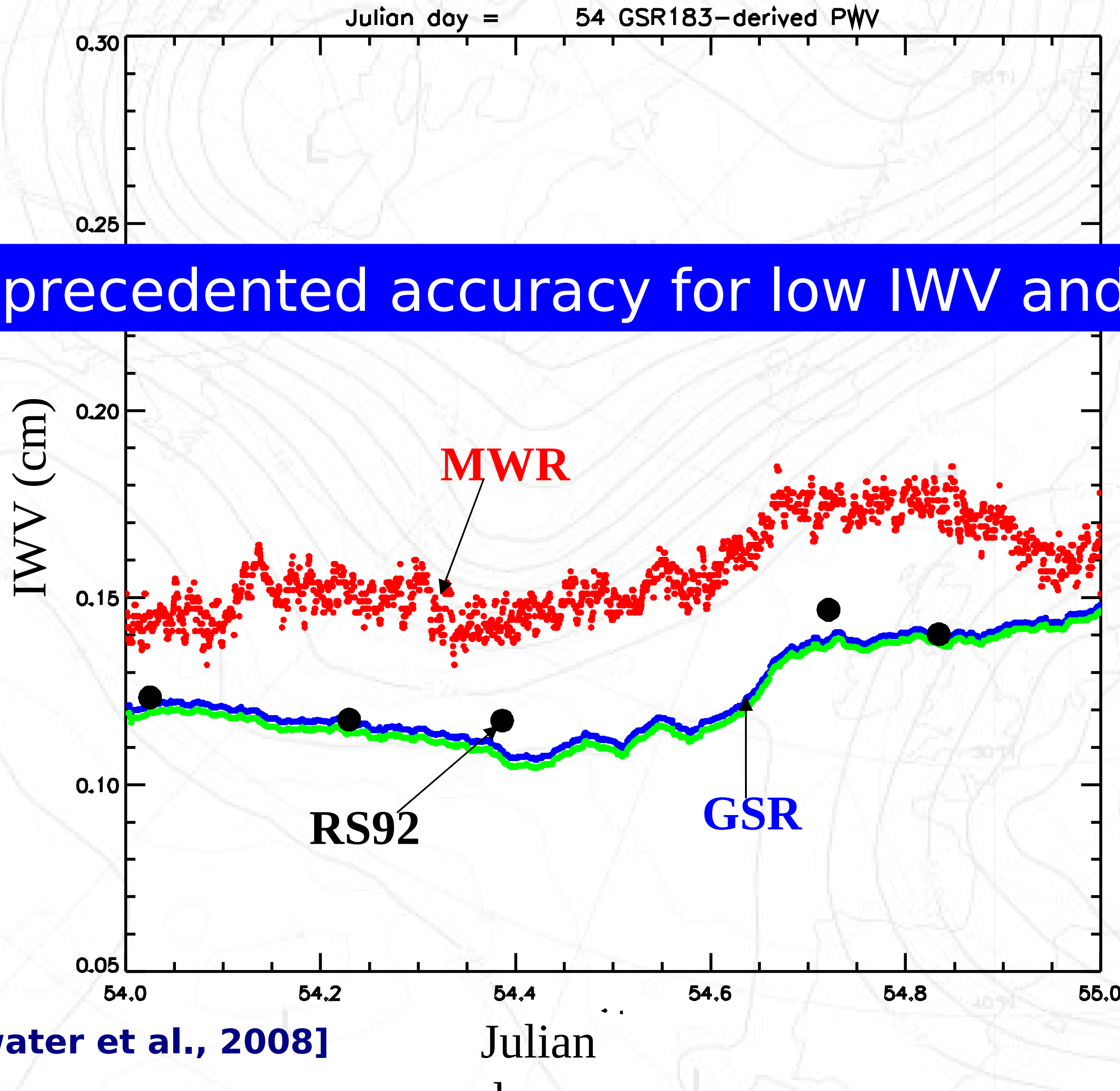


LWP Sensitivity increased by a factor from 3 to 4

[Cimini et al., 2007a; 2007b]

Comparison of MW and MMW retrieval of IWV



Unprecedented accuracy for low IWV and LWP

[Westwater et al., 2008]

Integration with other instruments

Instrument integration is promising for enhancing the strengths
and overcome the limitations of each single instrument

- MWR + LIDAR
  - Accurate WV profiles (Han et al.)
- MWR + Wind Profiler Radar
  - WV vertical gradients (Bianco et al.)
  - Enhanced WV vertical resolution (Klaus et al.)
- MWR + IR interferometer
  - Low IWV and LWP retrievals (Turner et al.)
- MWR + Cloud Radar + Ceilometer + …
  - NWP validation (Illingworth and CLOUDNET team)
  - Optimal Integration (IPT, Lohnert et al.)

Summary and Conclusions

- MW radiometry is a mature technique
- Commercial units are available at reasonable price
- Observations are ready for Data Assimilation in NWP
- On-going research
  - Data assimilition in NWP
  - Wapour and cloud tomography
  - mm-wave for polar research

Thank you very much for your attention!

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Back up slides

Representativeness error

4.4.1.3 Representativeness Error

"In objective analysis the desired resolution determines a scale, which may be described by saying a grid-point value represents an average in space and time. It is usual to define the analysis and background errors as deviations from the truth also truncated to this scale. Thus it is possible to conceive a 'perfect' analysis or background, even though they do no represent all atmospheric scales. To compensate for this it is usual to add errors of representativeness to the instrumental errors to get a larger observational error. It is important to realize that these errors are as much a function of background representativeness as the observational representativeness; they can be considered explicitly as the errors in the generalized interpolation from background to observations." [Lorenc, 1986]

MWR profiler performances

Radiometer-radiosonde statistics (red and blue) and radiosonde representativeness error (gray)

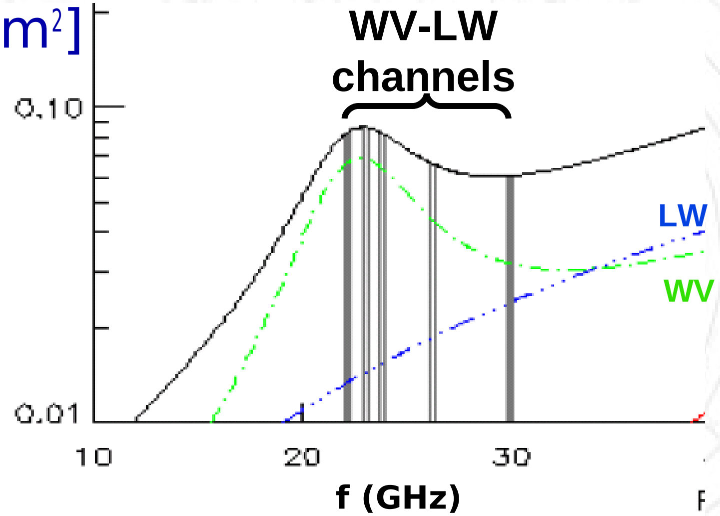
[Güldner and Spänkuch, 2003; Ware et al., 2003]

IWV-LWP MW radiometers

- Two-three channels
  - 20-24 GHz for IWV sensing
  - 30-34 GHz for LWP sensing

- Many units deployed in the world
  - Some operational since more than 10 years

- Accuracy
  - ~ 0.3 K in Tb
  - ~ 1.0 mm in IWV [mm = kg/m^2]
  - ~ 0.02 mm in LWP



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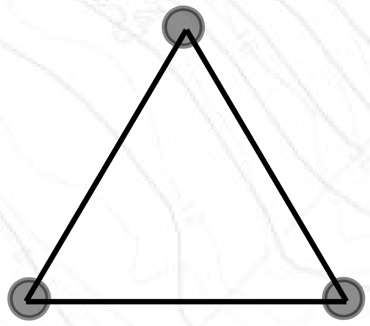
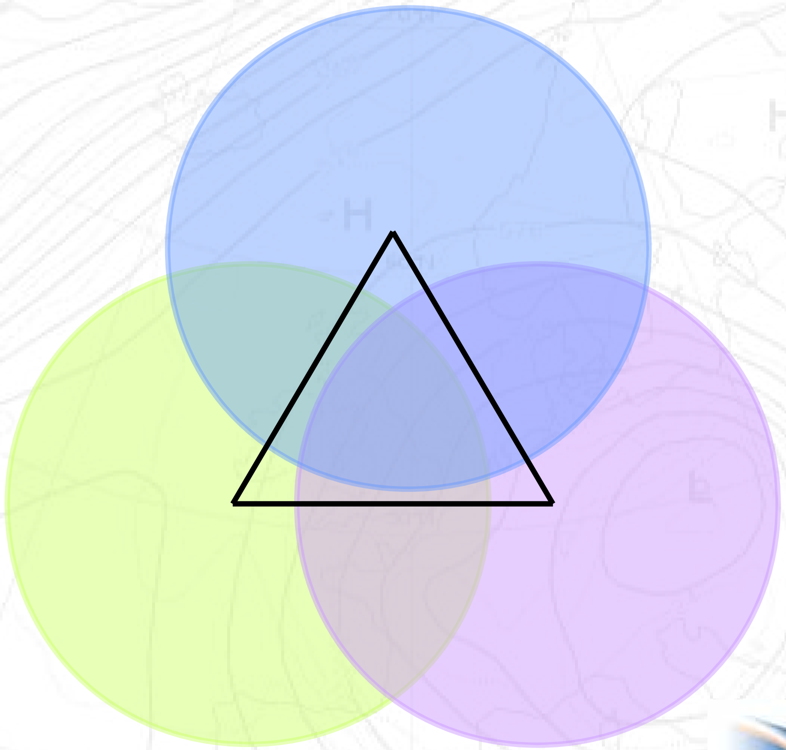
Area covered by Scanning and Zenith Pointing MWRs

Areas of coverage at 7 km above ground level (below which 95% of IWV exists)

Zenith Pointing Radiometers (6° Beamwidth)



Scanning Radiometers from 0° to 55° Zenith Angle



3-D Water Vapor Density Forward Model

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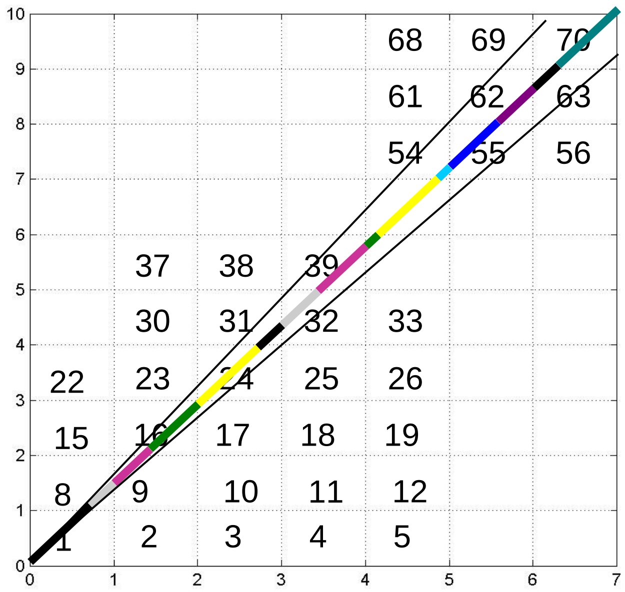
- Forward Model consists of a linearized Radiative Transfer Equation modified for a 3-D grid. [*Rodgers*, 2000; *Hewison*, 2007; *Cimini et al.*, 2006]

$$T_{Bi} = T_C e^{-\sum_{j=1}^{M} k_{abs\_j} \Delta r_{ij}} + \sum_{j=1}^{M} k_{abs\_j} T_j e^{-\tau_{ij}} \Delta r_{ij}$$

