Measurements of Temperature, Water Vapor, Clouds, and Winds Derived from Ground-Based Remote Sensors

James Liljegren
ARM Climate Research Facility Instrument Coordinator
Argonne National Laboratory

Reference Upper Air Observations for the Global Climate Observing System:
Potential Technologies and Networks
Applied Physics Lab, University of Washington, Seattle
22-24 May 2006

Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

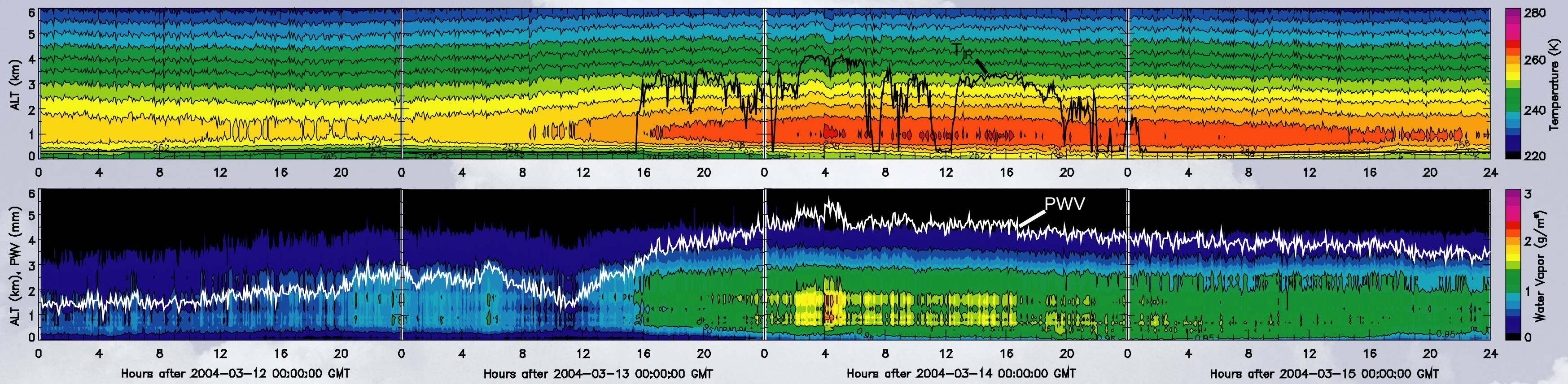
Contributors

- Wayne Feltz, Univ. of Wisc. (AERI)
- Maria Cadeddu, ANL (Microwave Radiometers)
- Suzanne Crewell, Univ. of Cologne (Microwave Radiometers)
- Ed Westwater, Univ. of Colorado (Microwave Radiometers)
- Diana Petty, PNNL (Raman Lidar)
- Zhien Wang, Univ. of Wyoming (Raman Lidar)
- Vic Morris, PNNL (Sky Imagers)
- David Turner, Univ. of Wisc. (Raman Lidar, LWP w/AERI+MWR)
- Richard Coulter, ANL (Wind Profiling Radar, Sodar)
- Ric Cederwall, BNL (Constrained Variational Analysis)
- Laurel Chapman, ANL (Operational Cost)

Overview

- Temperature and Water Vapor
  - Passive Microwave and Infrared Sensors
  - Active (Lidar, Radio-Acoustic) Sensors
- Clouds
  - Passive (microwave, IR, optical) for LWP; Sky Imagers
  - Active (Lidar, Radar) for base height, thickness, LWC/IWC)
- Winds
  - Radar, Sodar for vector profiles
- Capabilities of Individual Remote Sensors
- Complementary Aspects (vis-à-vis each other, soundings)
- Advantages of Combining Sensors

Passive Remote Sensing



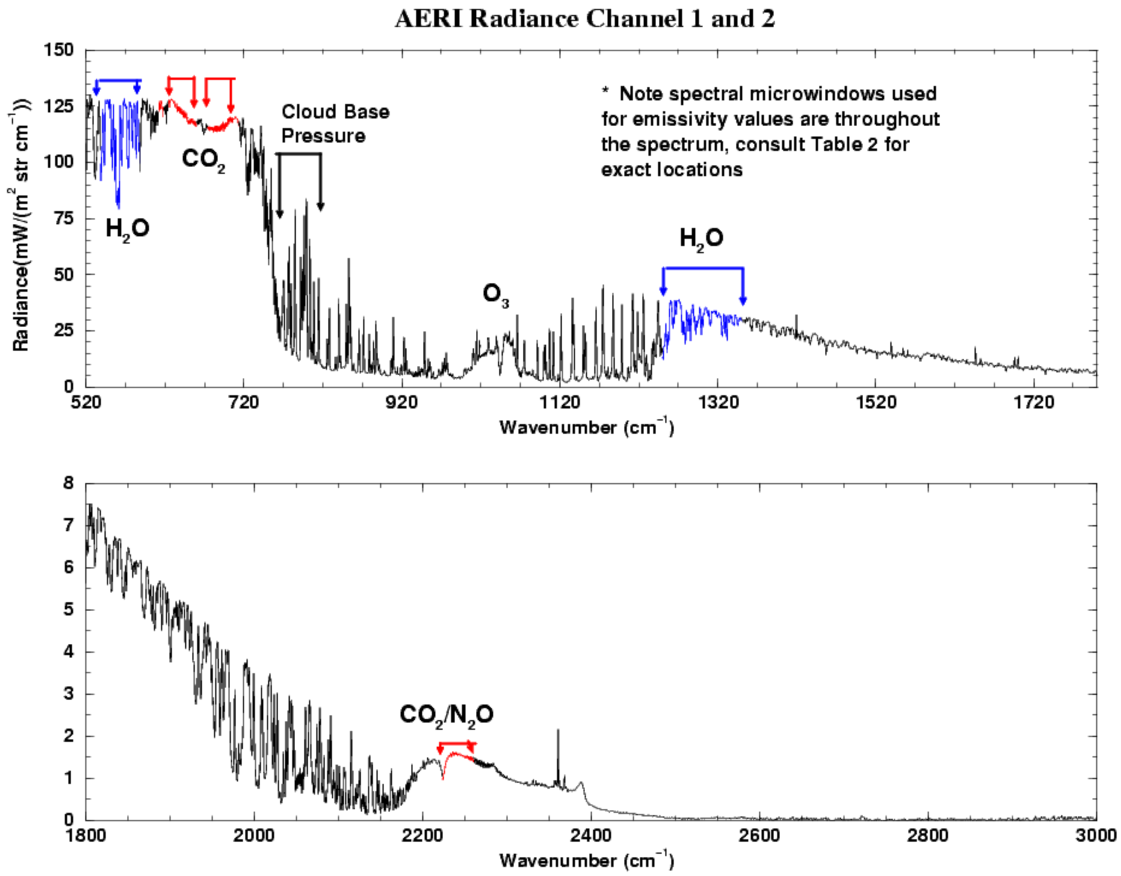
- Continuous profiling to supplement 1-2/day radiosondes
- Temporal and vertical resolution trade-off
- Elevated inversions and moisture gradients difficult to resolve
- Multi-angle retrievals, combined sensor retrievals
- Retrieval algorithm methodologies
- Effect of weather conditions
- Reliability, autonomy, calibration → operating cost

