Ground-based Microwave Radiometry for Humidity and Temperature Profiling: Current Status and Future Outlook

Steven C. Reising

Microwave Systems Laboratory
Colorado State University
Fort Collins, CO
USA

Acknowledgments

Many thanks to the following authors for their excellent review articles:

1. **Ed R. Westwater, Susanne Crewell and Christian Mätzler, "Surface-based Microwave and Millimeter wave Radiometric Remote Sensing of the Troposphere: a Tutorial," *IEEE Geoscience and Remote Sensing Society Newsletter*, March 2005.**
2. **Christian Mätzler, Ed R. Westwater, Domenico Cimini, Susanne Crewell, Tim Hewison, Jürgen Güldner and Frank S. Marzano, "COST-720 Final Report: Section on Microwave Radiometers," March 2006.**

Colorado State University
Knowledge to Go Places

Physical Principles of Microwave Radiometry

- **Planck's Law of blackbody radiation, where units of *B* are Wm^{-2}sr^{-1}Hz^{-1}**

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

- **Rayleigh-Jeans approximation for** $h\nu << kT$

$$B_\nu(T) \approx \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}$$

- **Radiative Transfer Equation for an upward-looking radiometer measuring T_b from a non-scattering medium:**

$$B_\nu(T_b) = B_\nu(T_{\cos})\exp\left(-\int_0^\infty \alpha_\nu(s)ds\right) + \int_0^\infty B_\nu(T(s))\alpha_\nu(s)\exp\left(-\int_0^s \alpha_\nu(s')ds'\right)ds$$

- **Rayleigh-Jeans approximation:**

$$T_b = T_{\cos}\exp\left(-\int_0^\infty \alpha_\nu(s)ds\right) + \int_0^\infty T(s)\alpha_\nu(s)\exp\left(-\int_0^s \alpha_\nu(s')ds'\right)ds$$

- **where** $\tau_\nu =$ **opacity** $= -\int_0^\infty \alpha_\nu(s)ds$ **, and** $\alpha_\nu(s) =$ **absorption coefficient.**

Radiative Transfer

$$T_b = T_{\cos}\exp\left(-\int_0^\infty \alpha_\nu(s)ds\right) + \int_0^\infty T(s)\alpha_\nu(s)\exp\left(-\int_0^s \alpha_\nu(s')ds'\right)ds$$

- **In the above Radiative Transfer Equation (RTE), assuming a vertically stratified atmosphere (and ignoring Earth curvature),** s **is related to** h**, the height, as** $s\cos(\theta) = h$ **, where** θ **is the zenith angle.**
- **The RTE is used in:**
  - **Forward model studies to compare measured** T_b **with modeled** T_b **based on radiosonde measurements.**
  - **Inverse problems, to retrieve meteorological parameters from** T_b**.**
  - **Modeling of the effects of instrument noise and calibration errors on retrievals and determining optimum frequencies and choice of** θ**.**

Microwave Absorption and Emission

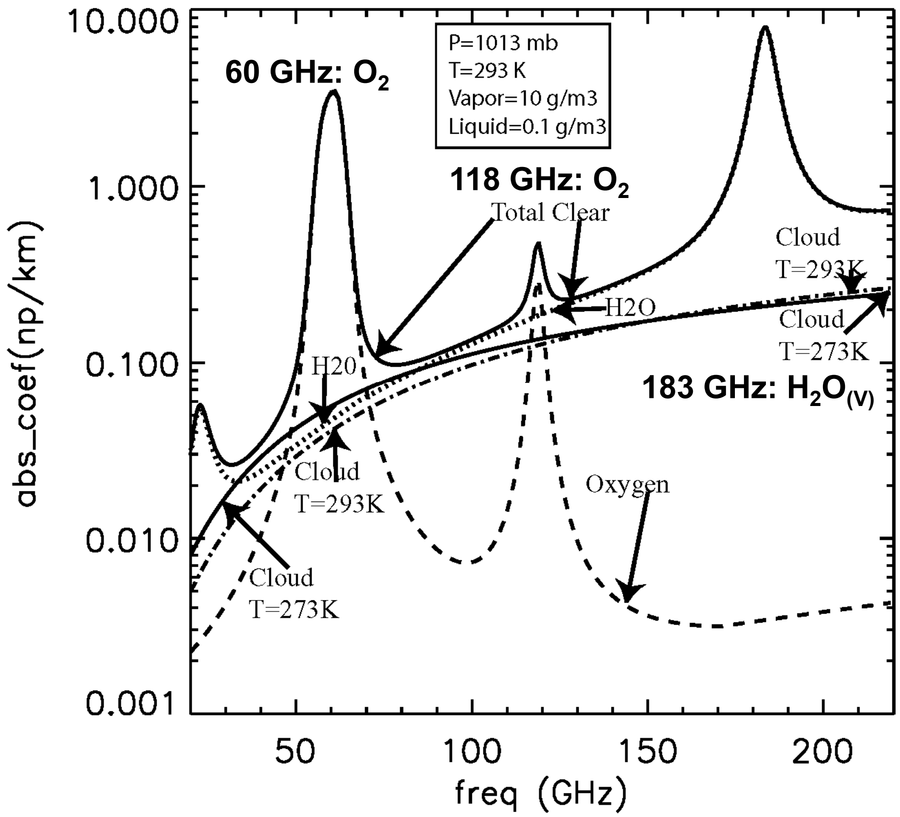
- At microwave and millimeter wave frequencies, water vapor has a weak electric dipole rotational transition ("resonance") at 22.235 GHz and a much stronger resonance at 183.31 GHz.
- Water vapor absorption also depends upon the "far wing" contributions of higher-frequency resonances, taken into account up to 750 GHz [*Rosenkranz*, 1998] or 1000 GHz [*Liebe*, 1989].
- Oxygen absorbs due to a number of magnetic dipole transitions ("resonances") near 60 GHz and a single line at 118.75 GHz.
- Transmission windows at 30-50, 70-100 and 130-150 GHz are used for the remote sensing of clouds, or surface studies for downward-looking radiometers.

- To achieve altitude resolution, pressure broadening is exploited, i.e. the broadening of resonance lines through molecular collisions. The collision rate is proportional to the partial pressures of the gases involved.

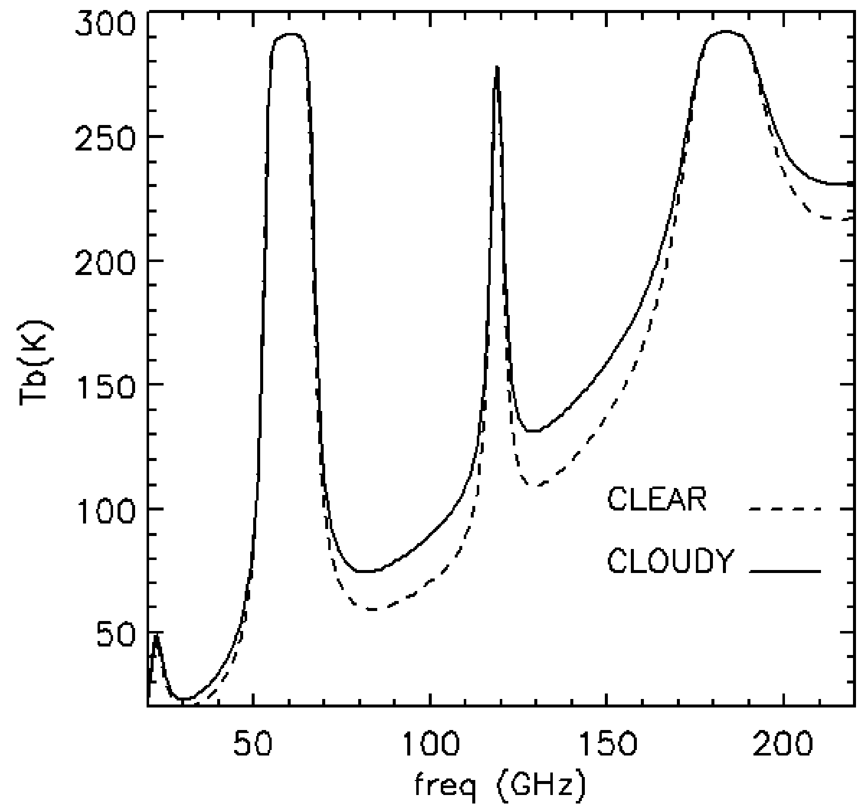
Modeling Microwave Absorption and Emission

- **Line shape: Van-Vleck and Weisskopf (1947) is very well accepted.**
- **Laboratory measurements starting in the late 60s by H. Liebe led to the widely distributed Microwave Propagation Model (MPM).**
  - ***Liebe and Layton*, 1987: L87**
  - **Changed line parameters and water-vapor continuum (far wings) in *Liebe et al.*, 1993: L93**
  - **To modify the line width of the 22.235 GHz line, *Rosenkranz*, 1998 used the foreign-broadened component from L87 and the self-broadened component from L93, due to the agreement with available measurements.**
- **Line-by-line Radiative Transfer Model (LBLRTM) is used extensively by the U.S. climate research community [*S. A. Clough et al.*, *JQSRT*, 2005].**
- **Recent updates:**
  - **Rosenkranz update (unpublished)**
  - ***Liljegren et al., TGARS,* 2005 uses the line width from HITRAN (2005).**

Atmospheric Absorption at Microwave Frequencies due to Water Vapor, Oxygen and Liquid Water



Microwave absorption spectra from 20 to 220 GHz. The absorption models used were *Liebe*, 1989 for clear absorption, and *Liebe et al.*,1991 for cloud liquid. *N.B.*: 60 and 118 GHz vary only 10-20%; 22 and 183 GHz vary 1000-2000% due to water vapor variability.



Calculated brightness temperatures (K) from 20 to 220 GHz. Clear calculations: P_S =1013 mb, T_S =293 K, ρ_S = 10 gm^{-3}, and IWV = 2.34 cm. Cloudy atmosphere: 1 mm of integrated cloud liquid with a cloud layer of liquid density of 0.1 gm^{-3} between 1 and 2 km.