- Jacobian [*Bosisio and Drufuca*, 2003] G matrix elements were calculated as



$$T_{Bi} - T_{B\,ref\,i} = G(K - K_{ref})$$

$$g_{ij} = \left.\frac{\partial(\Delta T_{Bi})}{\partial(\Delta k_j)}\right|_{K=K_{ref}}$$

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Inversion of Brightness Temperatures

Inversion of water vapor density absorption coefficient, ΔK_{abs}, from brightness temperature measurements, ΔT_A:

$$\Delta \mathbf{T_A} = G \cdot \Delta \mathbf{K}_{abs}$$

$$\begin{pmatrix} \Delta T_{A1} \\ \vdots \\ \Delta T_{Ai} \end{pmatrix} = \begin{pmatrix} g_{11} & \cdots & g_{1j} \\ \vdots & & \vdots \\ g_{i1} & \cdots & g_{ij} \end{pmatrix} \begin{pmatrix} \Delta K_{abs1} \\ \vdots \\ \Delta K_{absj} \end{pmatrix}$$

i: Number of elevation angle

j: Number of grid cells

The solution is underconstrained if i < j (measurements are discrete, but ΔK_{abs} is continuous) . Consequently there is not a unique solution:

$$\Delta \mathbf{K}_{abs} = G^{-1} \Delta \mathbf{T_A}$$

3-D Water Vapor Density Retrieval

Kalman Filter Optimal Estimator

- Algebraic tomographic reconstruction of 3-D absorption coefficients for each measurement frequency using Optimal Estimation and Kalman filtering.

$$\Delta K = \Delta K_{a-priori} + S^{-1}_{\Delta K_{a-priori}} G^T (G S_{\Delta K_{a-priori}} G^T + S_{\Delta T_B})^{-1} [\Delta T_B - G \Delta K_{a-priori}]$$

3-D water vapor density field is obtained by fitting a Van-Vleck Weisskopf line shape to the K_{abs} retrieved at the four measurement frequencies [*Rosenkranz*, 2006; *Liljegren*, 2005].

- Kriging at unsampled locations based on spatial correlation statistics of water vapor densities [*Webster and Oliver*, 2001].

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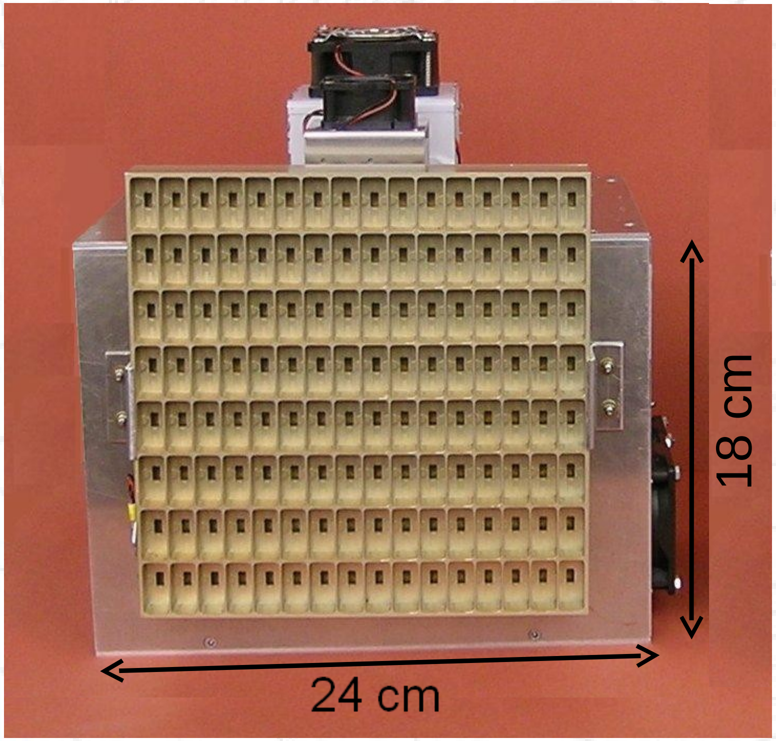
Compact Microwave Radiometer for Humidity Profiling (CMR-H)



CMR-H is a water vapor MWR:
- low-mass
- low-volume
- low-power consumption
- low-cost

Four channels near the 22.235 GHz line, selected for optimal retrieval of the water vapor profile

Mass (kg)	Dimensions (cm)	Power (W)	Beamwidth (deg)	Temp. Stability (°C)
6	24 x 18 x 16	50	3-4	0.1

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3-D WV tomography

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- Contribution from Microwave Systems Laboratory - Colorado State University (CSU), Fort Collins, CO

- 3-D Water Vapor retrieval (2D map + profile) using a network of 3 scanning Compact Microwave Radiometers (CMR)

CMR-H is a water vapor MWR:
- low-mass
- low-volume
- low-power consumption
- low-cost

4 channels near the 22.235 GHz line

3-D WV tomography

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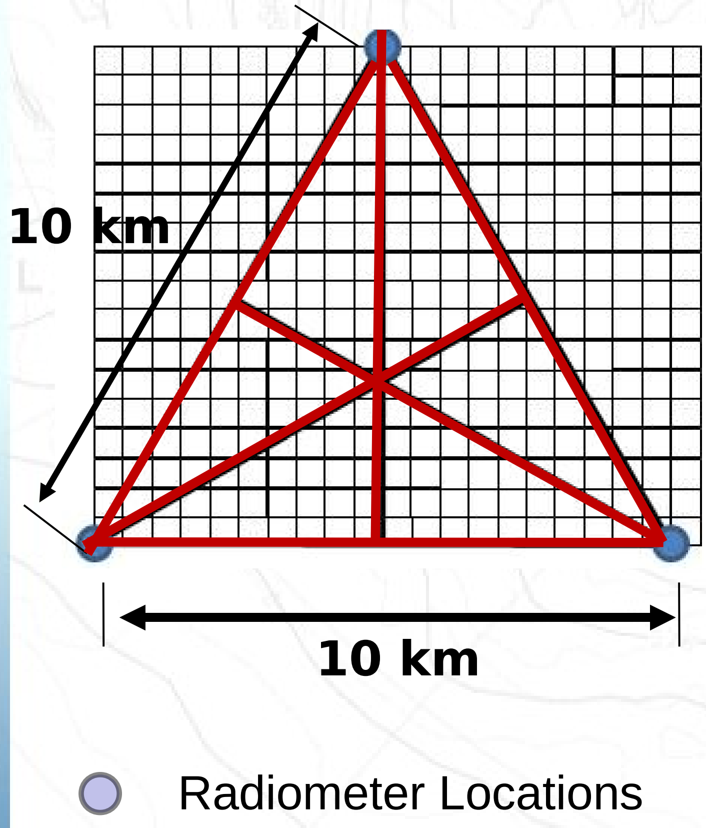


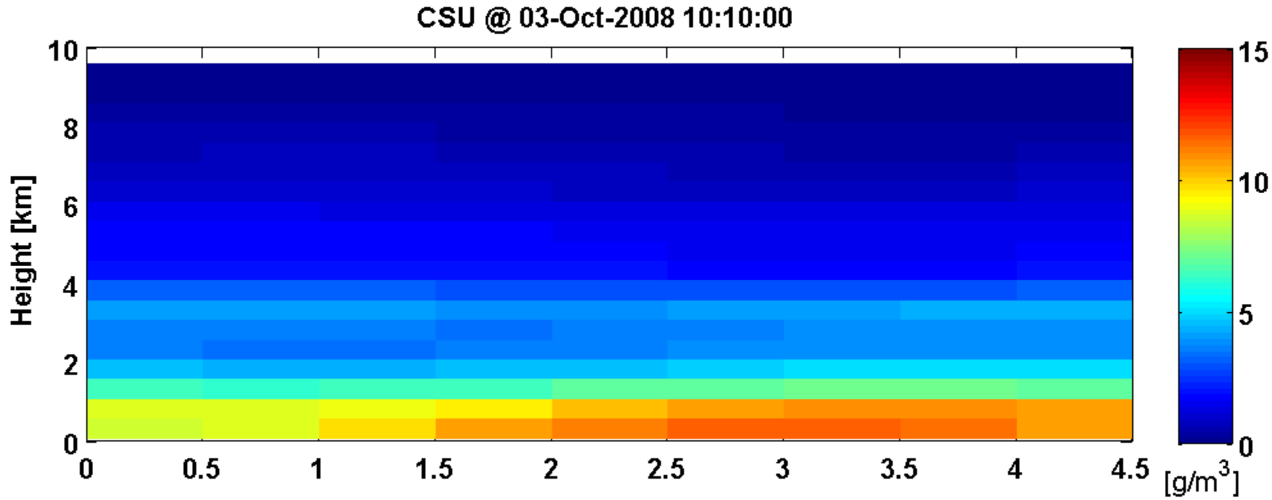
- Algebraic tomographic reconstruction will be used to retrieve the 3-D water vapor field from T_B' measured by each of the radiometer "nodes" in the network

- Each node will perform a complete hemispherical scan (6 azimuth and 10 elevation angles) in less than 10 minutes.