AERIs at SGP Site

Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

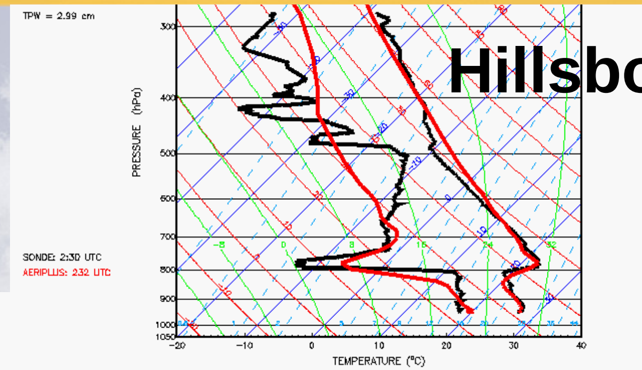
Spectral Regions used in AERI Retrieval

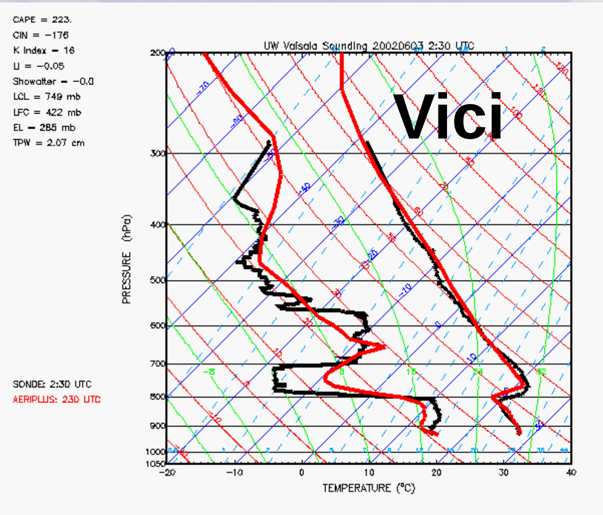


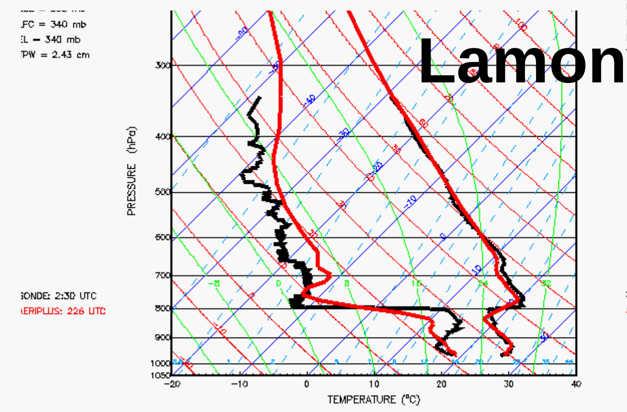
Courtesy of Wayne Feltz

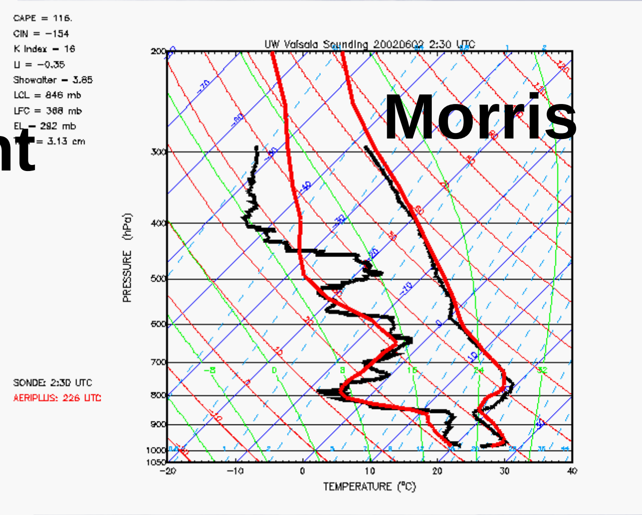
Comparison with Radiosondes

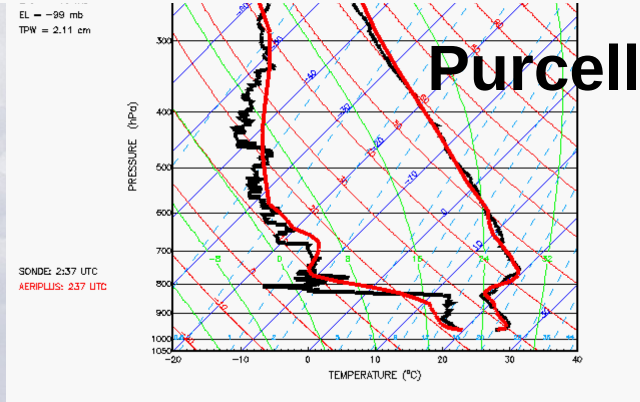
3 June 2003 0230 UTC











Courtesy of Wayne Feltz

Atmospheric Radiation Measurement
Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