Sensitivity of Brightness Temperature to Atmospheric Profiles

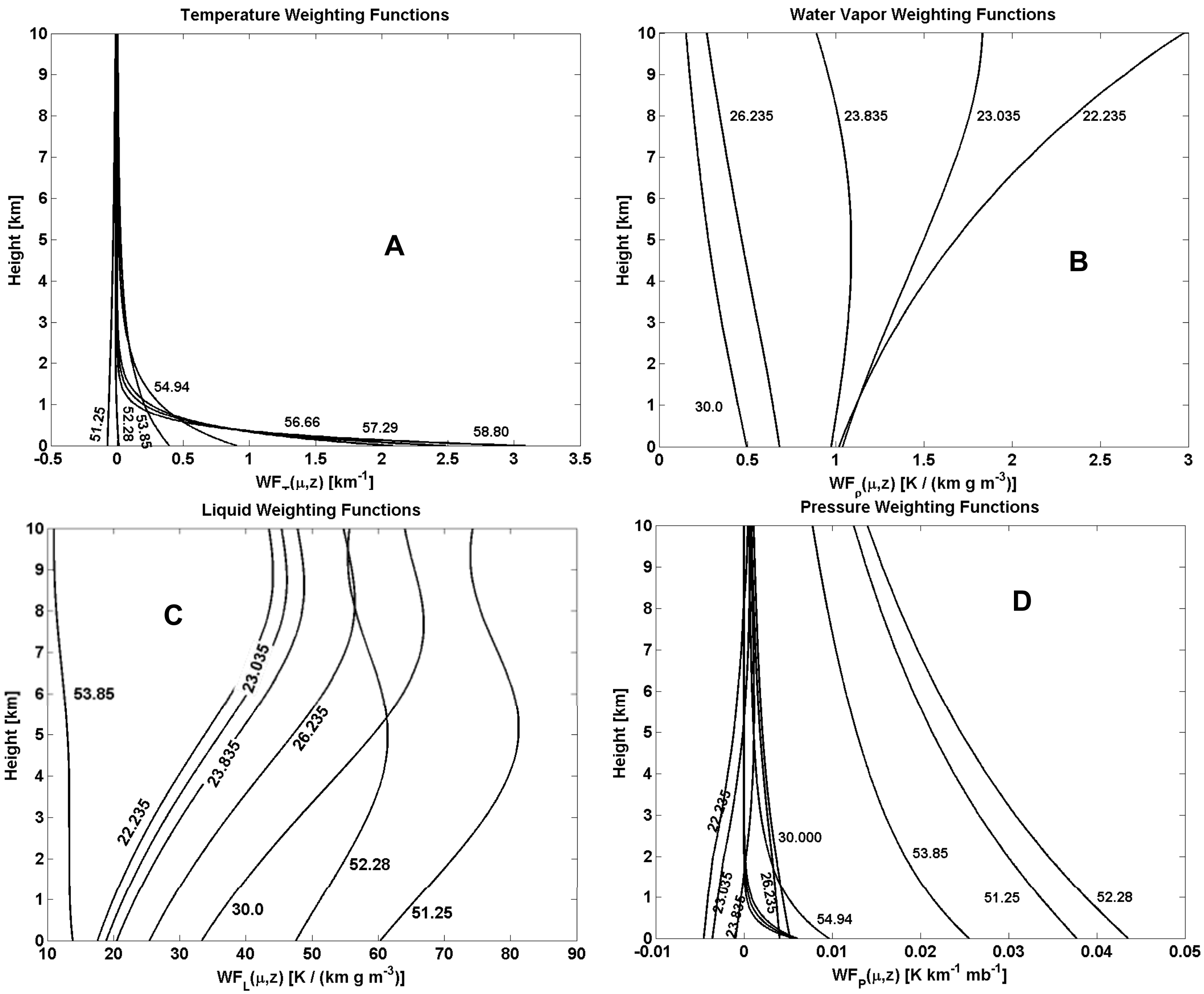
- **The absorption coefficient , $\alpha_\nu(s)$, in the Radiative Transfer Equations for an upward-looking radiometer is strongly dependent on the atmospheric state.**

- **Assume an initial "background state" of $\{T_0, P_0, \rho_{V0}, \rho_{L0}\}$ as a function of altitude. Then we can express any changes in the measured brightness temperature, δT_b , in terms of weighting functions, *W*, of the thermodynamic quantities, as**

$$\delta T_b = \int_0^\infty \left(W_T(s)\delta T(s) + W_P(s)\delta P(s) + W_{\rho_V}(s)\delta\rho_V(s) + W_{\rho_L}(s)\delta\rho_L(s) \right) ds$$

where the weighting functions, W, can be calculated explicitly from the dependence of $\alpha_\nu(s)$ on the background profiles.

Altitude Weighting Functions for Temperature and Humidity at Radiometrics Profiler frequencies



Notes:

A: Temp. profiling at V-band is useful up to 2 km height.

B: 23.8 GHz (and symmetric 20.6 GHz) is the best frequency to derive

$$IWV = \int_0^\infty \rho_V \, dh$$

C: Rayleigh droplets assumed for non-precipitating clouds. The addition of radar or IR is needed for cloud profiling

D. Surface pressure is needed, e.g. ΔP = 10 mbar gives ΔT_b = 0.45 K.

Retrieval of Atmospheric Profiles

- **Inversion is an ill-posed problem.**
- **Measurements can be regarded as constraints, and either:**
  - **Combined with supplementary observations or NWP results, or**
  - **Profiles can be projected onto linear functionals, such as PWV / LWP and geopotential height.**
- **Using a Fredholm integral of the first kind,**

$$g_e = Kf + \varepsilon$$

where g_e are the n measurements, f are the m unknown profile components, ε are the errors in the n measurements, and K is an $n \times m$ matrix relating the measurements to the unknown profile.

- **Physical retrievals involve calculation of K.**
- **Rodgers [1976] showed that for an initial guess f_0 and in the linear case,**

$$\hat{f} - f_0 = \left[S_f^{-1} + K^T S_\varepsilon^{-1} K\right]^{-1} K^T S_\varepsilon^{-1} \left(g_\varepsilon - Kf_0\right)$$

Where $S_f = E\{f - f_0\}\{f - f_0\}^T$ **and** $S_\varepsilon = E\{\varepsilon\varepsilon^T\}$**.**

This may be solved iteratively.

Calibration of Microwave Radiometers (1 of 2)

- **Internal noise sources may be switched / coupled into the receiver's input.**
  - **Involves a sacrifice of sensitivity for improved calibration**
  - **Switched noise diode(s)**
  - **Matched terminations (waveguide or microstrip) at known temperatures**
  - **Hach method measures the scene only 1/3 of the time, and samples two known noise sources [*Hogg et al., JAM,* 1983; *Tanner and Riley, RS*, 2003].**
  - **Dicke radiometer measures the scene half the time and a matched termination half the time, alternating at least 10 times the sample rate. Radiometer output is the *difference* between the two equivalent temperatures. Gain calibration is independent of the system noise figure.**
- **Blackbody Target Requirements:**
  - **Two, with a wide range of temperatures**
  - **High emissivity, to avoid measuring reflections from external sources**
  - **Thermal gradients need to be minimized. This is especially important in heterogenous thermal environments. Need to measure target's physical temperature at several locations [*Kunkee*; *McKague*, MicroRad, 2006].**

Calibration of Microwave Radiometers (2 of 2)

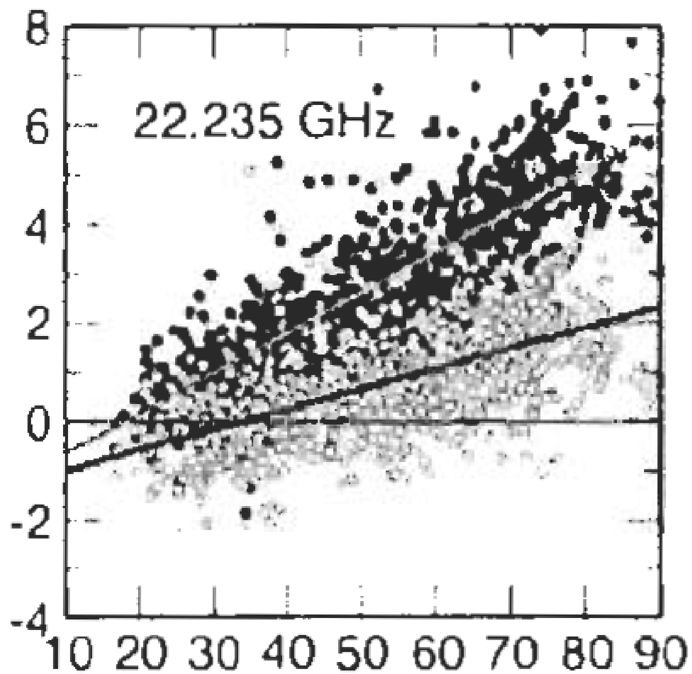
- **Tipping Curve Calibration (developed by Dicke in 1946)**
  - **To give a reference comparable to observed T_b's in atmospheric windows, T_b's are measured as a function of θ and converted to atmospheric opacity $\tau(\theta)$ using the mean radiating temperature approx.:**

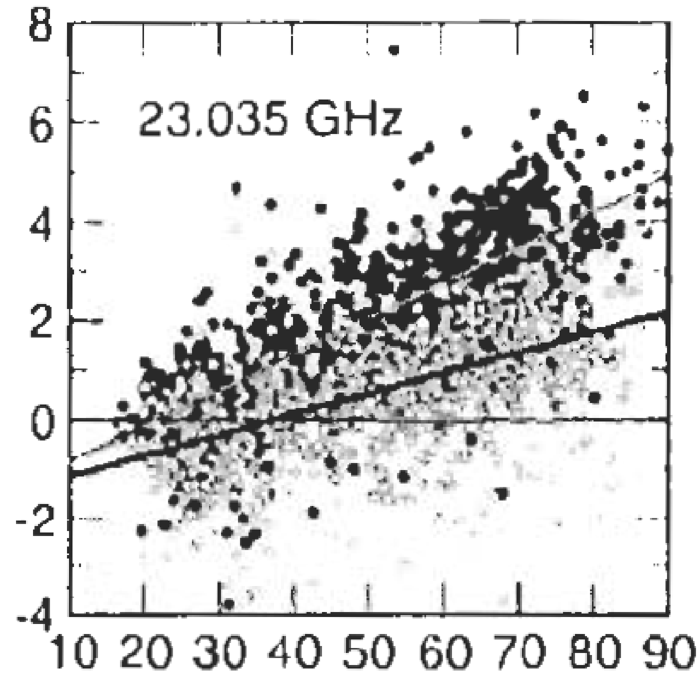
$$\tau(\theta) = \frac{\tau_0}{\cos\theta} = \ln\left(\frac{T_{mr}(\theta) - T_{\cos}}{T_{mr}(\theta) - T_b(\theta)}\right)$$

  - **Then $\tau(\theta)$ will be a linear function of the air mass** sec(θ)**, with an intercept at the origin. The slope of the line is the opacity.**
  - **Therefore, at the equivalent of zero air masses, the radiometer measures T_{cos}, the cosmic background temperature.**
  - **Most important error is when the atmosphere is not vertically stratified. Horizontal variations in clouds and water vapor need to be considered [*Han and Westwater, TGARS*, 2003].**
  - **Two-sided tipping curves can help detect these and pointing errors.**
- **Cryogenic: Blackbody loads immersed in LN_2 can calibrated to 0.7 K if done properly [*Cimini et al., TGARS,* 2003].**

Recent Update of 22.235 GHz Line Width (1 of 3)

From *Liljegren et al., TGARS*, 2005.