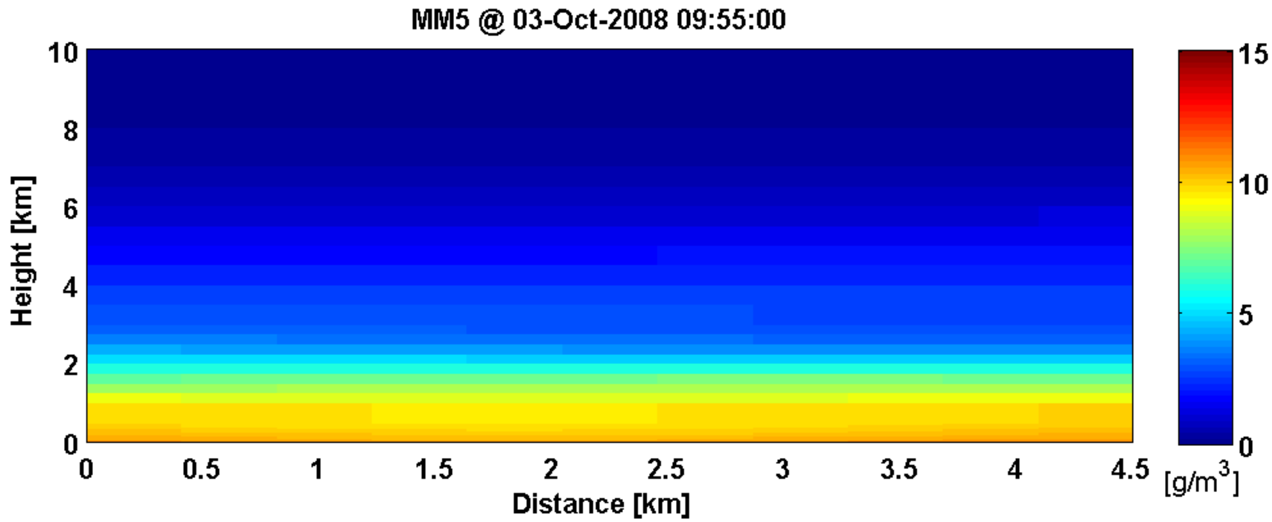
WV 2D tomography from CMR (H2+H3)

Water Vapor density profiles [g/m³] @ 03 Oct 10:10

- CMR



- MM5



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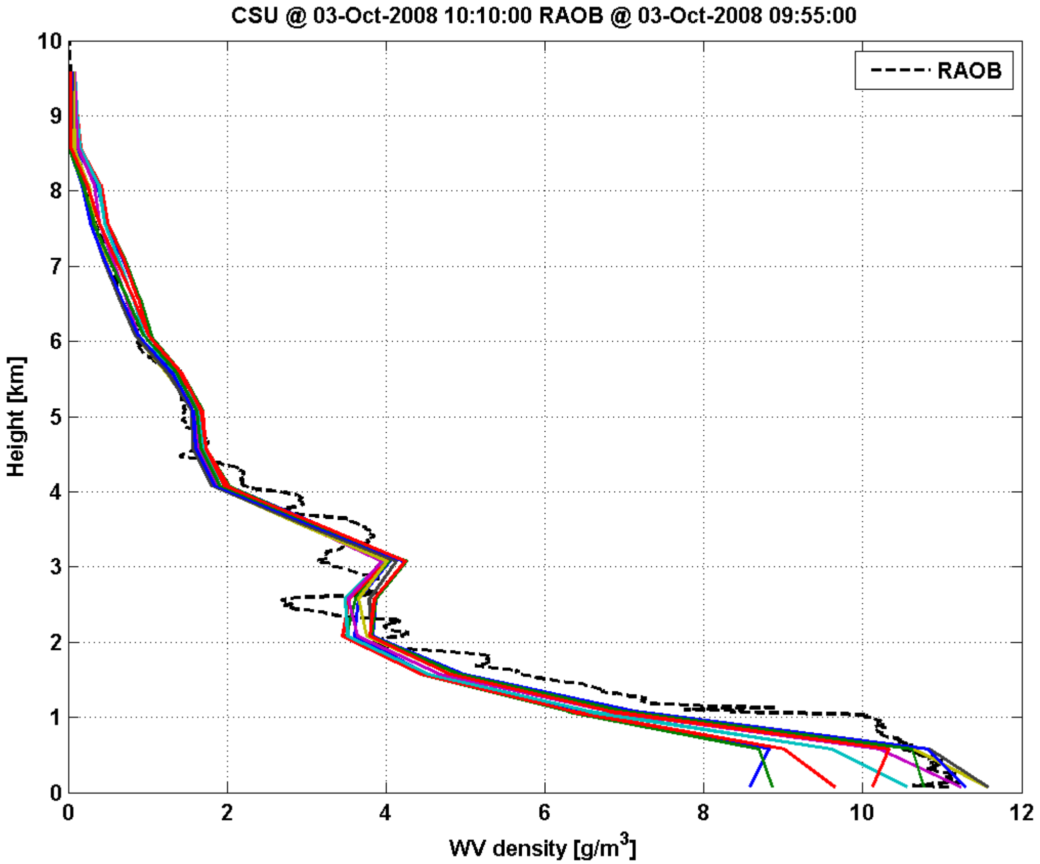
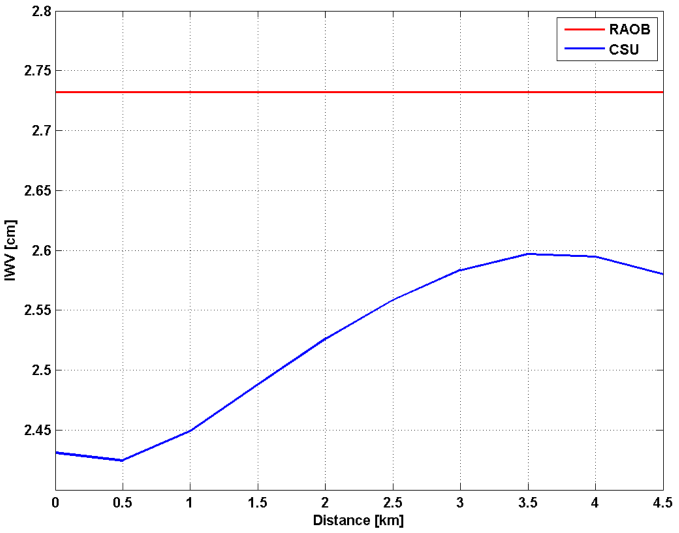
Preliminary Comparison with RAOBs

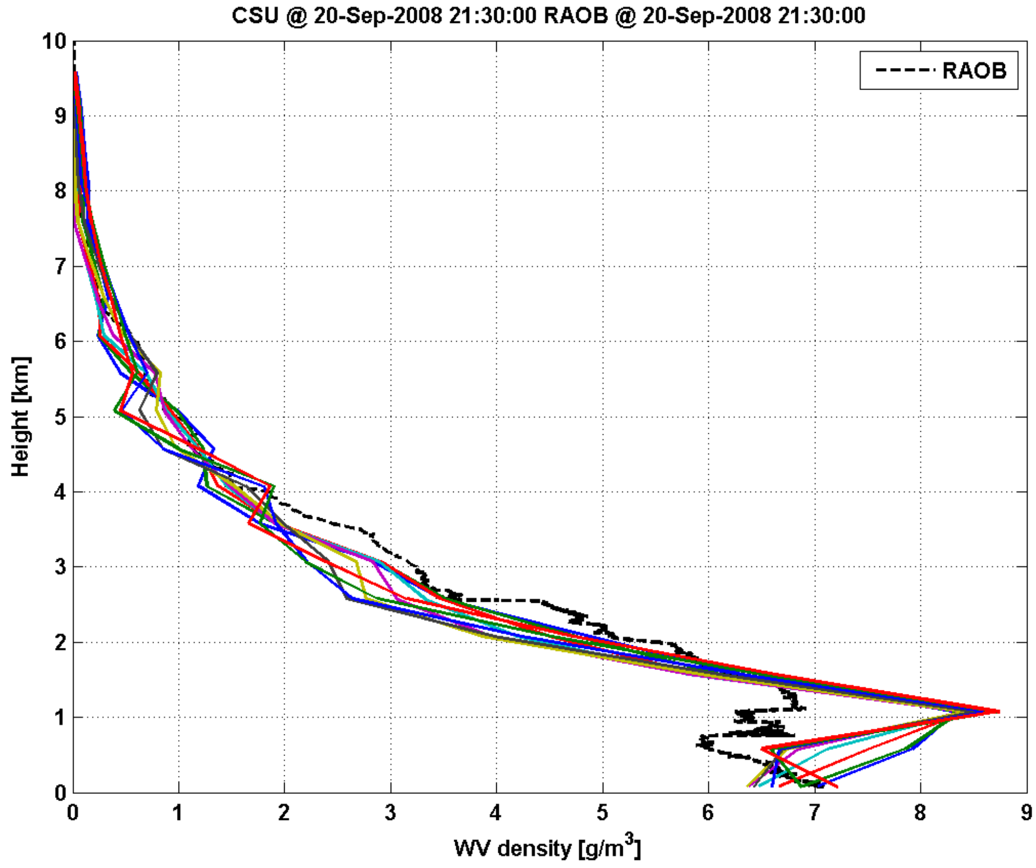
- Water Vapor density profile [g/m³] @ 03 Oct 10:10