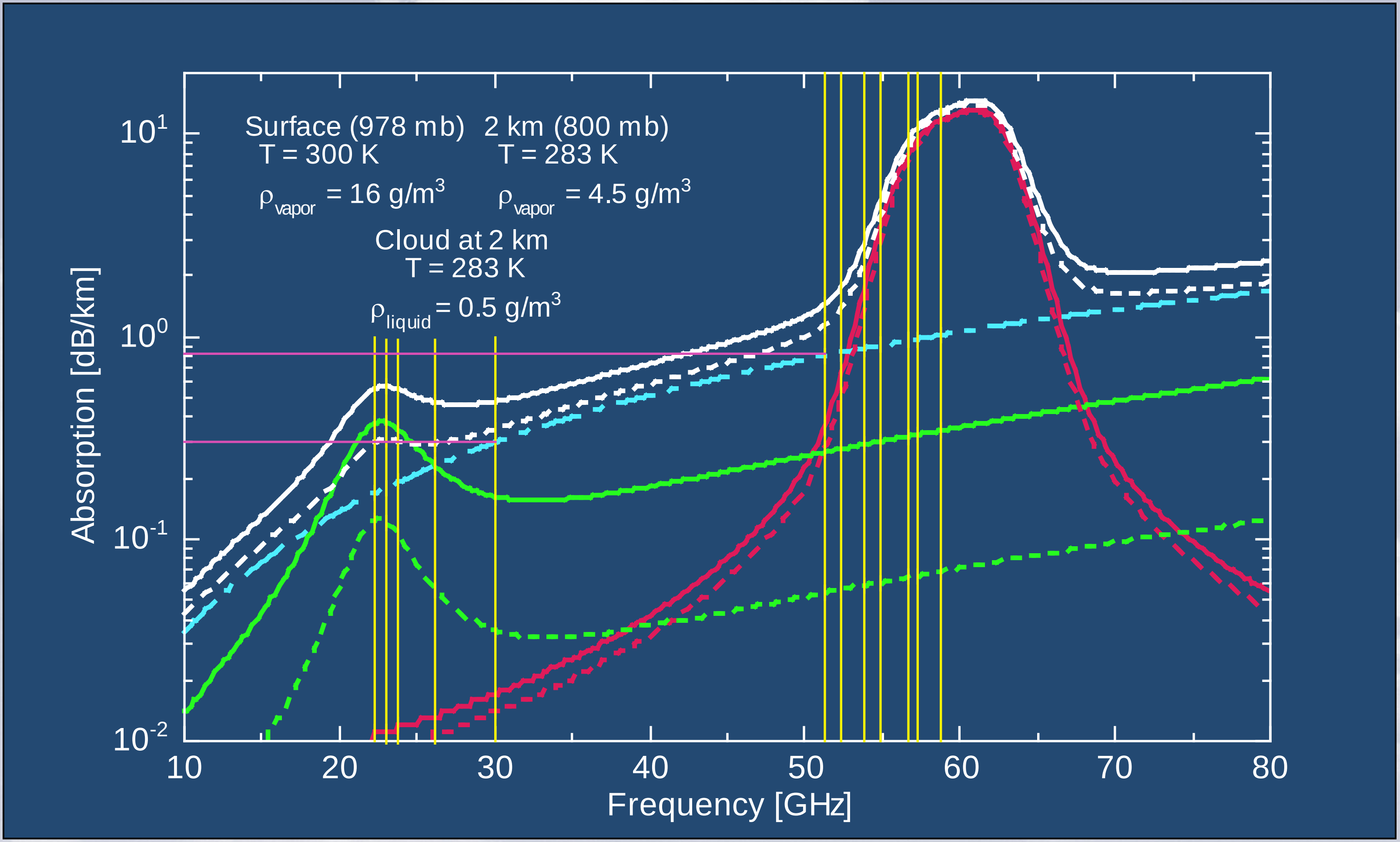
Passive Infrared (AERI)

- **Wavelength/frequency:** 3300-520 cm^{-1}, 3-20 µm; 1.0 cm^{-1} resolution
- **Vertical Range:** 0-3 km (clear sky) or to cloud base height
- **Vertical Reporting Interval:** 5 mb (~50 m) from surface to 900 mb, 20 mb (~200 m) 900-600 mb, 50 mb above 600 mb (RUC)
- **Vertical Resolution:** varies with height
- **Temporal Resolution:** 6-10 minutes; upgraded ARM systems will be 20 seconds
- **Accuracy:** < 1 K for temperature; 5% for water vapor mixing ratio compared with radiosondes (radiance accuracy < 0.1% ambient blackbody radiance)
- **Accuracy constraints:** spectroscopy (bias spectrum), first guess/a priori information
- **Precision:** ~1 K RMS for temperature; varies with height for water vapor mixing ratio
- **Calibration:** two blackbody references (50° C, ambient); no LN_2 required
- **Weather constraints:** no measurements during precipitation (hatch closed), cloudy sky limitations on retrievals
- **Shelter requirements:** shelter with roof port/hatch; controlled environment for electronics
- **Initial cost:** $250,000 (Univ. of Wisc/SSEC)
- **Operating cost:** $100,000/year (interferometer, stirling cooler, cryogenic dewar)

ARM Site at Barrow, Alaska

- **MWRP: 5 channels 22-30 GHz, 7 channels, 50-60 GHz**
- **GVR: 4 channels, 183.31±1, ±3, ±7, ±14 GHz**
- **MWR: 2 channels at 23.8 and 31.4 GHz**
- **New: 90 and 150 GHz (summer 2006)**