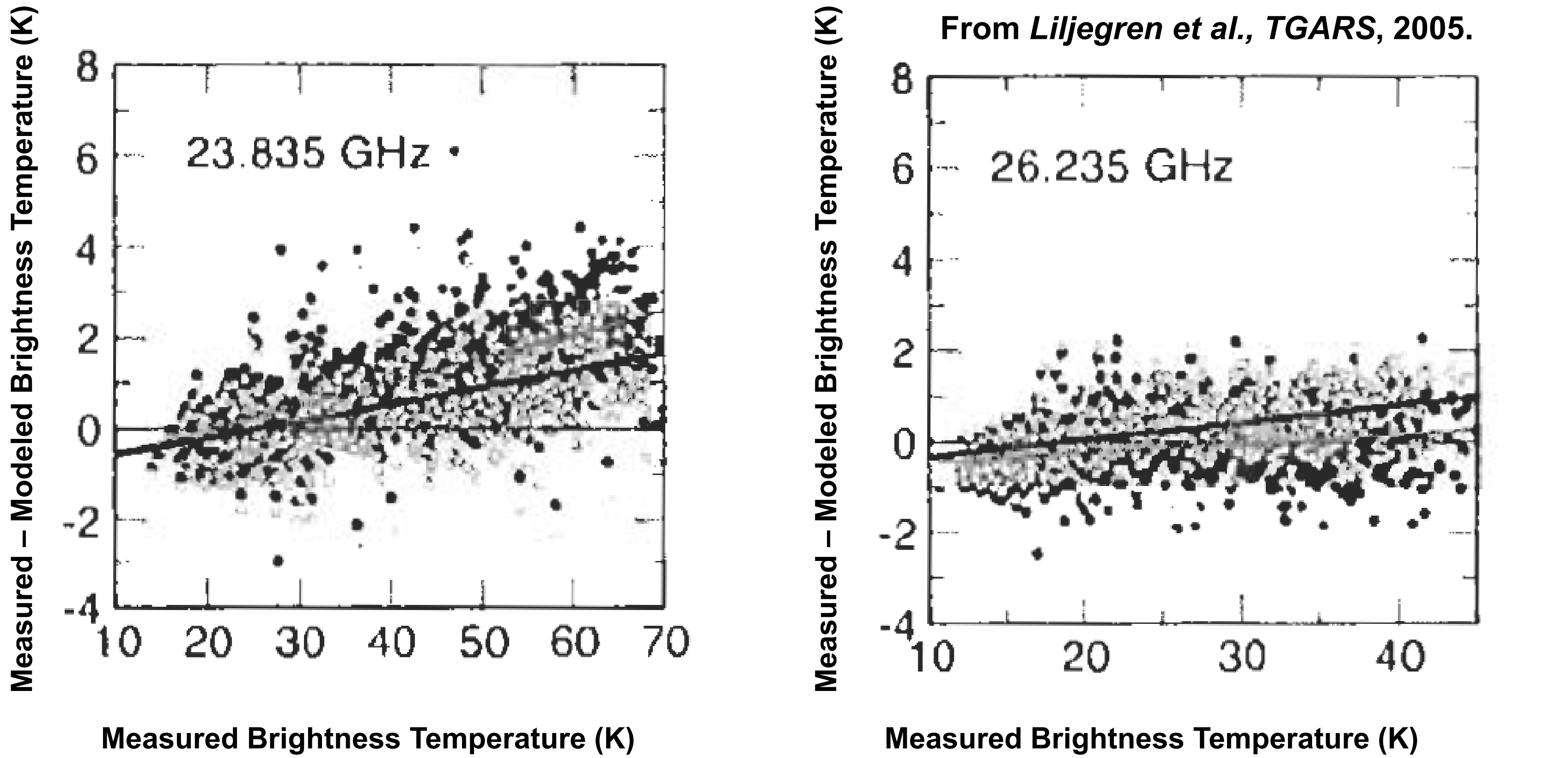




Difference between measured and model-calculated brightness temperature for the half-width of 22-GHz absorption line of *Liebe and Dillon* [1969] (solid circles, gray regression line) and the half-width from HITRAN [*Rothman et al., JQSRT*, 2005] (open circles, black regression line) for liquid-water-cloud free conditions

Recent Update of 22.235 GHz Line Width (2 of 3)

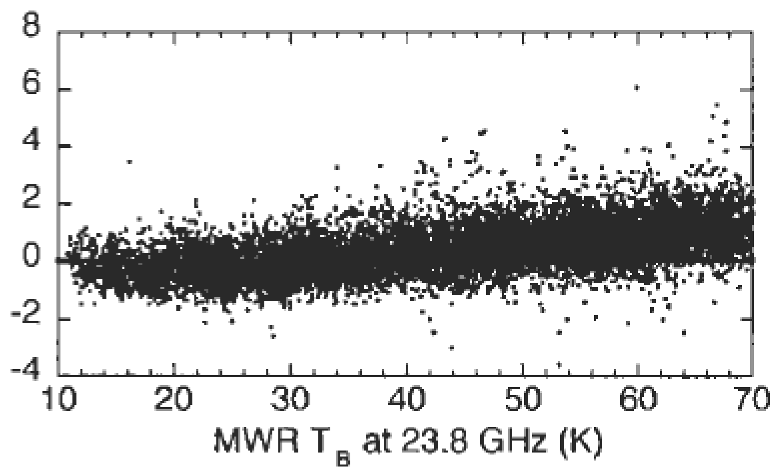
From *Liljegren et al., TGARS*, 2005.



Difference between measured and model-calculated brightness temperature for the half-width of 22-GHz absorption line from *Rosenkranz* [2003] or RO3 (solid circles, gray regression line) and the half-width from *Rosenkranz* [2003]-HITRAN or RO3-H (open circles, black regression line) for liquid-water-cloud-free conditions

Recent Update of 22.235 GHz Line Width (3 of 3)

T_B MWRP $_{23.835\ GHz}$ – T_B MWR $_{23.8\ GHz}$ (K)



T_B MWR $_{23.8\ GHz}$ (K)

Differences in measured brightness temperature T_B between the MWRP at 23.835 GHz and the collocated two-channel MWR at 23.8 GHz for liquid-water-cloud free sky conditions.

From *Liljegren et al., TGARS*, 2005.

Microwave Radiometers for Atmospheric Measurement and Profiling

- **Dual-frequency radiometers (e.g. U.S. DOE ARM MWR) measure Integrated Water Vapor (*IWV*) and Integrated Liquid Water (*ILW*) using either 20.6 GHz or 23.8 GHz (nearly insensitive to altitude) and one frequency in the 30-32 GHz band, to separate liquid water from water vapor.**
- **At low temperatures (-10 to -40ºC) and in dry conditions (IWV < ~ 3 kg/m^2), the sensitivity of brightness temperature measurements near 22.235 GHz to water vapor is fairly low. A way to overcome this lack of sensitivity is to measure brightness temperature near 183.31 GHz, which is 10-100 times more sensitive.**
- **However, the strong 183.31 GHz line is nonlinearly dependent on water vapor and temperature [*Racette et al.*, JAOT, 2005]. Therefore the weighting functions change markedly, depending on the amount of water vapor in the atmosphere.**
- **Examples of atmospheric profiling radiometers and recent results are provided in the following slides.**

TP/WVP-3000 Temperature and Humidity Profiling Radiometer: Radiometrics Corporation

- Humidity profiling and LWP: 22.035, 22.235, 23.835, 26.235 and 30.0 GHz (5 channels)
- Temperature profiling: 51.25, 52.28, 53.85, 54.94, 56.66, 57.29 and 58.8 GHz (7 channels)
- Infrared pyrometer to calculate cloud base height using temp. profile
- Surface meteorological station
- Rain effect mitigation system included
- Calibrates using tipping curves and a patented cryogenic blackbody target

From http://www.radiometrics.com

- Superheterodyne receiver with single IF bandwidth
- Measures frequency channels sequentially (complete in <20 sec.)
- Frequency agility to accomodate RFI in RF band

From *Ware*, “Principles of Ground-Based Radiometric Profiling, 2004.

U.S. DOE, Barrow, Alaska

DWD, Lindenberg, Germany

UKMO, Camborne, U.K.

Meteo Swiss, Payerne

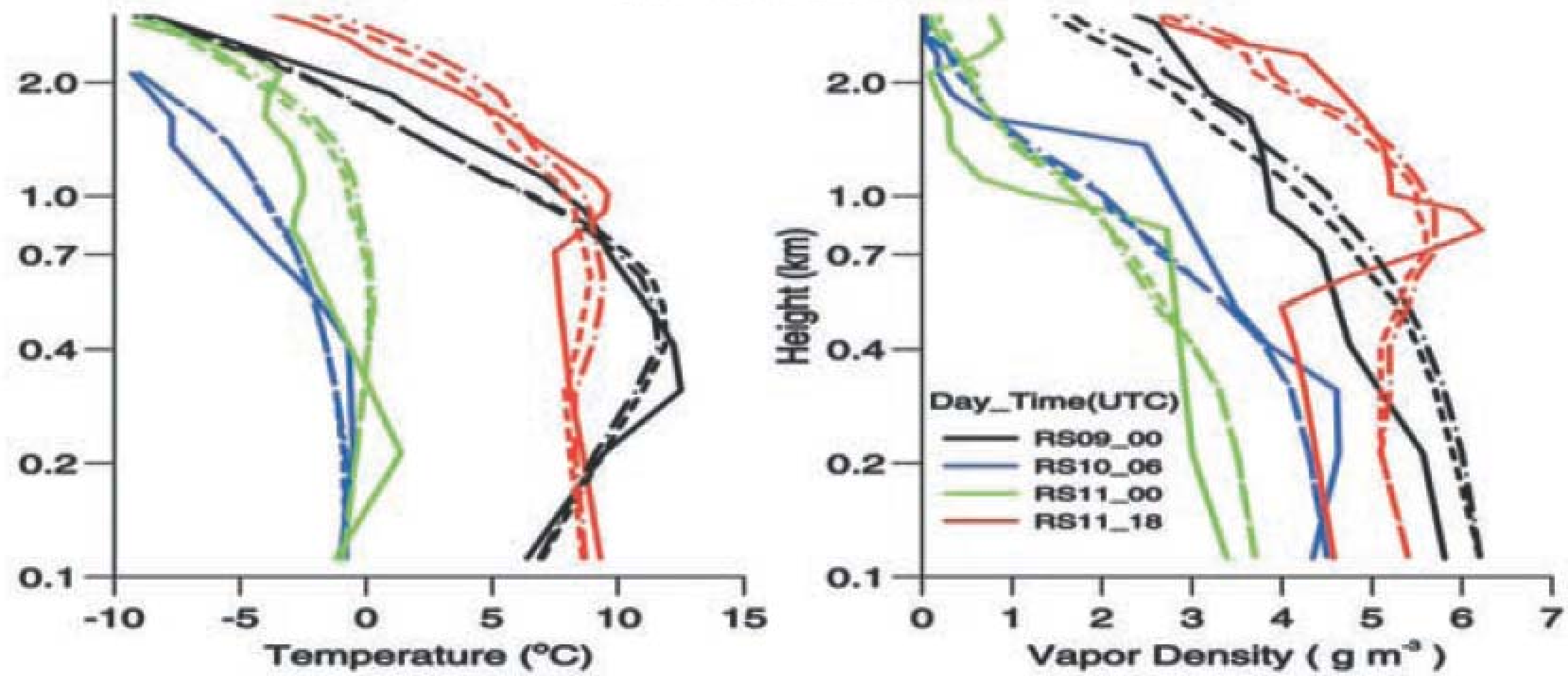
HKO, Hong Kong Airport

MSC, Ottawa, Canada

Radiometric profiler installations for operations and operations research.