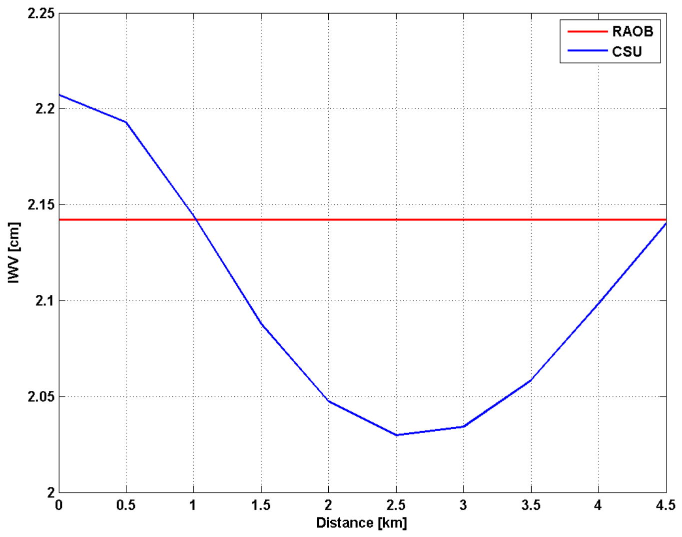




Preliminary Comparison with RAOBs

- Water Vapor density profile [g/m³] @ 20 Sept 21:30





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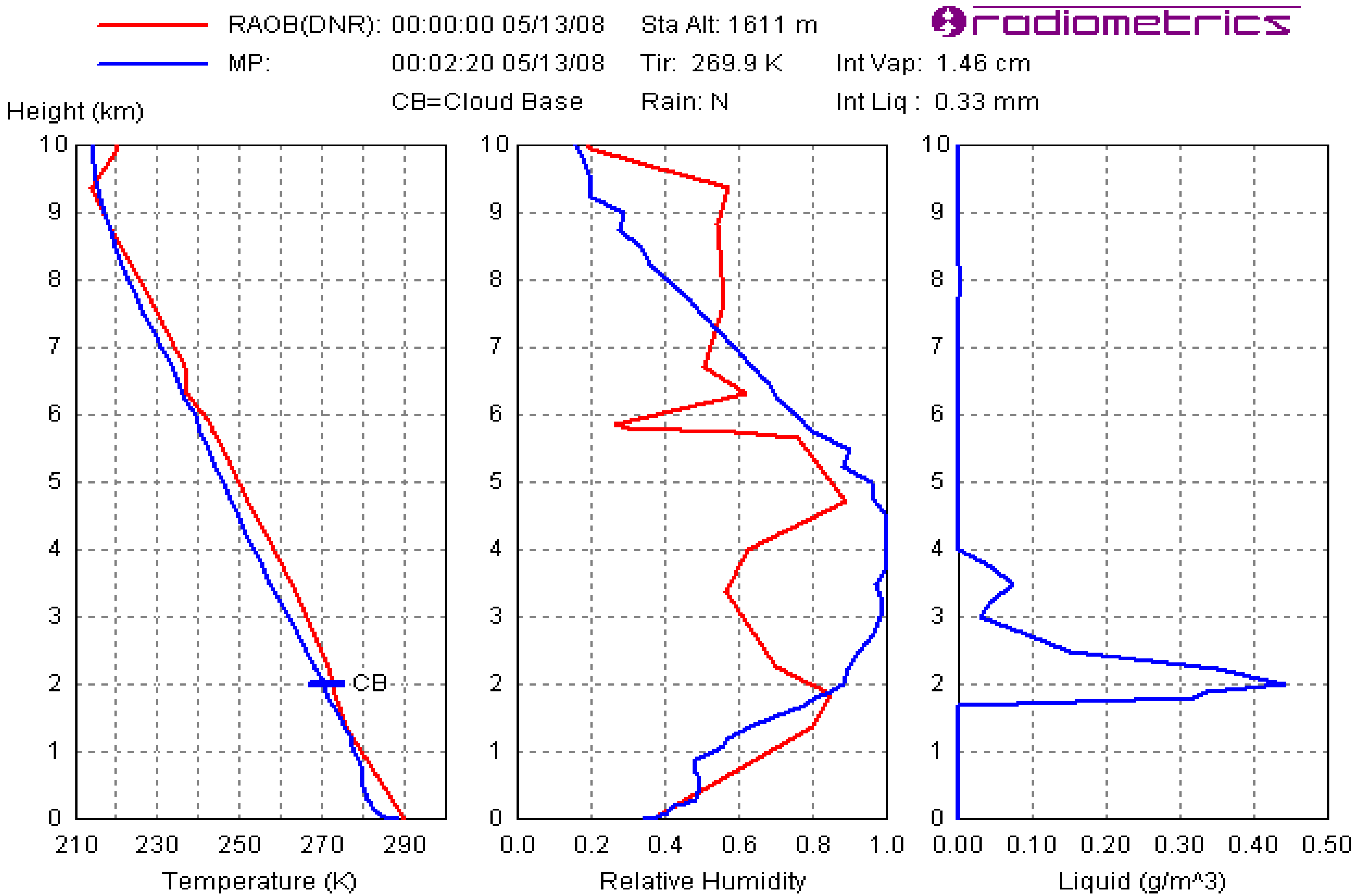
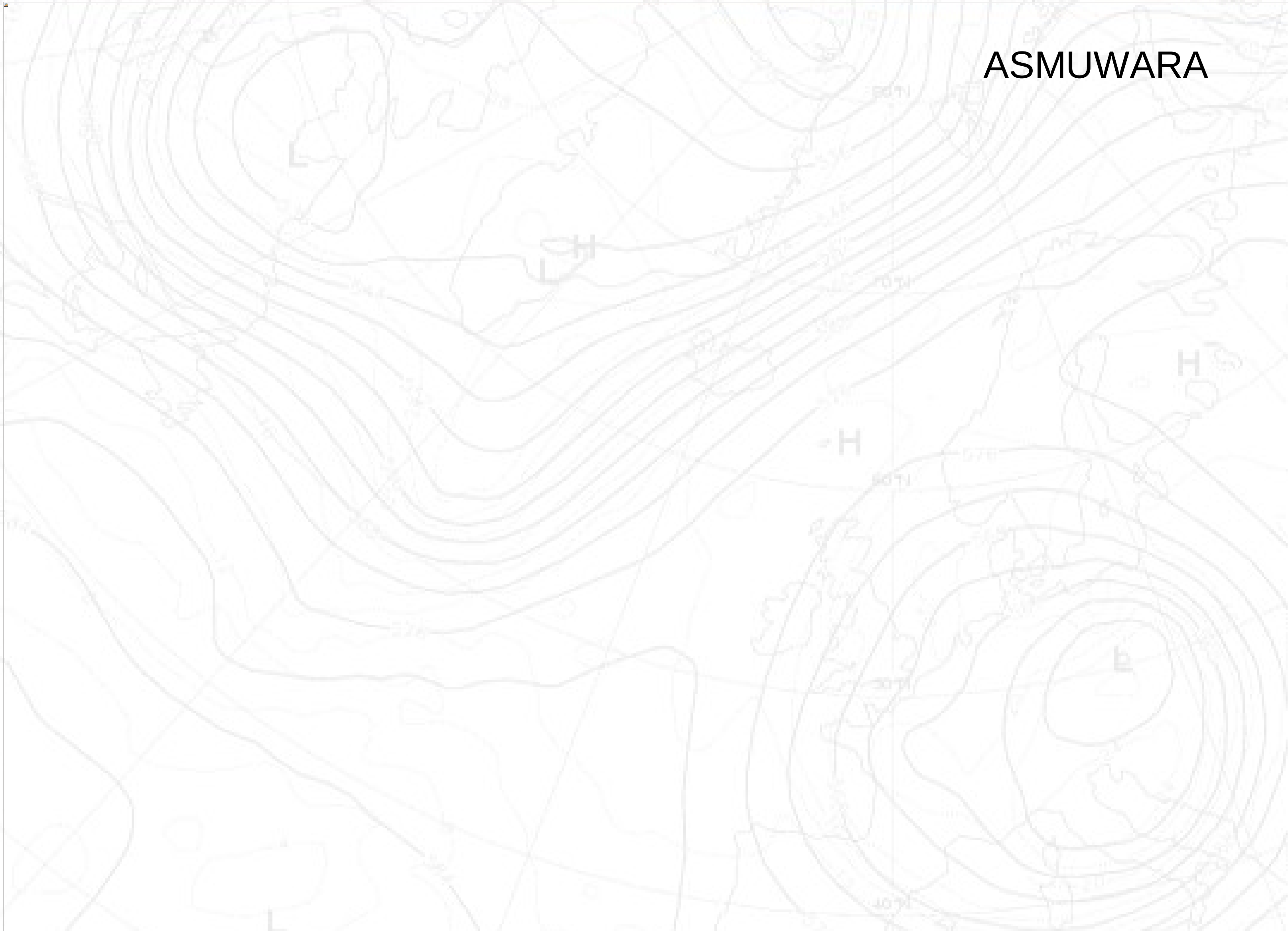


MP-3000A WeatherCam and radiosonde temperature, humidity and liquid profile comparison at 00 UT 13 May 2008.

Hemispheric IR temperature

ASMUWARA



[After Martin et al. 2003]

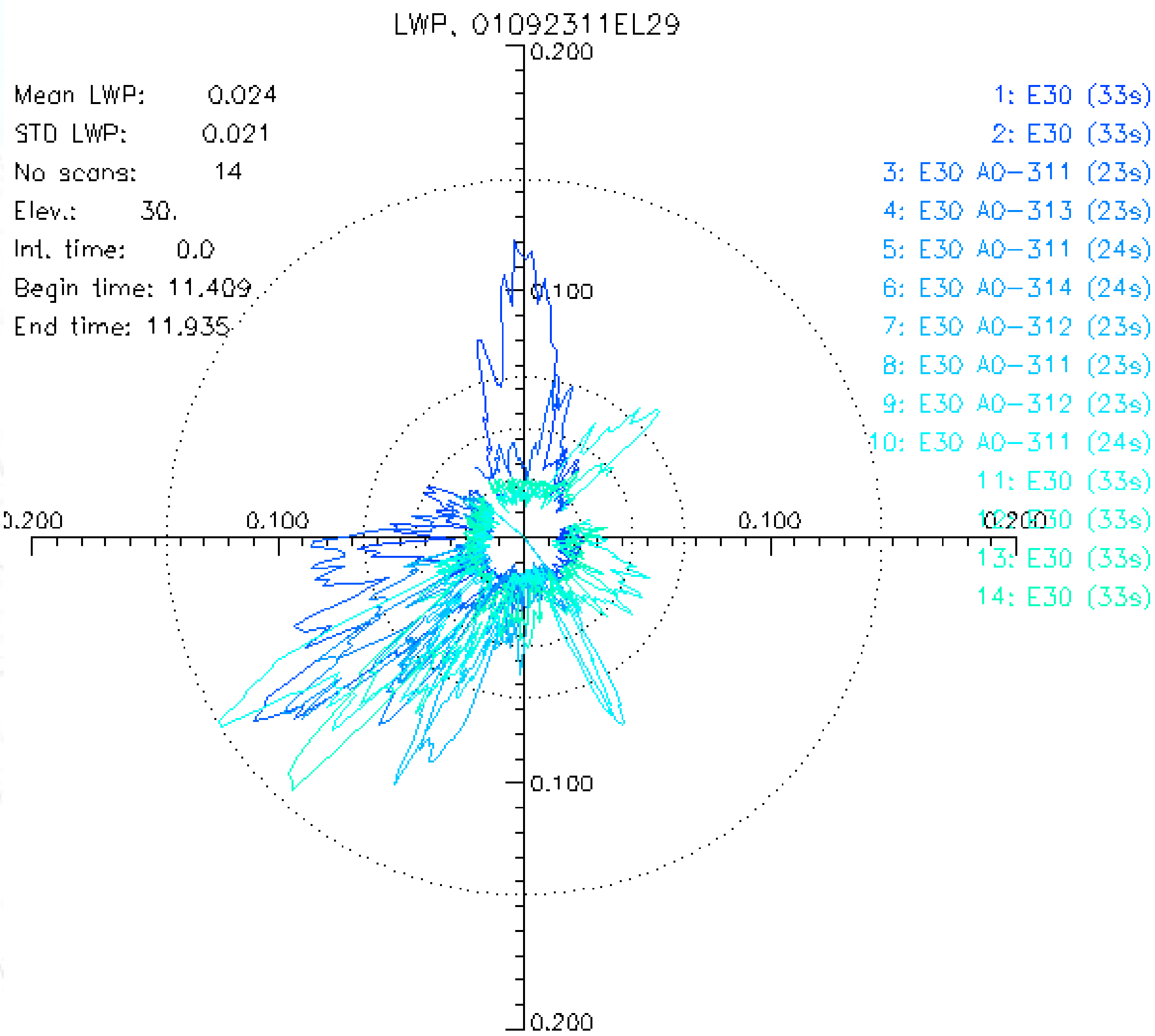


Figure 2. Series of 14 successive azimuth scans at 30 deg elevation with the multi-channel microwave radiometer MICCY having a beam width of less than 1 deg in all channels. Liquid water path was derived using a regression algorithm employing four frequency channels [Löhnert and Crewell, 2003].