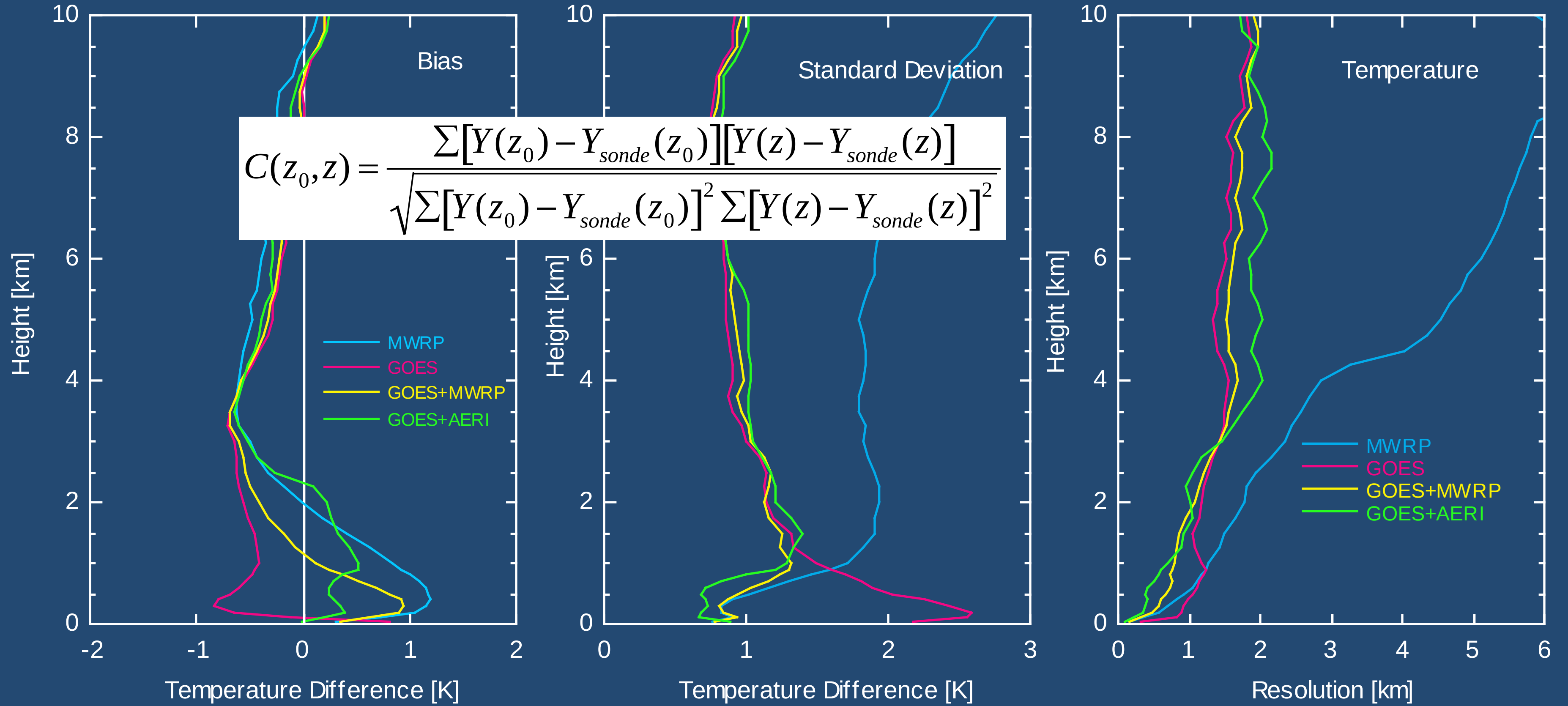
Measurement Channels



Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

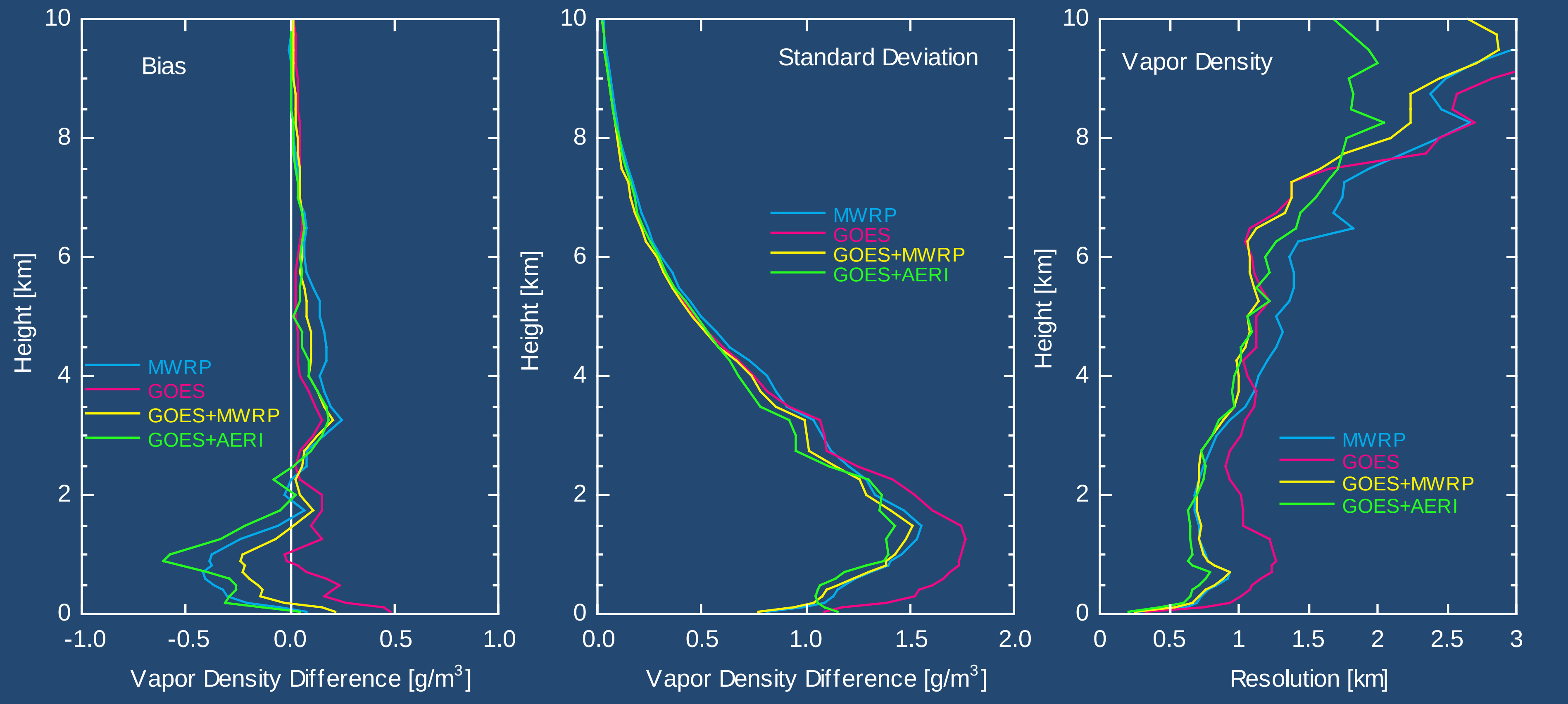
Office of Science
U.S. Department of Energy