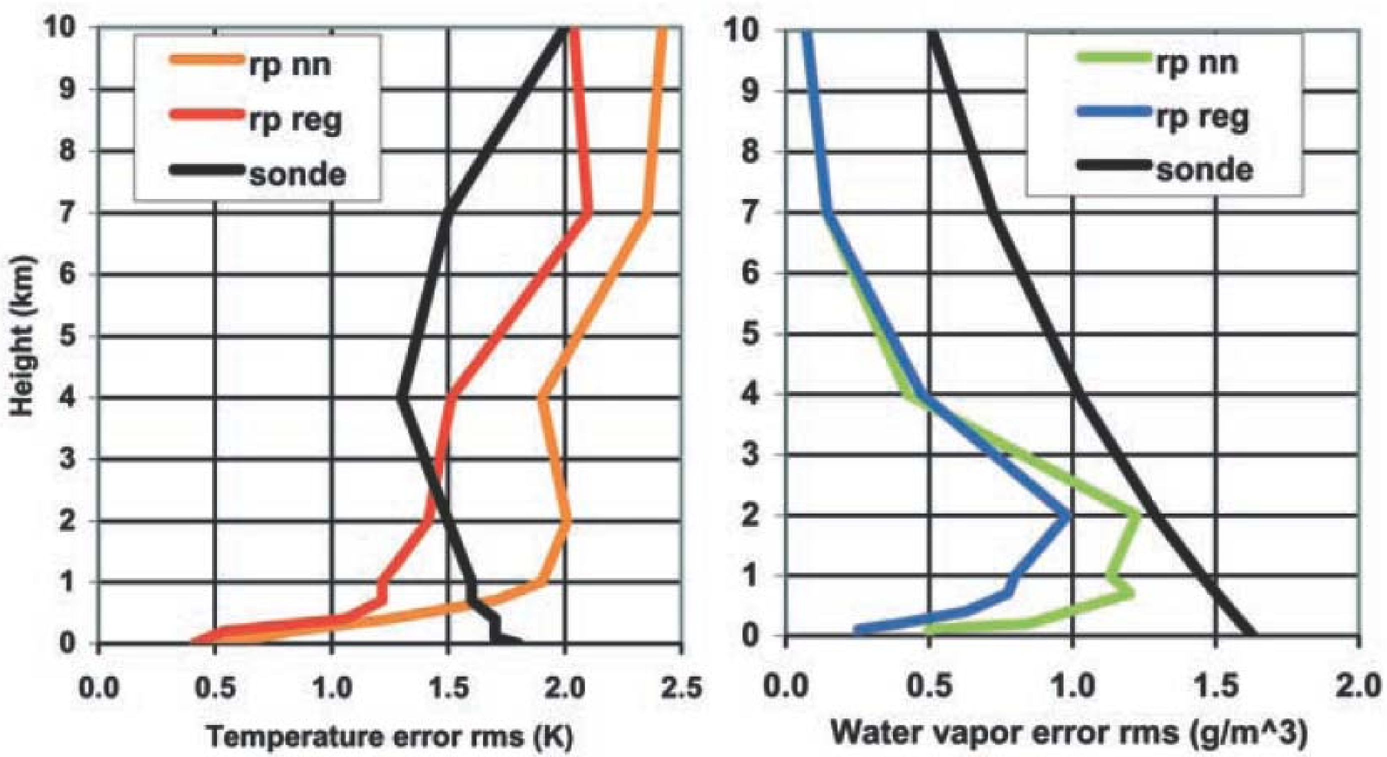
Comparison of Radiometric and Radiosonde Profiles: Radiometrics TP/WVP-3000

From *Ware et al., RS*, 2003.



Radiosonde (solid) and radiometric soundings before (dashed) and after (dot-dashed) the radiosonde launch in Lindenberg, Germany, are shown with logarithmic height scale. Differences show the high vertical resolution of radiosonde point measurements vs. the volumetric radiometer measurements with lower vertical resolution. Ground vapor differences may be due to high spatial variability in 100 m between radiometer and radiosonde sites.

Statistical Comparison of Radiometric and Radiosonde Profiles: Radiometrics TP/WVP-3000



From *Ware et al., RS*, 2003. For statistical analysis of 237 soundings during summer and 254 during winter, see *Güldner and Spänkuch, JAOT*, 2001.

Calibration accuracy from tipping curves at K-band and cryogenic load observations at V-band is 0.5 K during clear sky. Retrievals using regressions against radiosondes are insensitive to calibration and forward model errors. Regression retrieval errors are smaller than neural network retrieval errors. The NCEP sonde errors shown in black are dominated by spatial sampling errors.

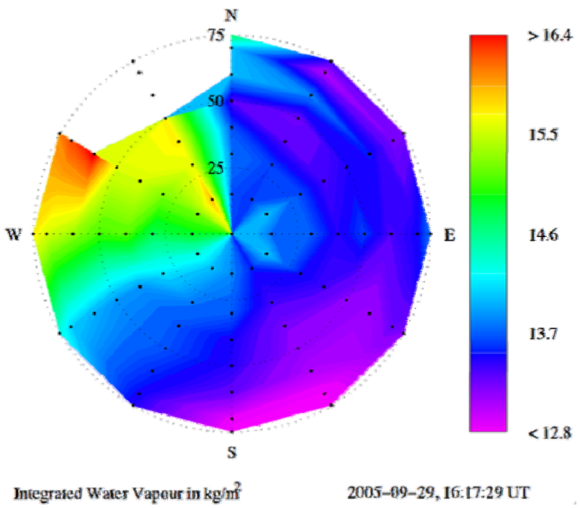
ASMUWARA: All Sky Multiwavelength Watervapor Radiometer: University of Bern

From *Kämpfer et al.*, MicroRad 2006, San Juan, PR, USA

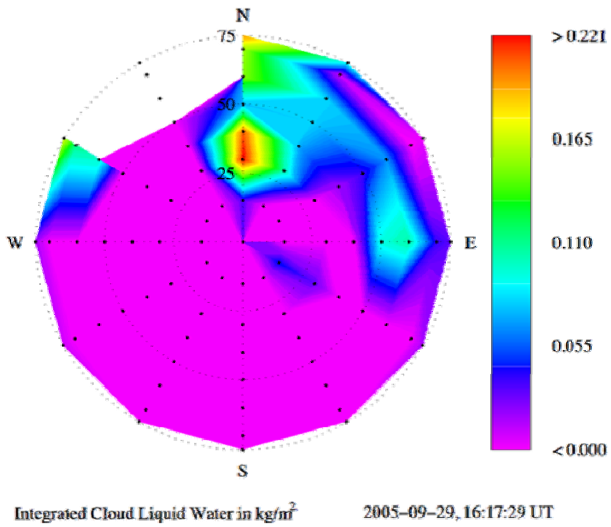
- **Detects infrared and microwave radiation at 10 frequencies**
- **Measures temperature, humidity and clouds automatically and in near-real time**
- **Generates images of water vapor and cloud liquid water over the sky**
- **Generates profiles of tropospheric humidity and temperature**

Examples of Skymaps of IWV and ILC (ILW):
University of Bern

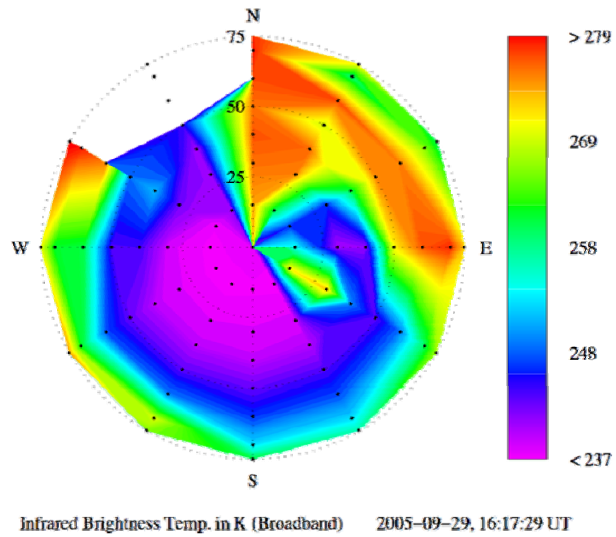
IWV



ILW

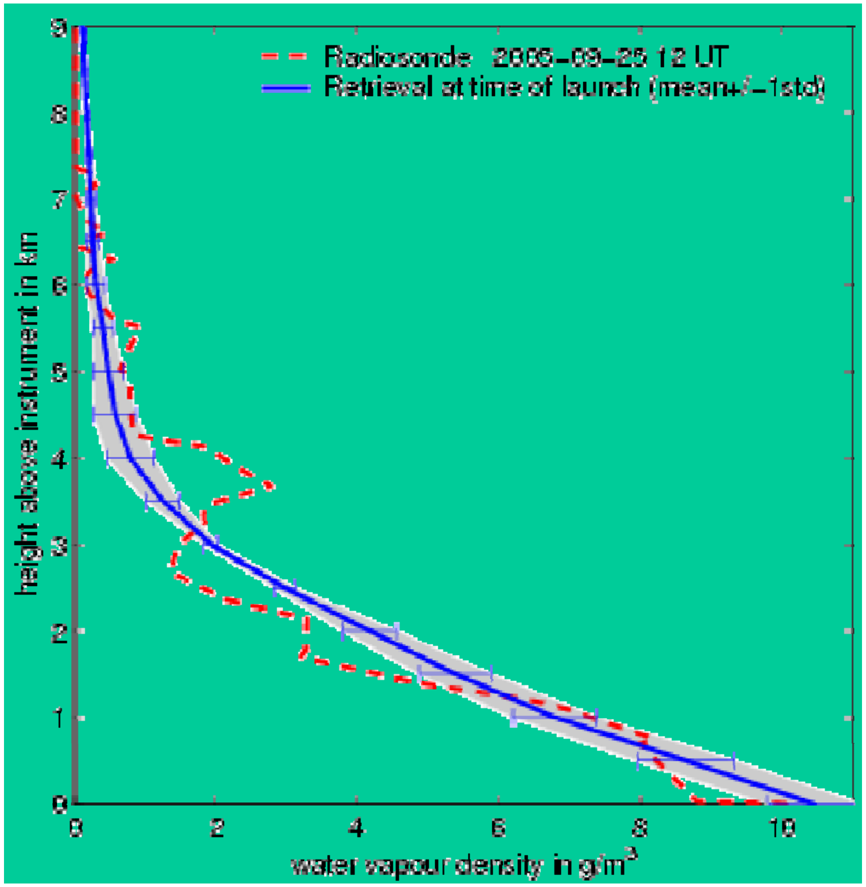


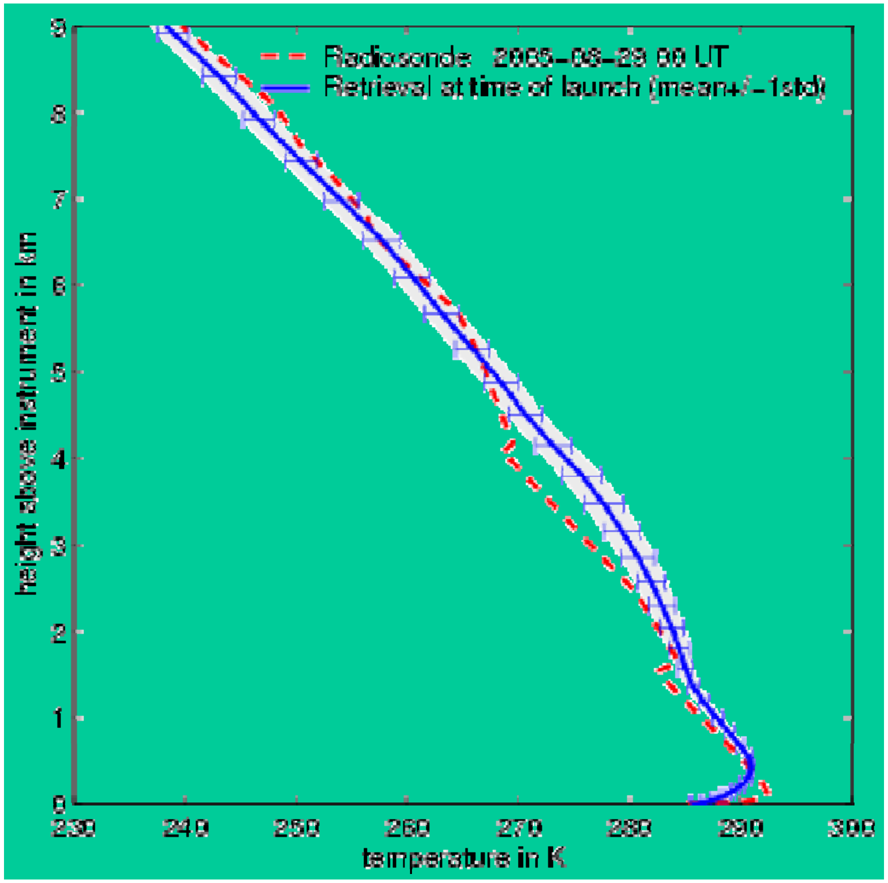
IR



From Ph.D. thesis M.Schneebeli and *Kämpfer et al.*, MicroRad 2006, San Juan, PR, USA