Rain Mitigation

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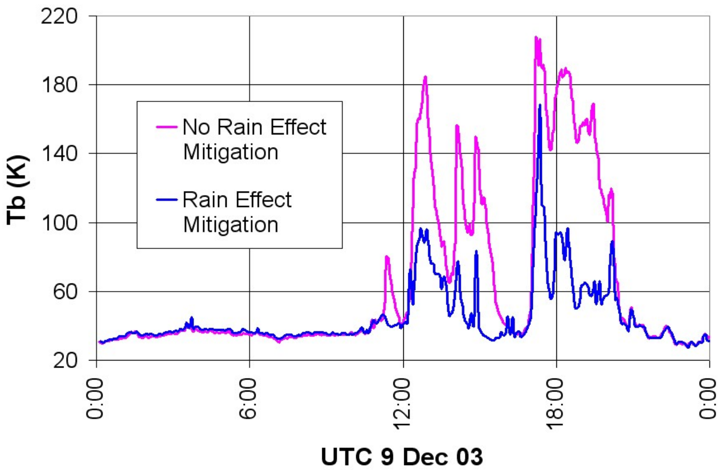
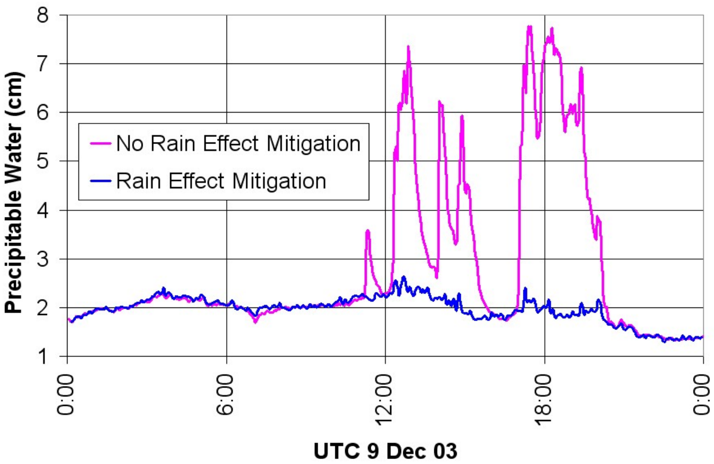
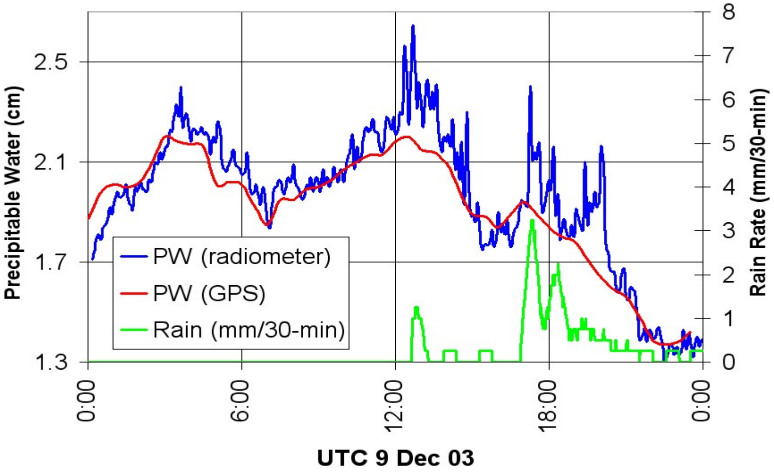
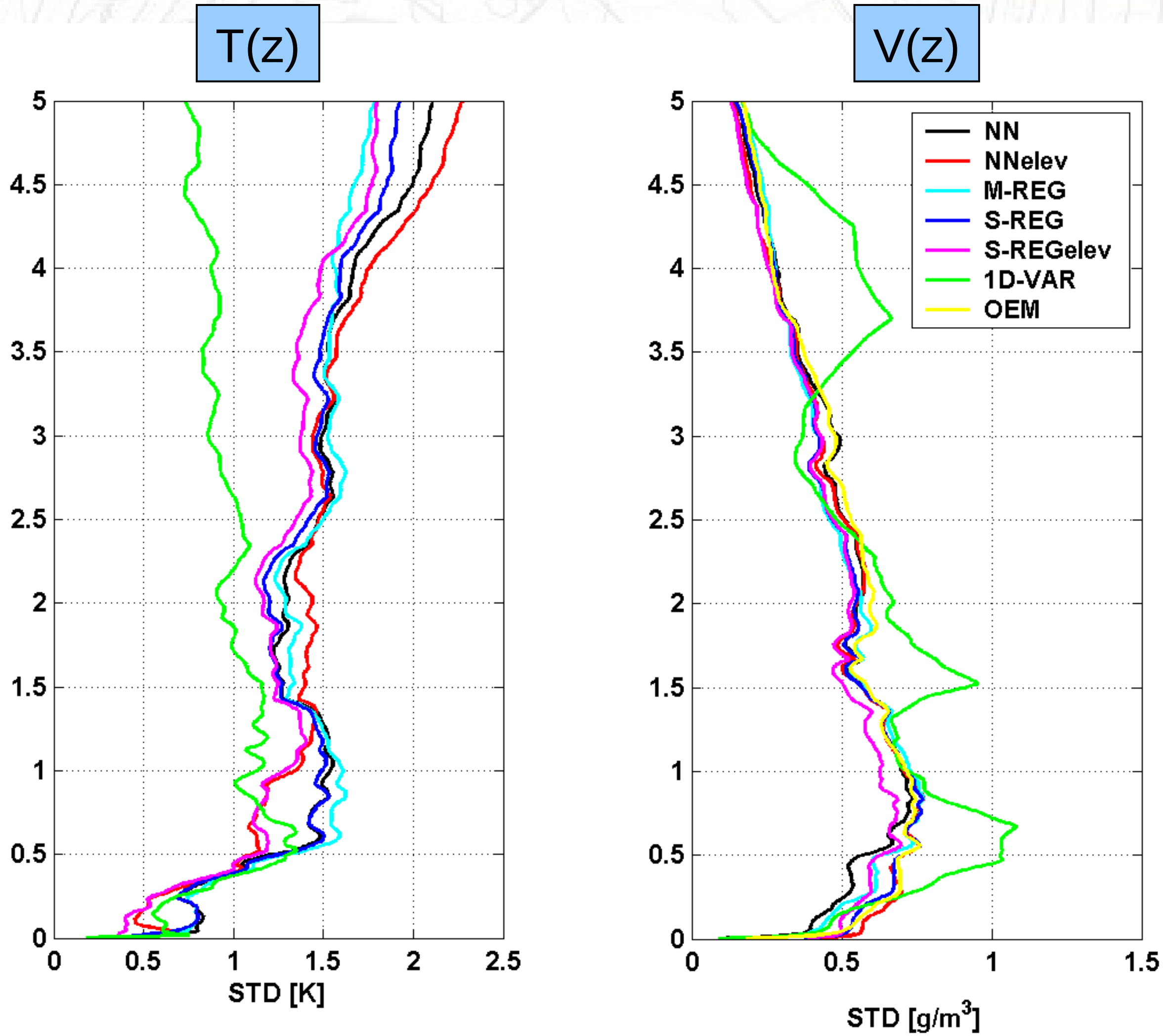
Hydrophobic film over the radome







MWR profiler performances



COST720 Temperature, hUmidity and Cloud profiling (TUC) Campaign Payerne (CH)

[Cimini et al., 2006]

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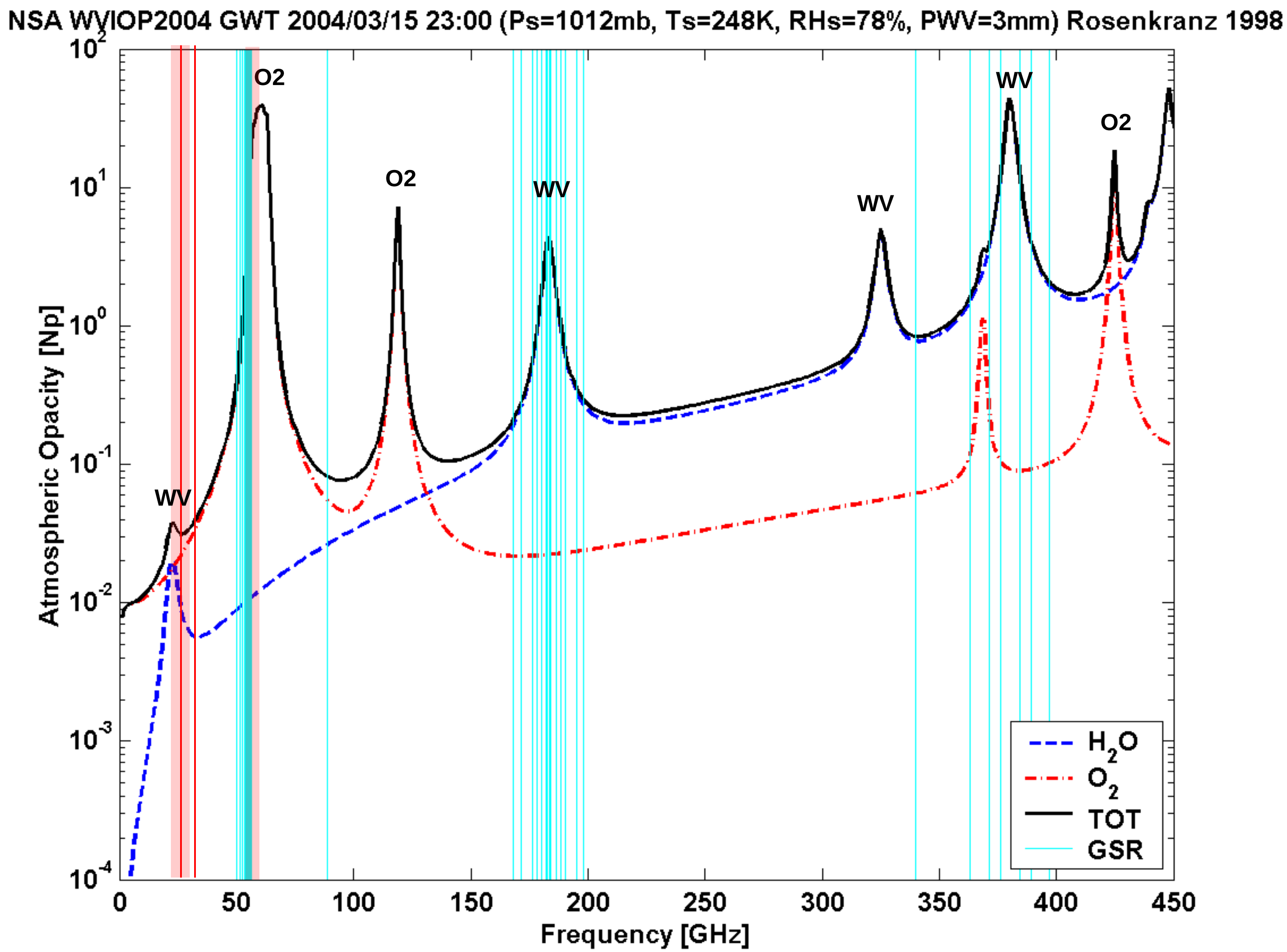
Atmospheric opacity in MW-MMW for Arctic