Temperature Combined with GOES

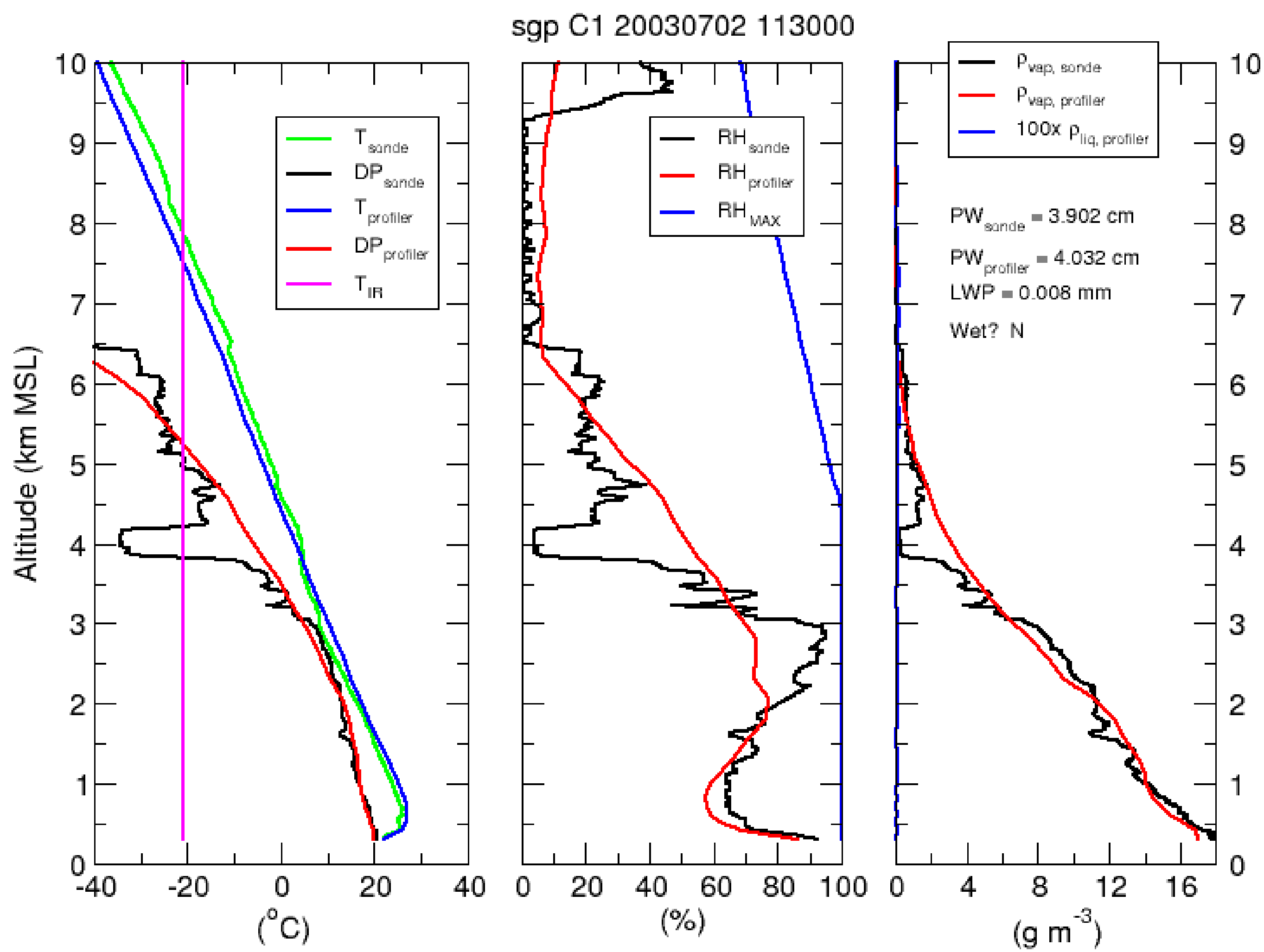


$$C(z_0,z)=\frac{\sum\left[Y(z_0)-Y_{sonde}(z_0)\right]\left[Y(z)-Y_{sonde}(z)\right]}{\sqrt{\sum\left[Y(z_0)-Y_{sonde}(z_0)\right]^2\sum\left[Y(z)-Y_{sonde}(z)\right]^2}}$$