Example Comparison of Radiometer Temperature and Humidity Profiles to Radiosondes: Univ. of Bern





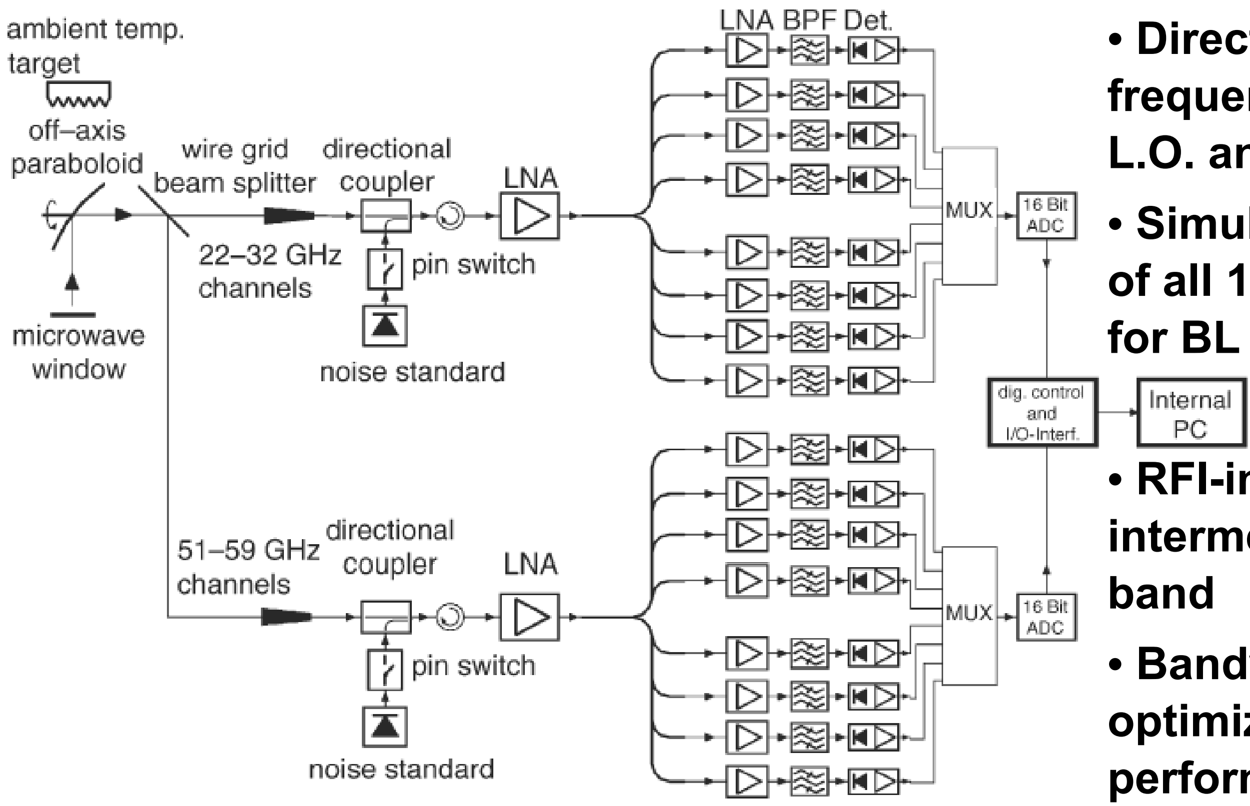
From Ph.D. thesis M.Schneebeli and *Kämpfer et al.*, MicroRad 2006, San Juan, PR, USA

RPG-HATPRO Temperature and Humidity Profiling Radiometer: Radiometer-Physics GmbH

- **Humidity profiling: 22-31.4 GHz band (7 channels)**
- **Temperature profiling: 51-58 GHz band (7 channels)**
- **BL profiling: 54-59 GHz (4 chans.)**
- **IWV / LWP: 23.8 / 31.4 + 90 GHz**
- **Integrated meteorological station**
- **Rain detector and strong blower to eliminate water due to rain or dew**

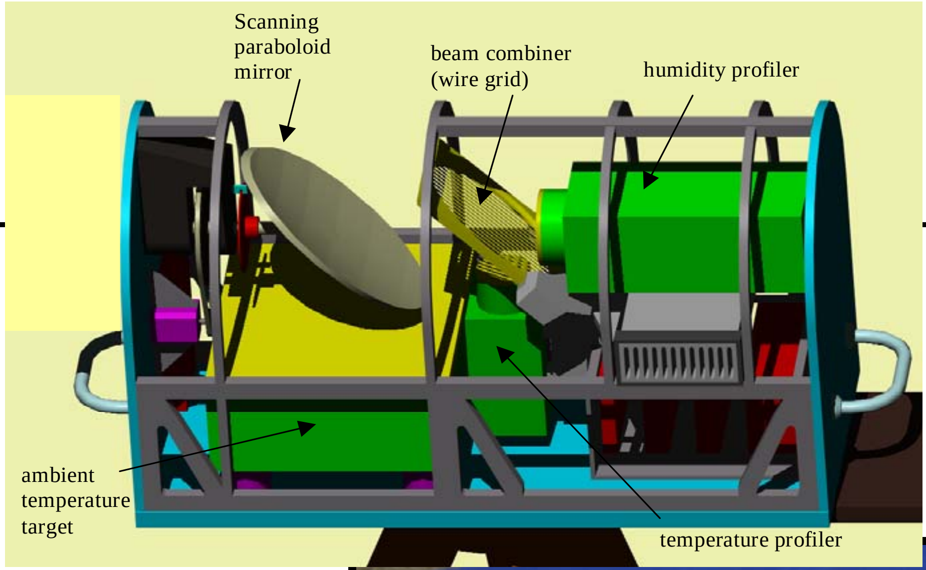
From *Rose and Czekala*, MicroRad 2006, San Juan, PR, USA

RPG-HATPRO: Network Suitable 14-Channel Filterbank Radiometer: Radiometer-Physics GmbH



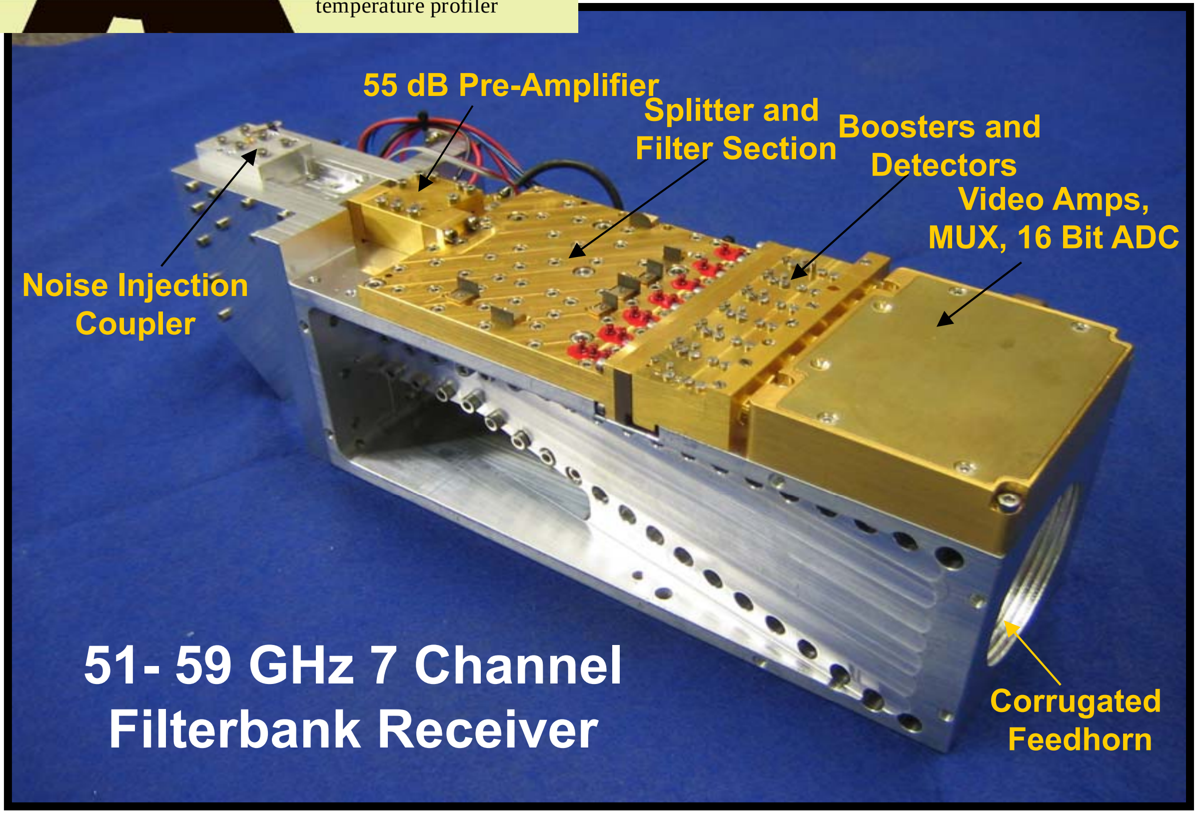
From *Rose et al., Atmospheric Research,* 2005.