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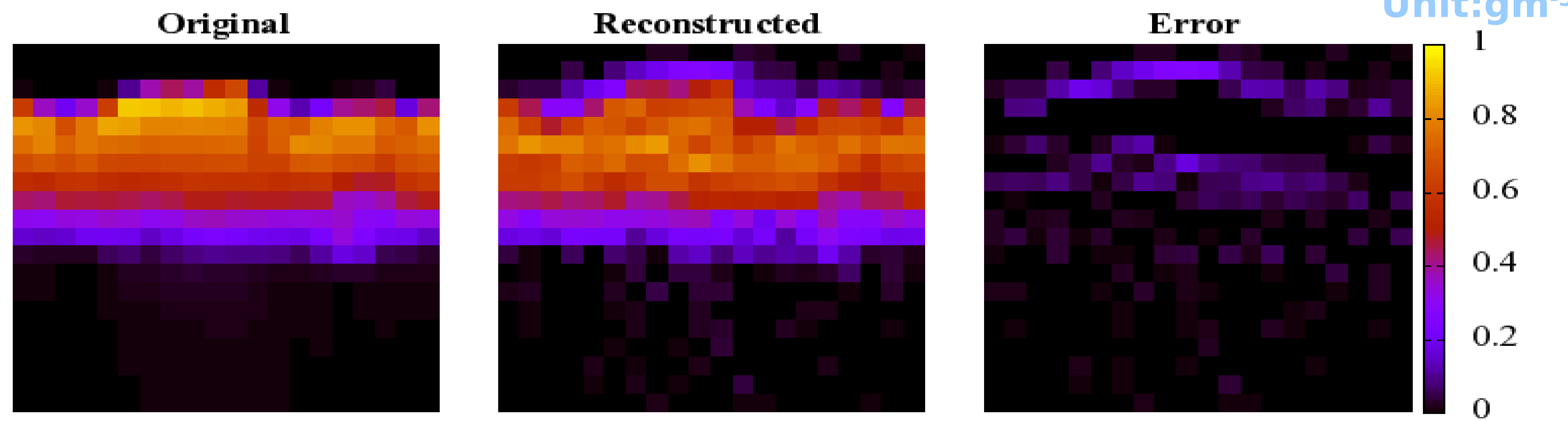
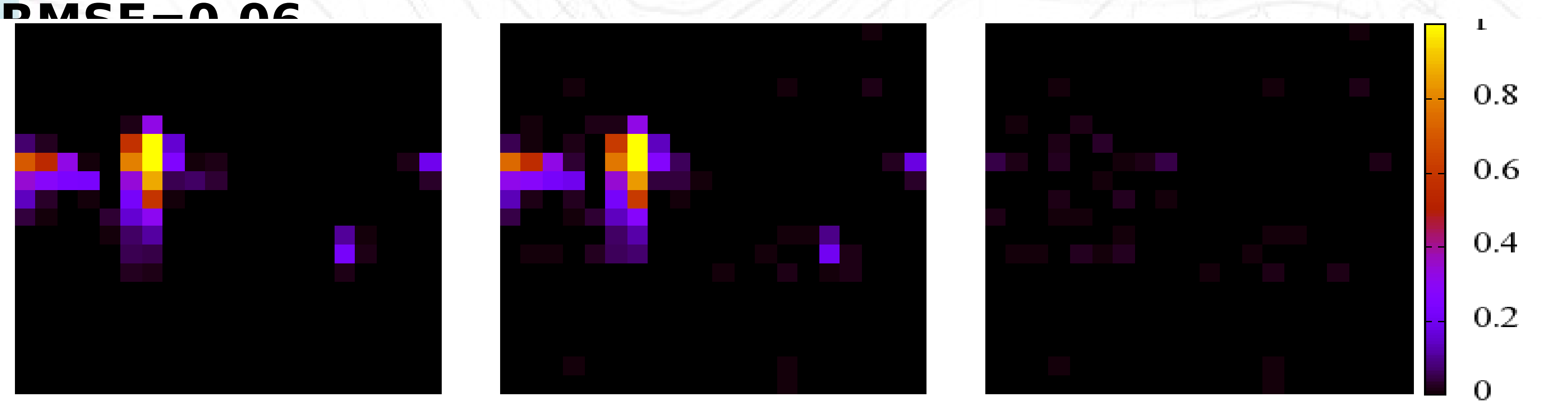
8 nodes well capture the spatial pattern



Stratocumulus, max(LWC)=0.97, mean(LWC) =0.31, RMSE=0.06



Broken cumulus, max(LWC)=1.0, mean(LWC) =0.04, RMSE=0.006

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3-D Cloud Tomography

Reconstruction accuracy depends on:

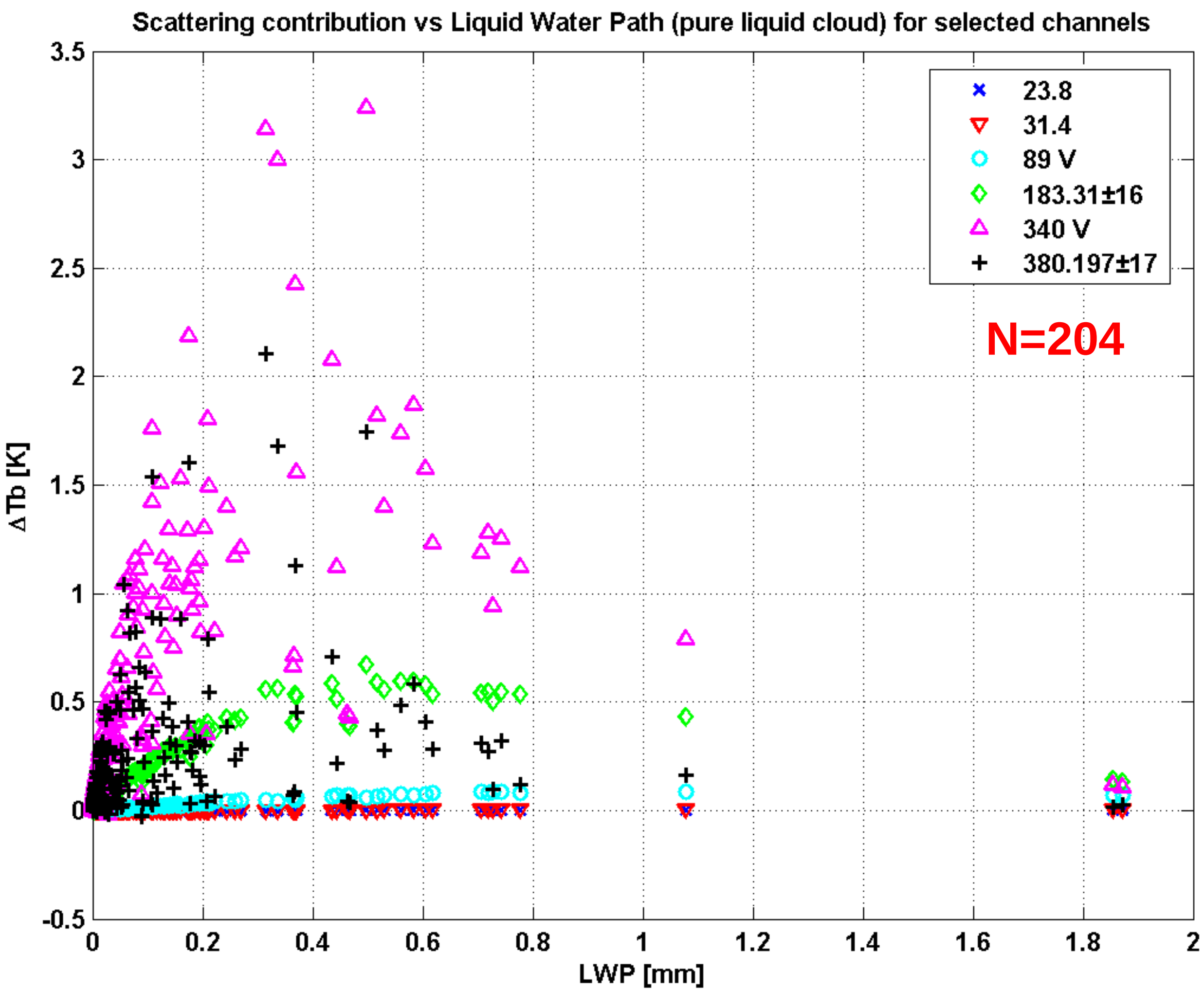
- Radiometer noise level
- Total number of scan directions
- Output resolution
- Number of radiometers

At resolution of ~100 meters with a 4-radiometer setup cloud tomography is able to retrieve LWC within 20% of the mean LWC (based on synthetic data)

Evaluating Scattering Contribution

DOTLRT - Voronovich, Gasiewski, and Weber, TGRS, 2004*

PURE LIQUID CLOUD



*Cloud parameterization described in Skofronick-Jackson, Gasiewski, and Wang, TGRS, 2002

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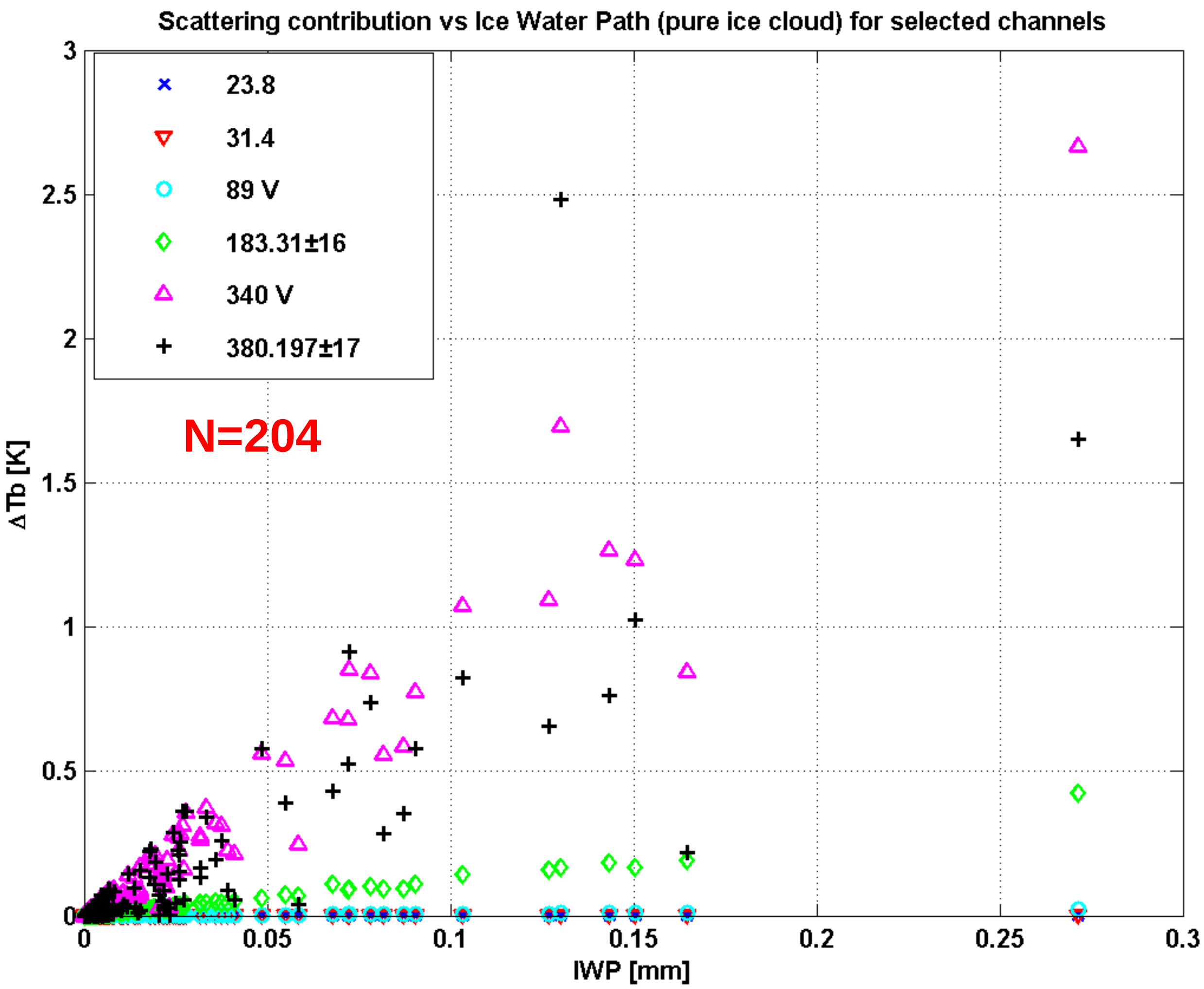
Evaluating Scattering Contribution