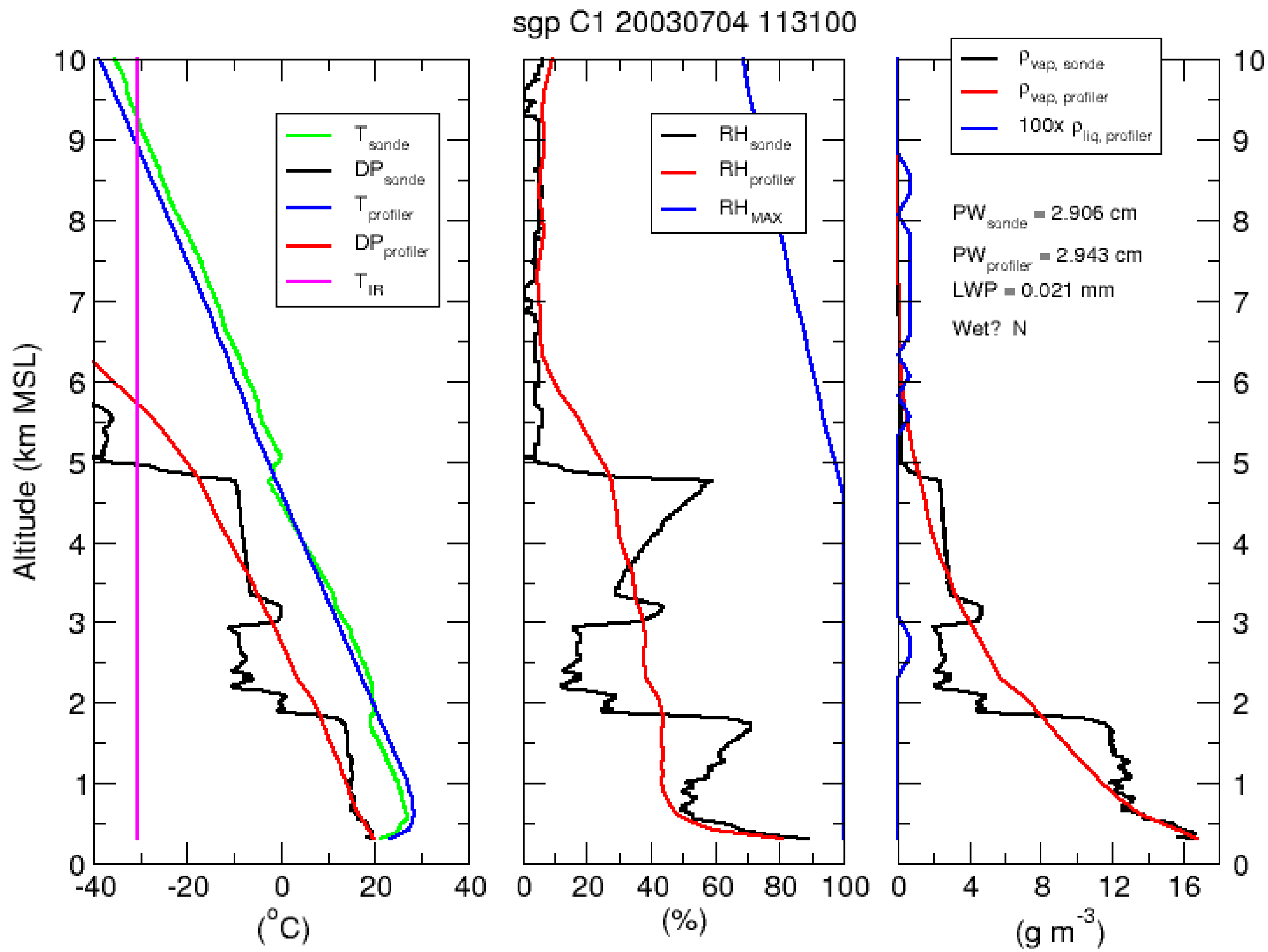
Water Vapor Combined with GOES



Comparison with Radiosonde



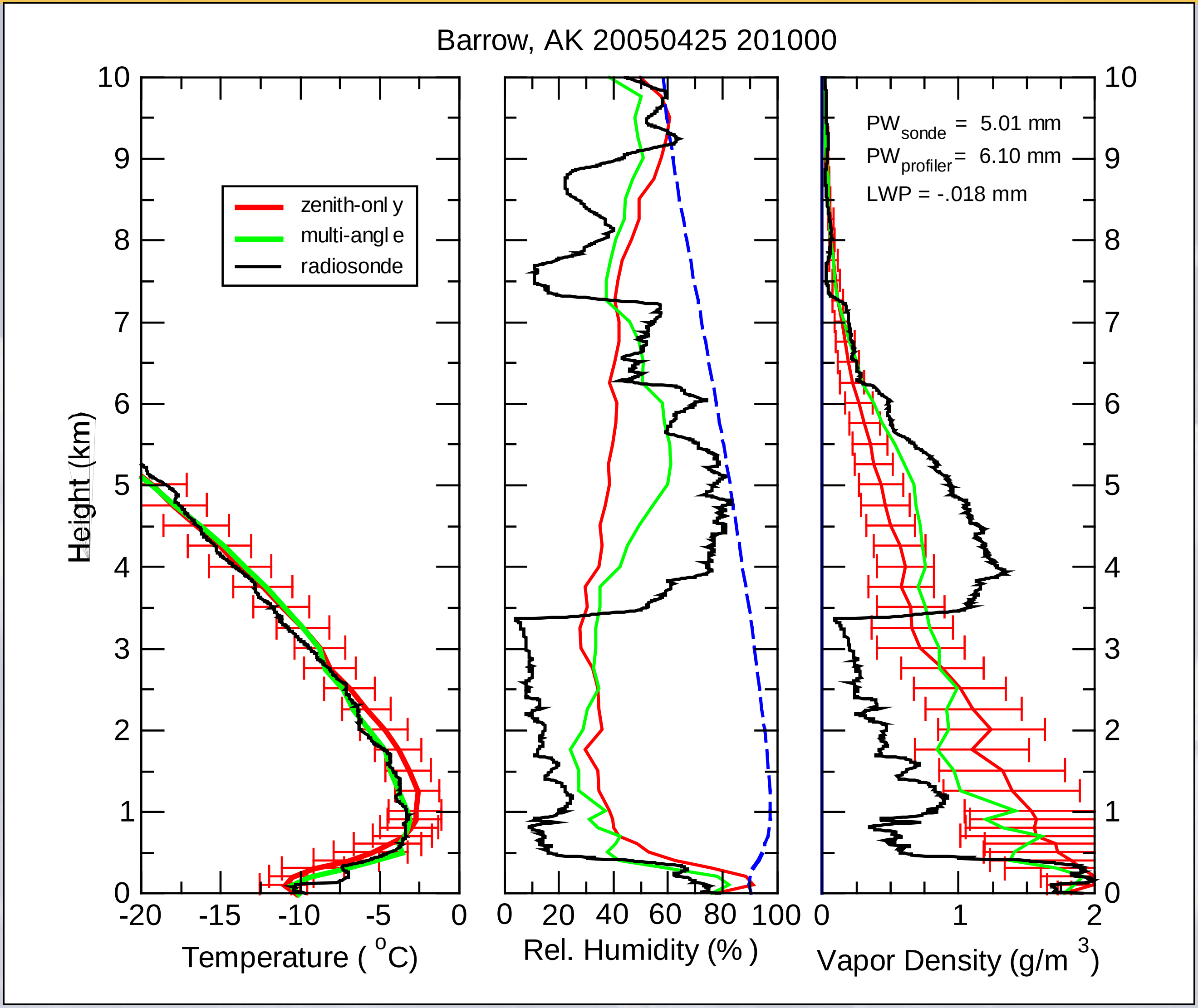
Comparison with Radiosonde



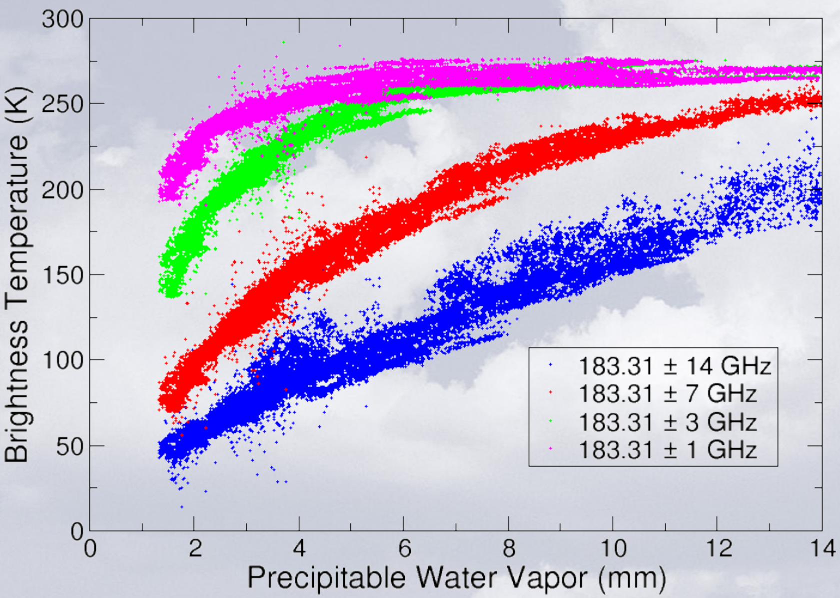
Atmospheric Radiation Measurement
Climate Research Facility
U.S. Department of Energy

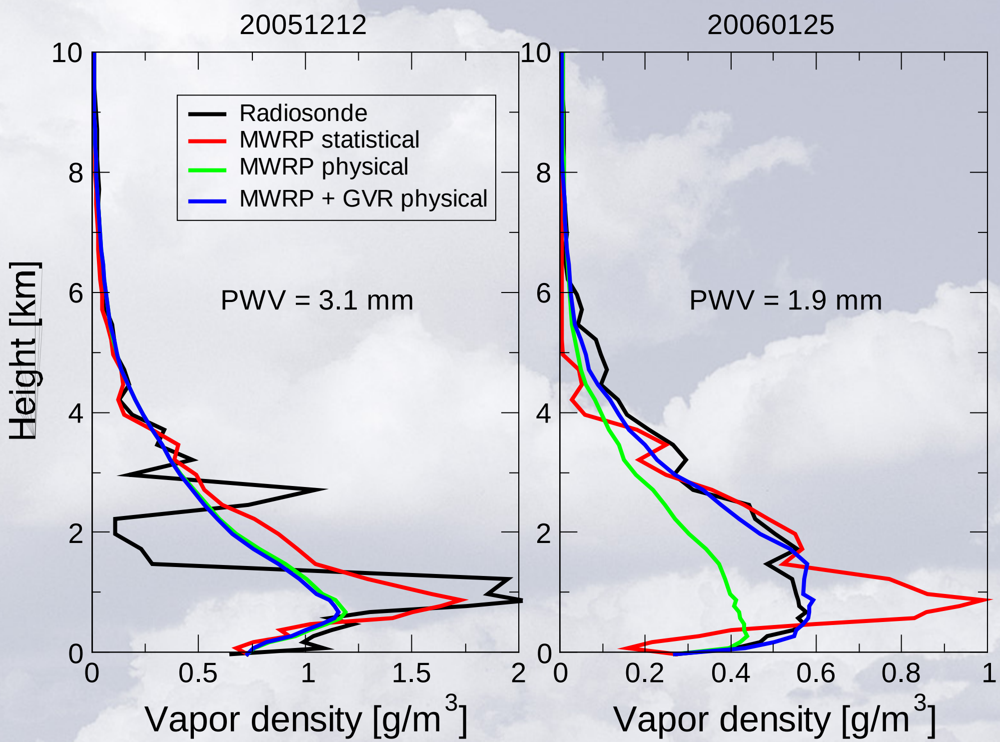
Office of Science
U.S. Department of Energy