- **Direct Detection at RF frequencies: avoid possible L.O. and mixer problems**
- **Simultaneous measurement of all 14 channels – important for BL elevation scanning**
- **RFI-insensitive in intermediate frequency (IF) band**
- **Bandwidth is selectable to optimize radiometric performance for temperature profiling:**
  - **300 MHz at 50-54 GHz**
  - **2 GHz at 58 GHz for BL elevation scanning**



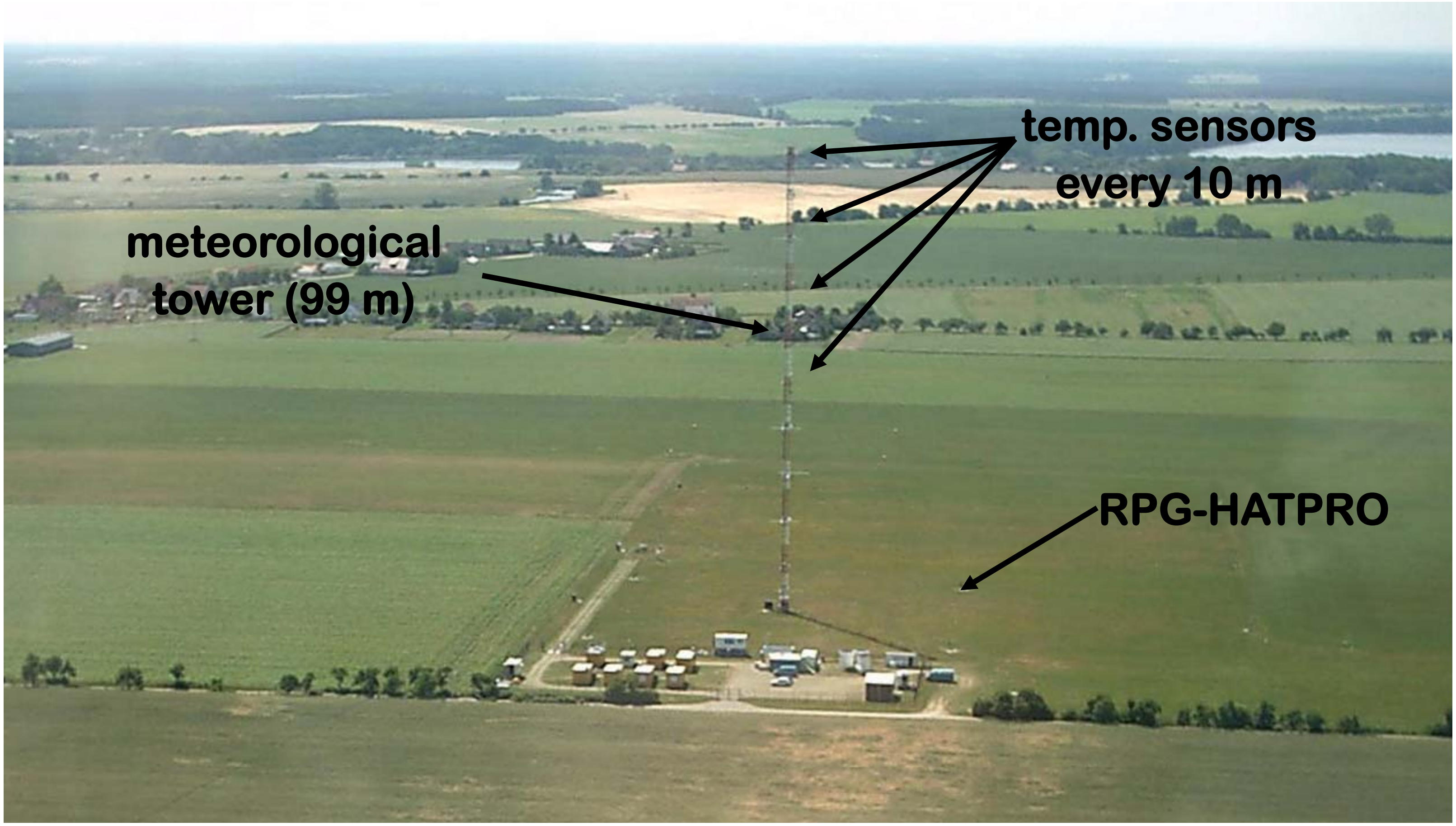
RPG-HATPRO:
Radiometer-Physics GmbH

- Receiver control to <30 mK
- Absolute Calibration:
  - LN_2 cryogenic load
  - Internal ambient load
- Periodic Calibration:
  - 2 noise sources
  - Tipping curve
  - Internal ambient load
- Antenna beamwidth 3 - 4°
- Sidelobe levels < -30 dB
- Projected diameter 0.25 m



Boundary Layer Scanning for Temperature Profiling:
Radiometer-Physics GmbH

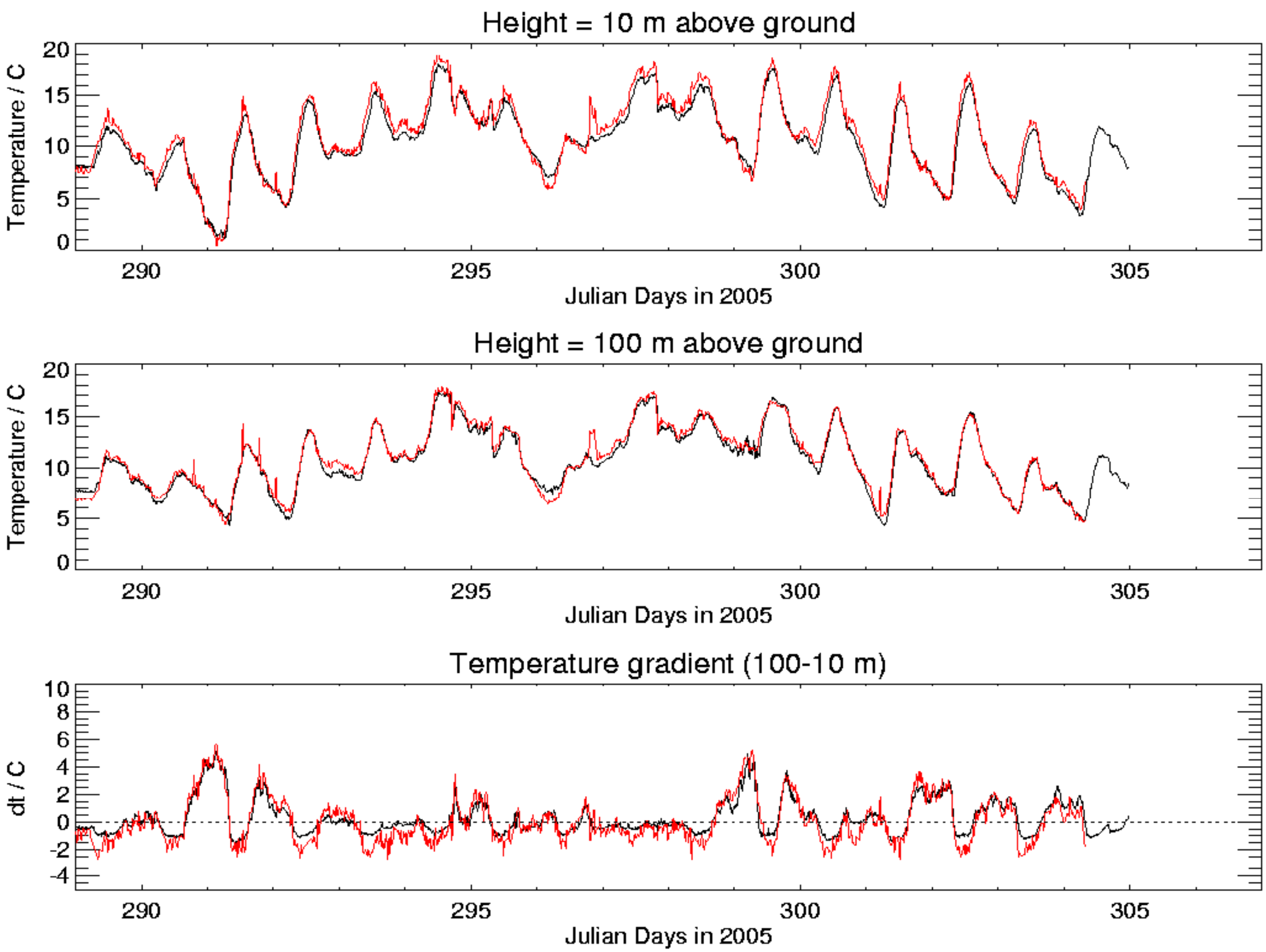
RPG-HATPRO at DWD Lindenberg, Sept. 2005



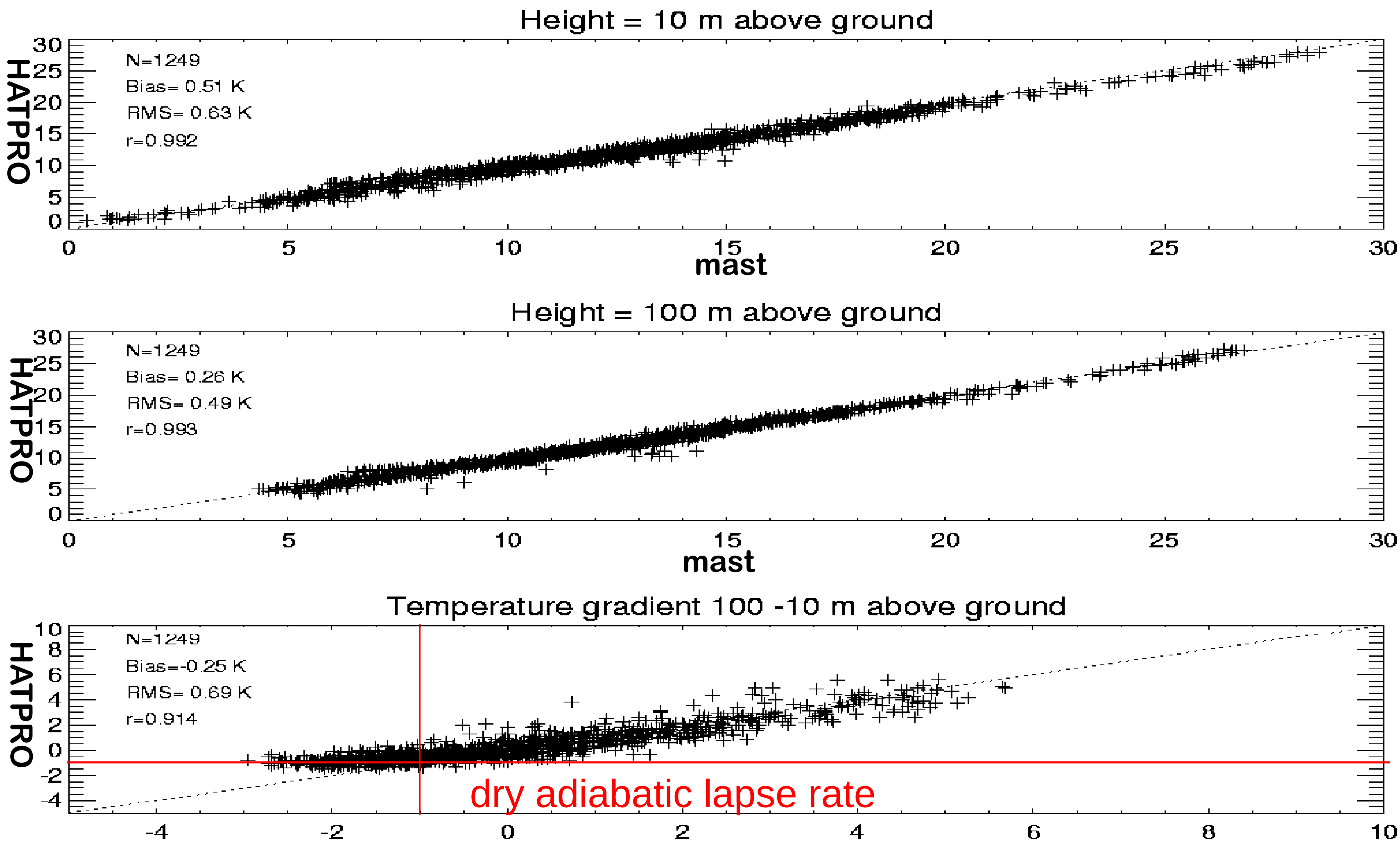
Direct Comparison of Temperature at 10 and 100 m Levels: Radiometer-Physics GmbH