DOTLRT - Voronovich, Gasiewski, and Weber, TGRS, 2004*

PURE ICE CLOUD



*Cloud parameterization described in Skofronick-Jackson, Gasiewski, and Wang, TGRS, 2002

Comparison of MW and MMW retrieval of IWV

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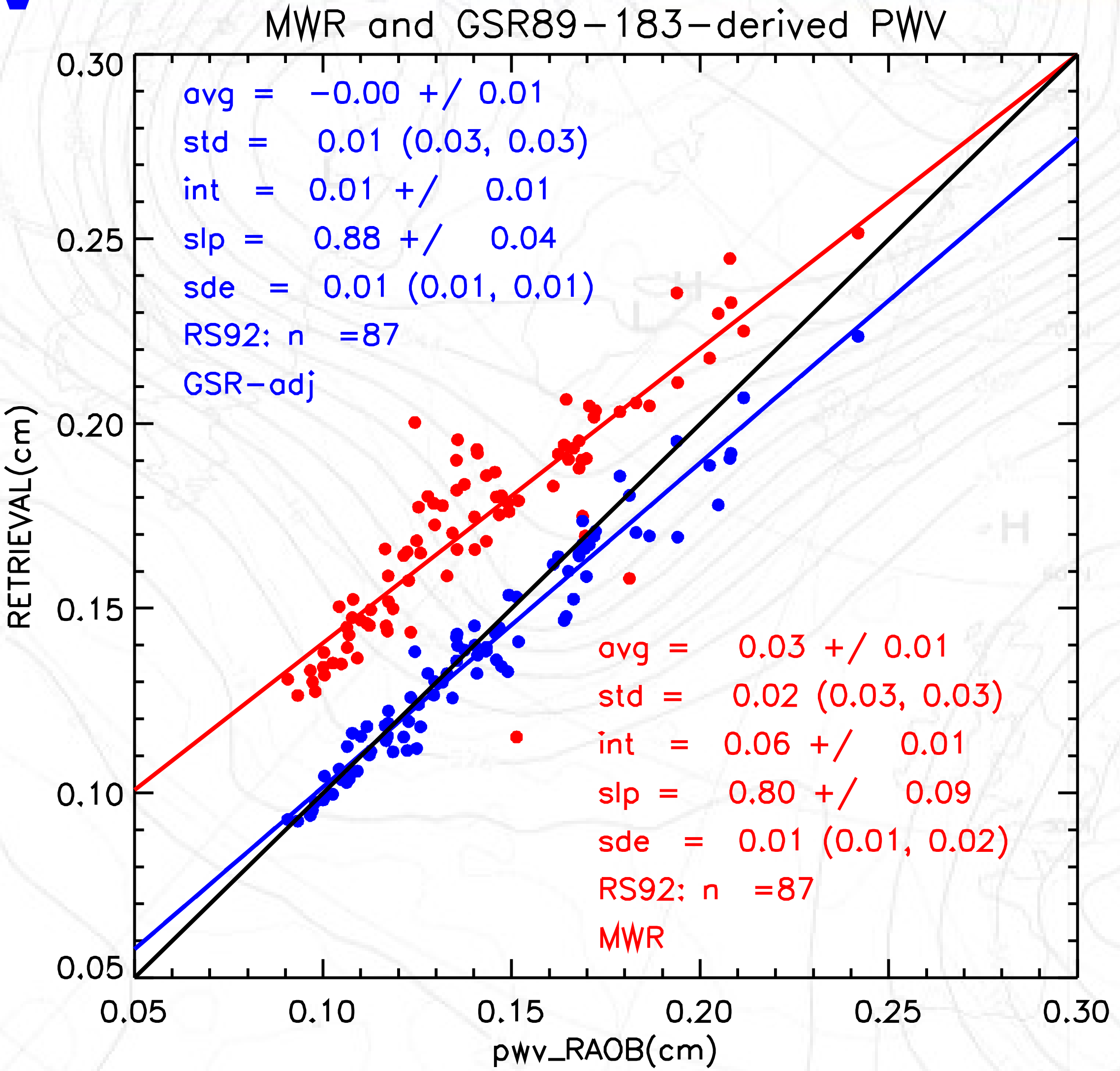
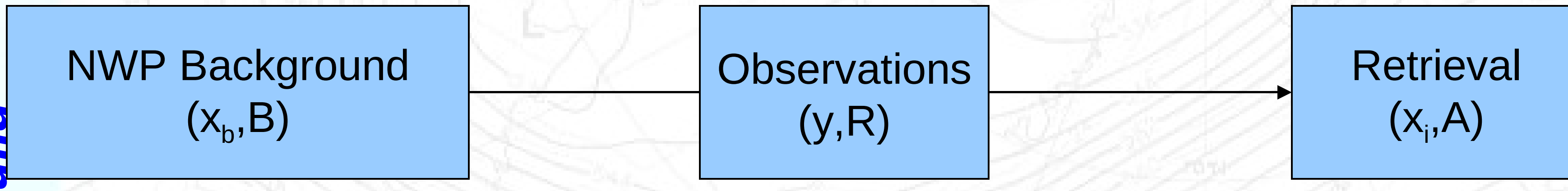


[Westwater et al., 2008]

One Dimensional Variational Assimilation Retrieval (1D-VAR)

Nonlinear retrieval technique based on **Optimal Estimation Method** with a first guess taken from a **Numerical Weather Prediction** (NWP) model output



Assumptions: Moderately non-linear problem, Gaussian-distributed errors

Method: Gauss-Newton (Newtonian iteration with small residuals)

Cost function* **(to be minimized)**

$$J = [\mathrm{y} - F(\mathrm{x})]^{\mathrm{T}} R^{-1} [\mathrm{y} - F(\mathrm{x})] + [\mathrm{x} - \mathrm{x}_{\mathrm{b}}]^{\mathrm{T}} B^{-1} [\mathrm{x} - \mathrm{x}_{\mathrm{b}}]$$

Iterative solution

$$\mathrm{x}_{\mathrm{i+1}} = \mathrm{x}_{\mathrm{i}} + \left(B^{-1} + K_i^{\mathrm{T}} R^{-1} K_i\right)^{-1} \left[K_i^{\mathrm{T}} R^{-1} \left(\mathrm{y} - F(\mathrm{x}_{\mathrm{i}})\right) - B^{-1} (\mathrm{x}_{\mathrm{i}} - \mathrm{x}_{\mathrm{b}})\right]$$

Error covariance

$$A = \left(B^{-1} + K_i^T R^{-1} K_i\right)^{-1}$$

Convergence criterium

$$[F(\mathrm{x}_{\mathrm{i+1}}) - F(\mathrm{x}_{\mathrm{i}})]^{\mathrm{T}} S^{-1} [F(\mathrm{x}_{\mathrm{i+1}}) - F(\mathrm{x}_{\mathrm{i}})] << n(obs)$$

$$S = R\left(R + K_i B K_i^T\right)^{-1} R$$

***Hewison, 2007 - Standard notation of Ide et al. 1997**

1D-VAR: Control variables and Jacobians

TEMPERATURE

Control variable:

T (K) at 100 levels (0-5 km)

Jacobian:

K = dF/dT (K/K)

Observations:

GSR 50-55 GHz Tb + T_{surf}

HUMIDITY

Control variable:

$\ln(Q_t)$ - Natural logarithm of total water at 100 levels (0-5 km)

In clear sky, Q_t reduces to Q (specific humidity)

Jacobian:

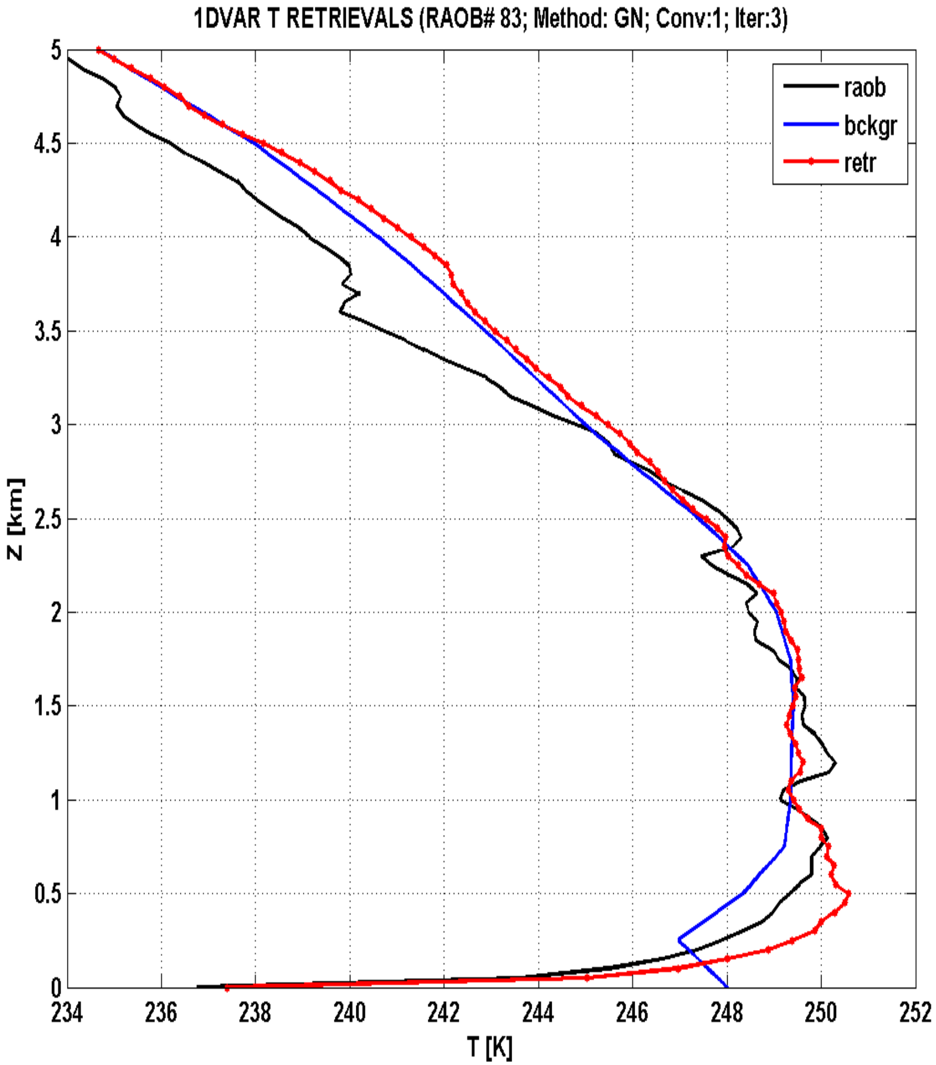
$K = Q_t \cdot dF/dQ_t$

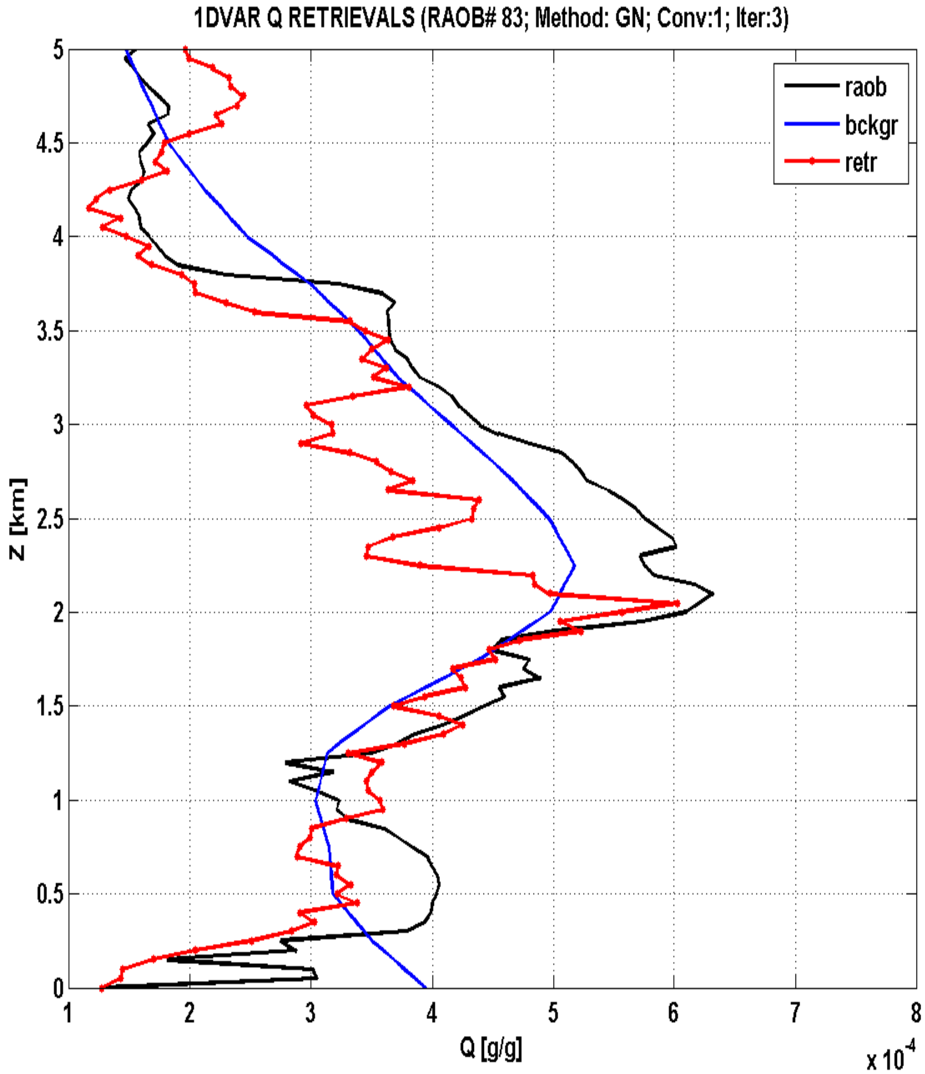
Observations:

GSR 89-183 GHz Tb + Q_{surf}

Examples of 1D-VAR Retrievals during RHUBC

T(K) **Q(g/g)**



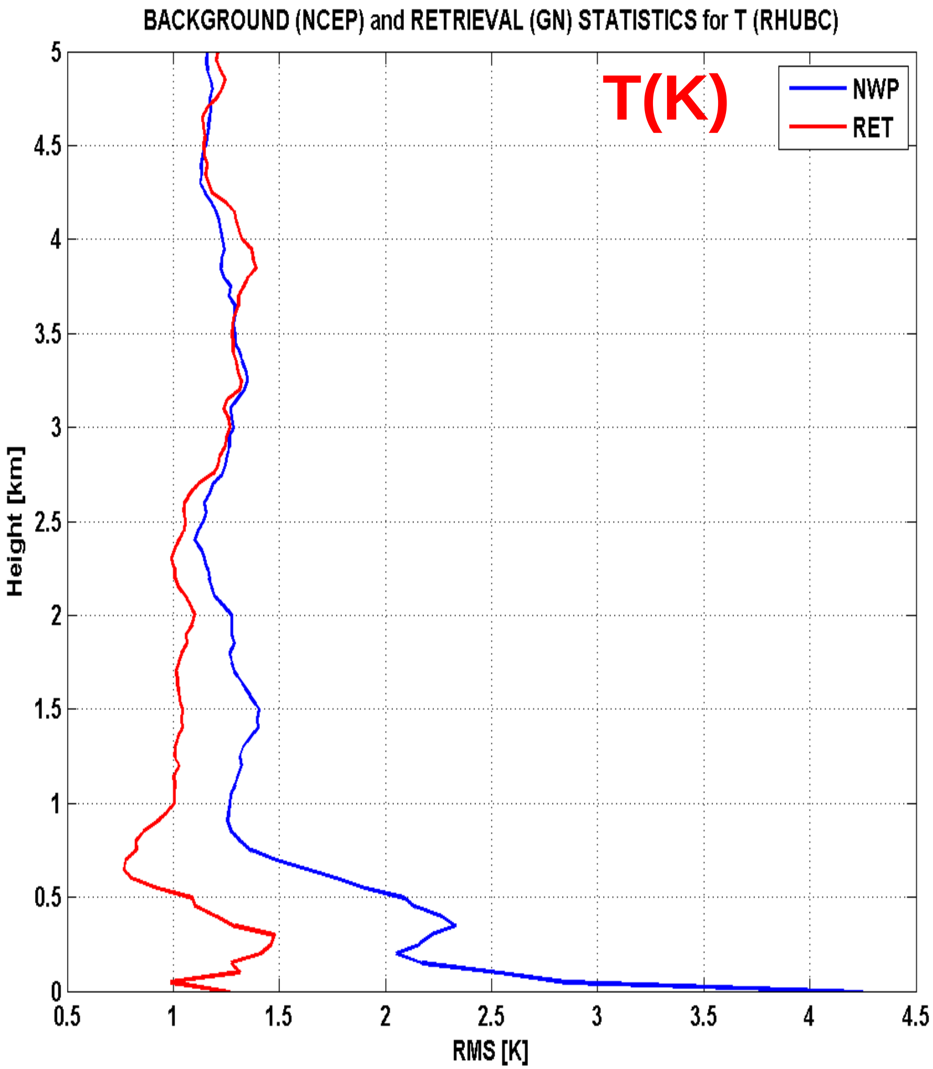


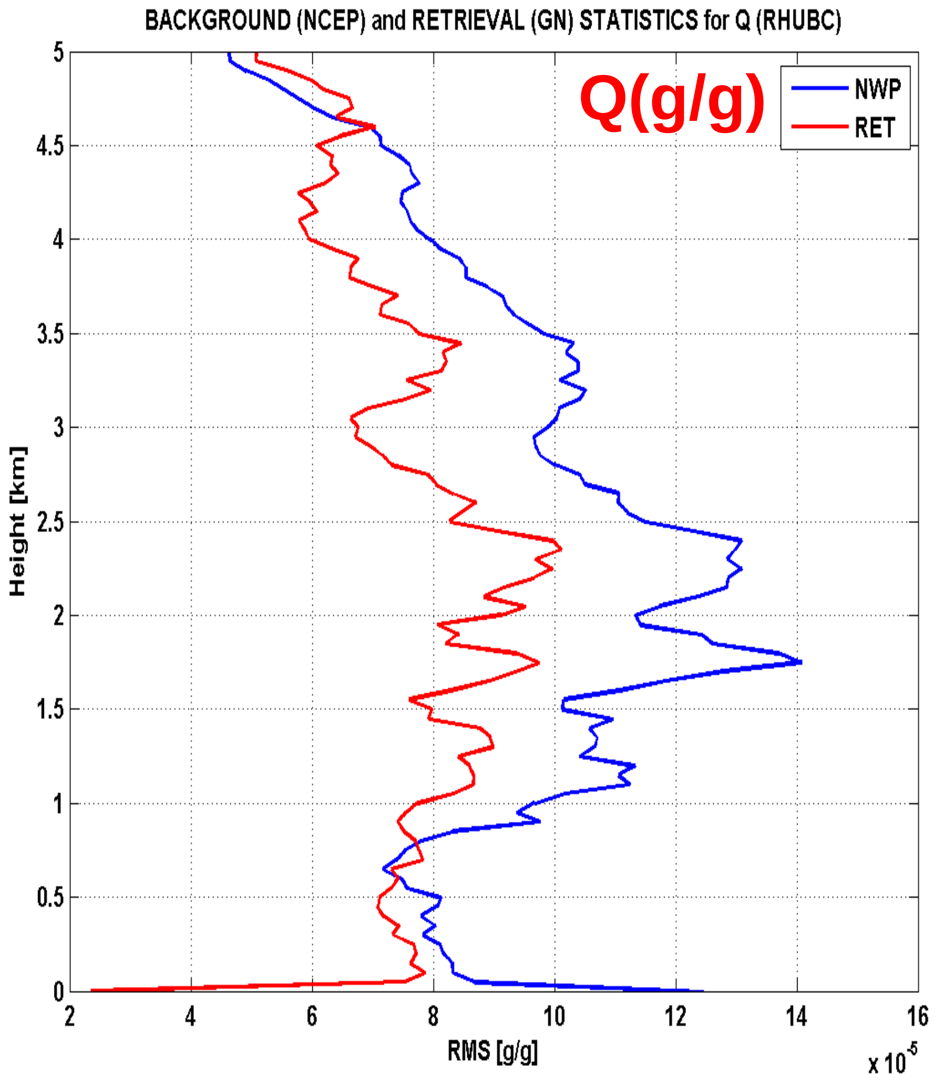
Statistics of 1D-VAR Retrievals during RHUBC

(with respect to RAOB)

Convergence: 100% (T) and 98% (Q)

Consistency: 98% (T) and 60% (Q)





Arctic Winter Radiometric Experiments

Periods: March-April 2004
February-March 2007 (RHUBC)
Location: ARM NSA, Barrow, Alaska

Radiometers

1) 2-channel Microwave Radiometer (MWR):
23.8; 31.4 GHz
2) 12-channel Microwave Radiometer Profiler (MWRP):
22.235; 23.035; 23.835; 26.235; 30.0 GHz
51.25; 52.28; 53.85; 54.94; 56.66; 57.29; 58.8 GHz
3) 27-channel Ground-based Scanning Radiometer (GSR)
50.2; 50.3; 51.76; 52.625; 53.29; 53.845; 54.4; 54.95; 56.215;56.325 GHz
89 V; 89 H GHz
183.31±0.55; ±1; ±3.05; ±4.7; ±7; ±12; ±16 GHz
340 V; 340 H GHz
380.197 ± 0.4, ± 1.5; ±4; ±9; ±17 GHz

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IWV and LWP mapping

- Contribution from IAP University of Bern (CH)
- 9 channels, azimuth and elevation scanning
- Hemispheric IWV and LWP retrieval (2D map)

ASMUWARA – IAP/University of Bern

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