Multi-Angle Results



Combined MWRP and GVR

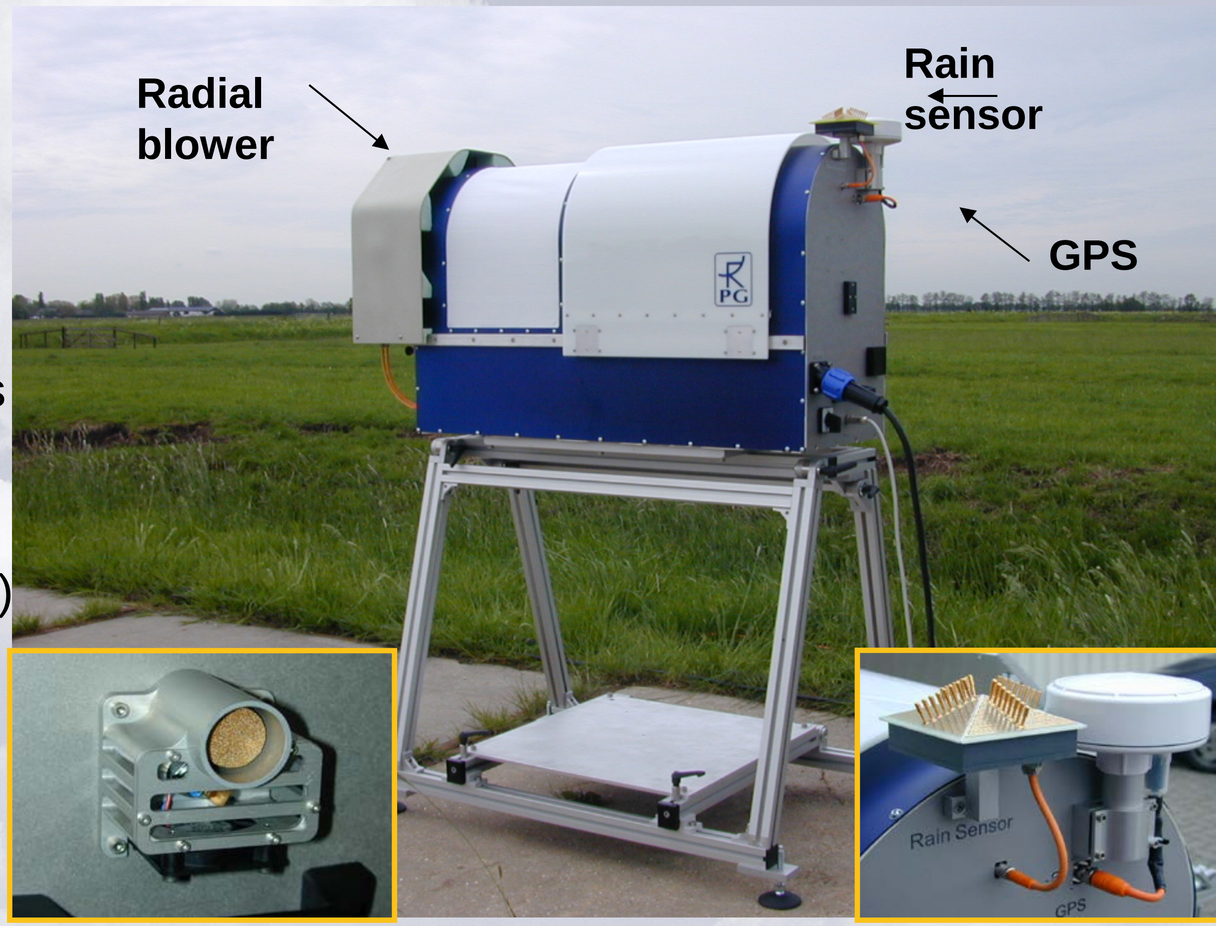




Courtesy of Maria Cadeddu

Humidity and Temperature Profiler (HATPRO)