Mast

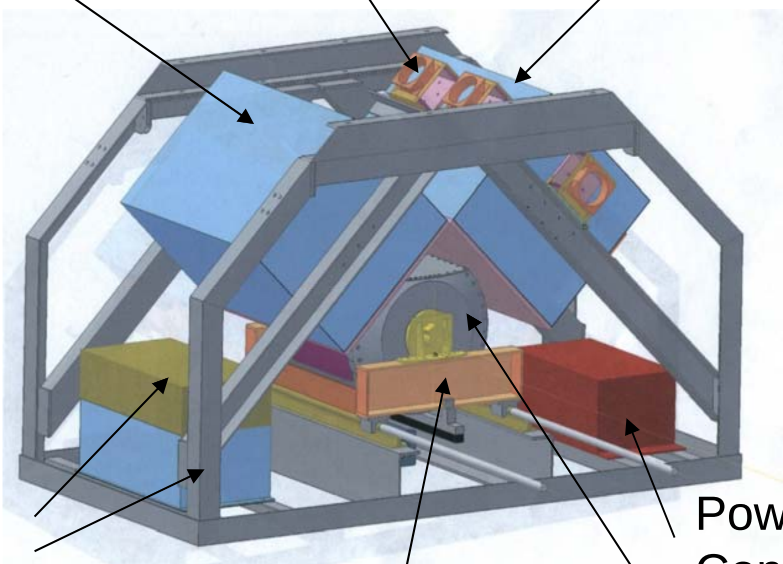
HATPRO

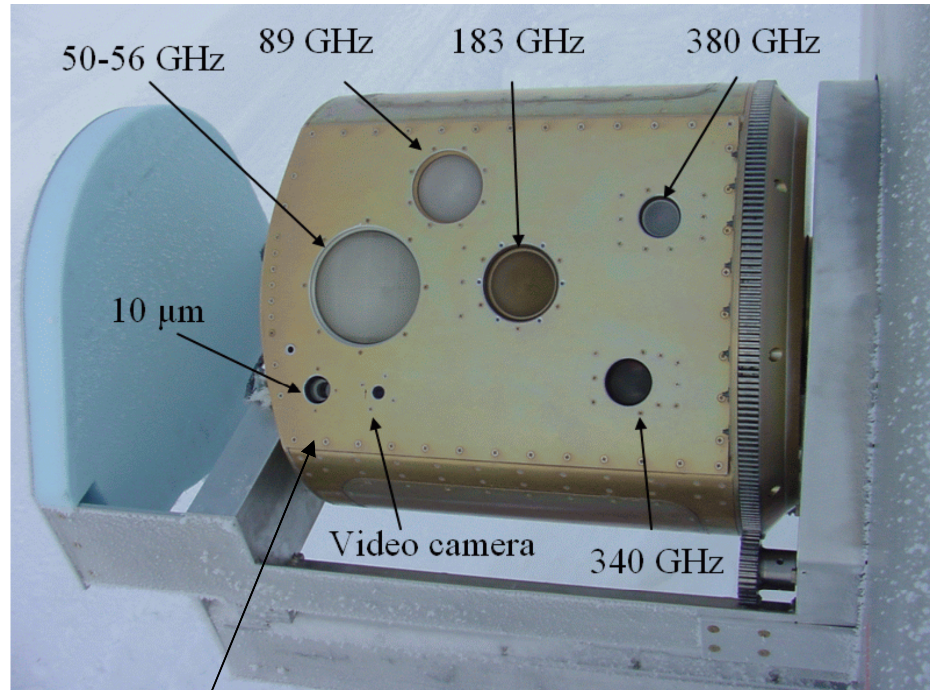


Direct Comparison of Temperature at 10 and 100 m Levels: Radiometer-Physics GmbH



Ground-Based Scanning Radiometer:
NOAA/ESRL - University of Colorado Boulder





Principal features:

From *Cimini et al.*, MicroRad 2006, San Juan, PR, USA

– 25 channels, high sensitivity to water vapor and clouds

– Three levels of calibration, high accuracy

– Highly appliciable to Arctic Research

The Arctic Winter Radiometric Experiment
WVIOP2004: NOAA/ESRL - CU Boulder

PI: E.R. Westwater

Co-PIs: A.J. Gasiewski, M. Klein, V. Leuski

Period: March-April 2004

Location: ARM NSA, Barrow, Alaska

Instruments:

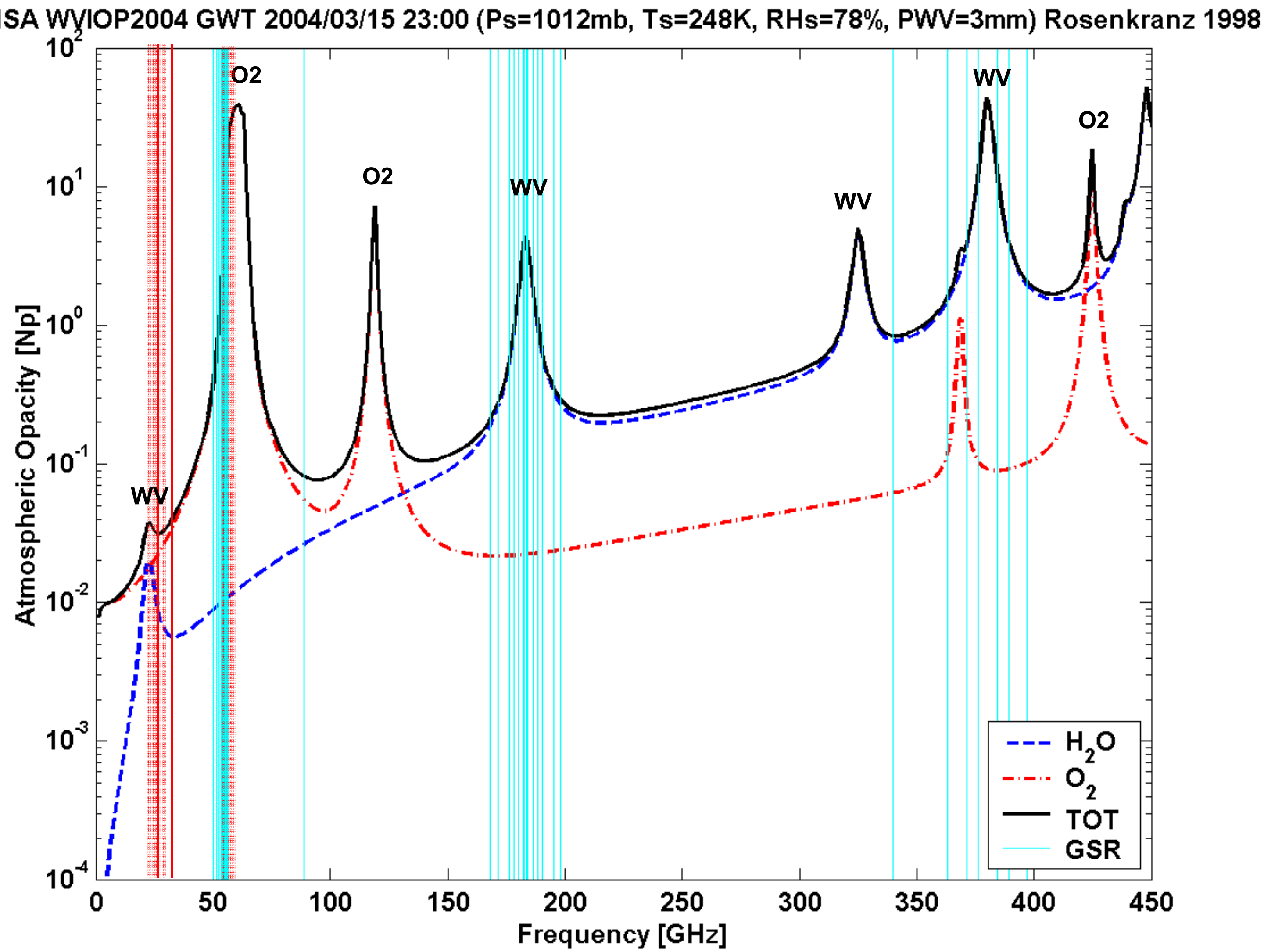
1) Dual channel Microwave Radiometer (MWR):
   23.8; 31.4 GHz

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) 25-channel Ground-based Scanning Radiometer (GSR)
   50.2; 50.3; 51.76; 52.625; 53.29; 53.845; 54.4; 54.95; 55.52; 56.025; 56.215; 56.325
   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±4; ±9; ±17 GHz

From *Cimini et al.*, MicroRad 2006, San Juan, PR, USA

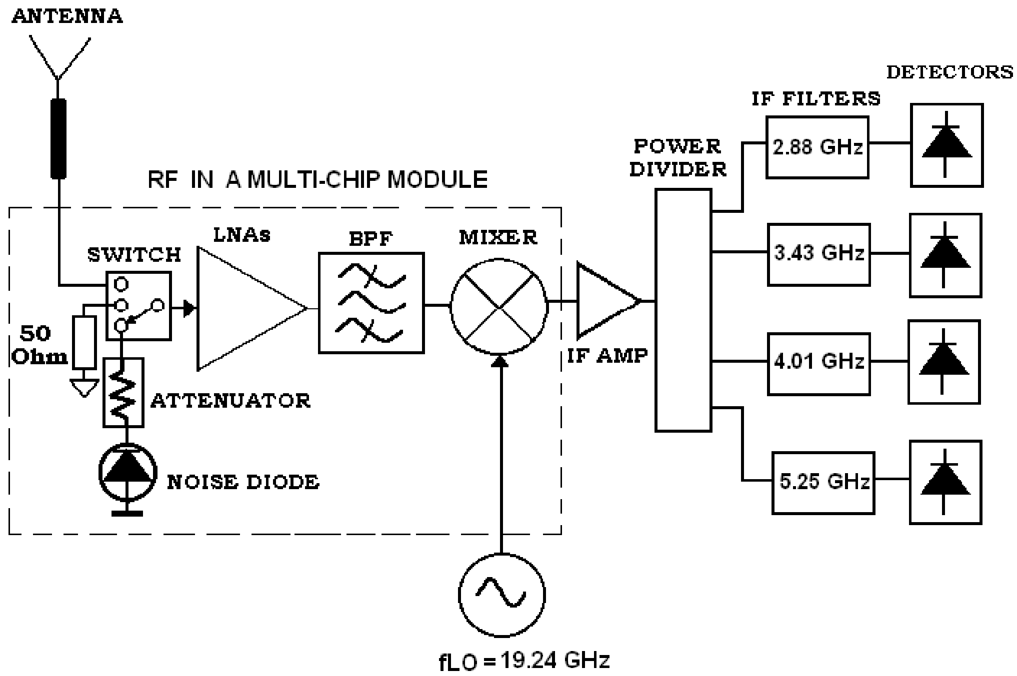
Atmospheric Opacity for Arctic Conditions:
NOAA/ESRL - CU Boulder



Miniaturized Water Vapor profiling Radiometer (MWVR): Colorado State University

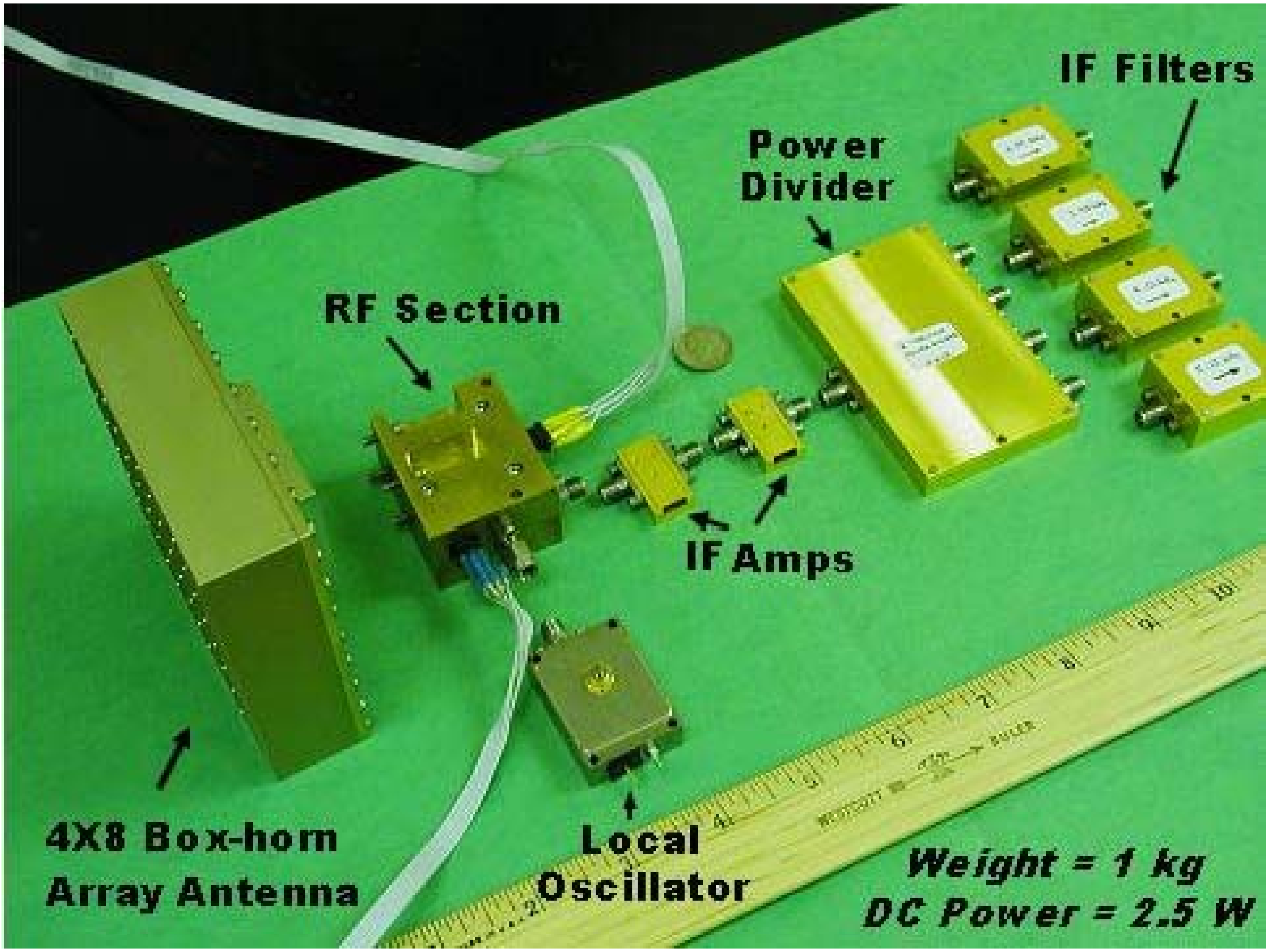
Colorado State University
Knowledge to Go Places

The MWVR is a MMIC-based spectral radiometer with four frequency channels around the 22.235 GHz water vapor resonance: 22.12, 22.67, 23.25 and 24.49 GHz



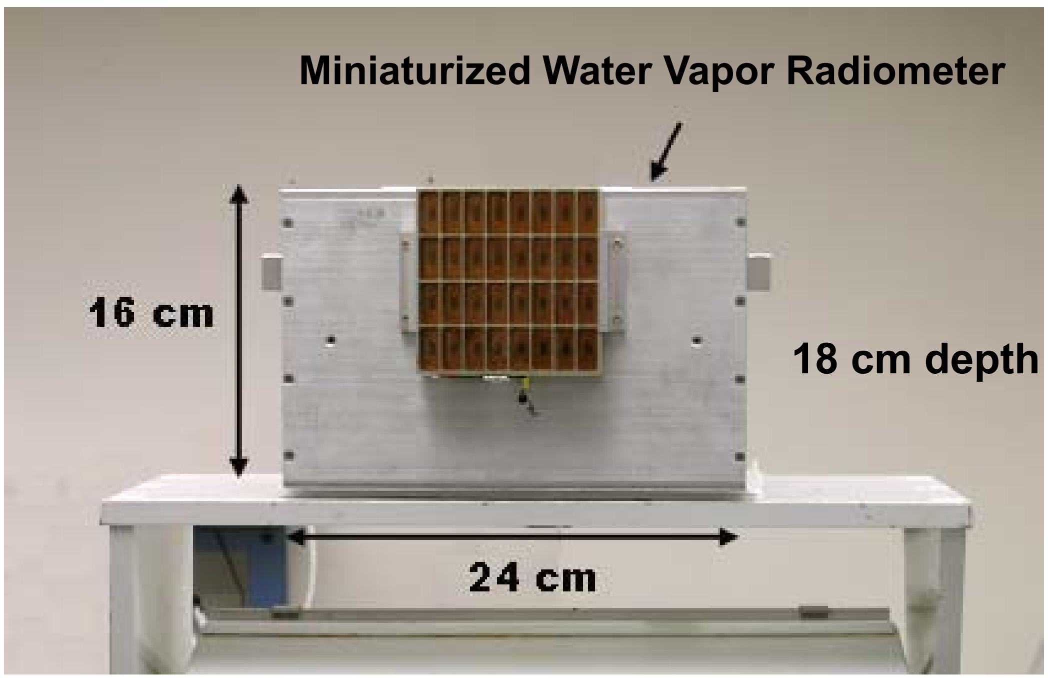
Block Diagram of the MWVR subsystem

RF and IF Subsystems of MWVR:
Colorado State University



Specifications of the Miniaturized Water Vapor profiling Radiometer: Colorado State University

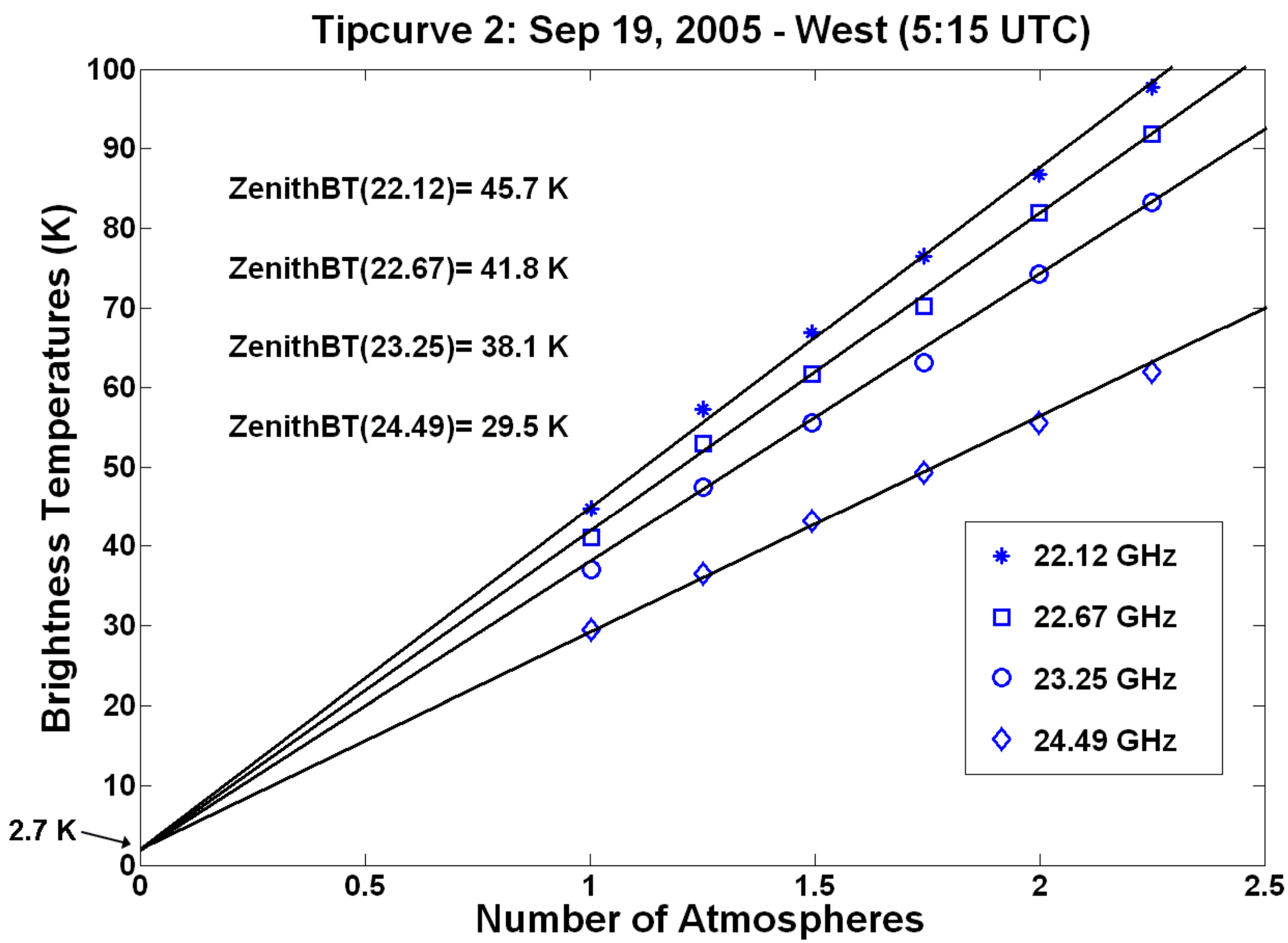
Radiometer	Mass (kg)	Size (cm)	Volume (cm^3)	Power (W)	Sensitivity @ 1-sec (K)
MWVR	6	24 x 18 x 16	6.9 x 10^3	30 (max.)	0.2 - 0.3



Additional Internal Components:

- **Temperature Control System**
- **Embedded Computer**
- **Hard Disk**

Tipping Curve Calibration of Miniaturized Water Vapor profiling Radiometer: CSU



Sensitivity of Miniaturized Water Vapor profiling Radiometer: Colorado State University