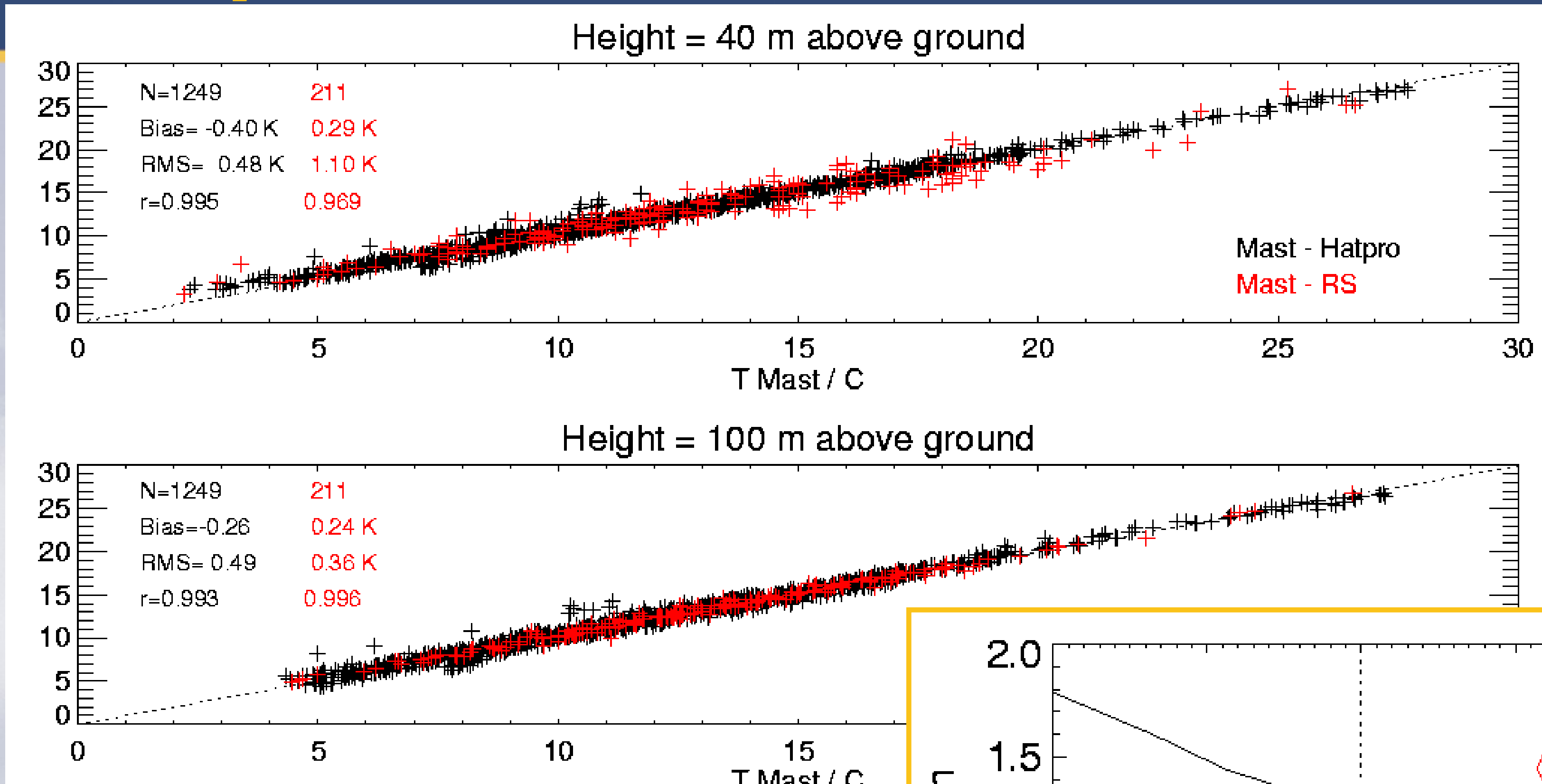
- Design based on BBC results
- suitable for **LWP** & **IWV** as well as **humidity** & (**boundary layer**) **temperature profile**
- rain sensor, GPS, clock
- environmental humidity, pressure and temperature

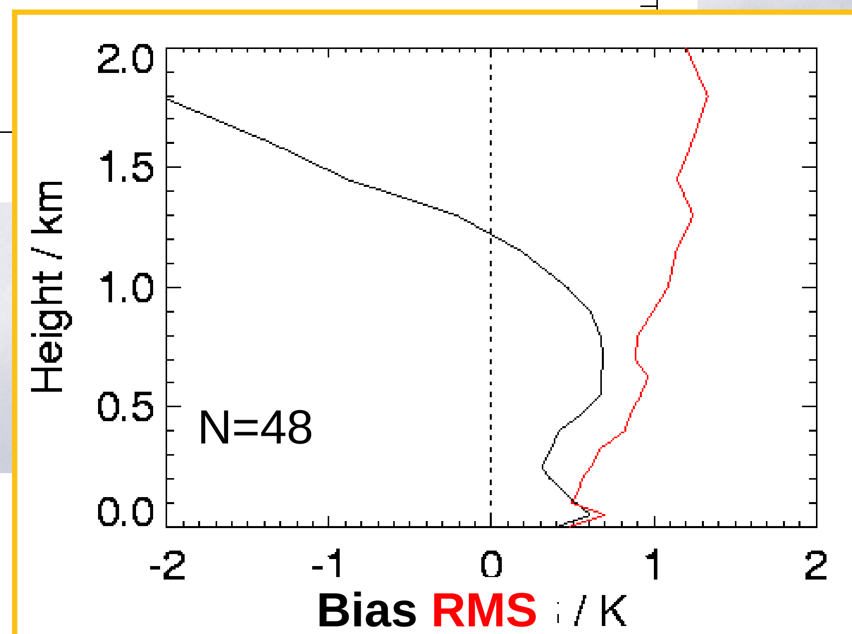


Radiometer Physics GmbH, Meckenheim

Courtesy of Susanne Crewell

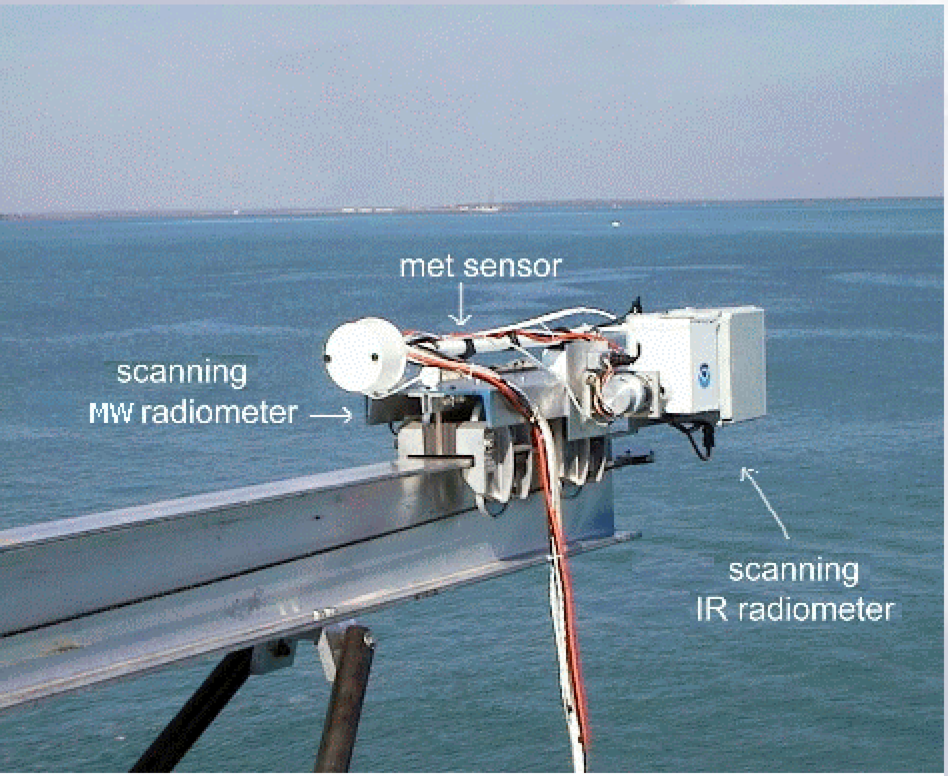
Comparison with Tower, Radiosonde

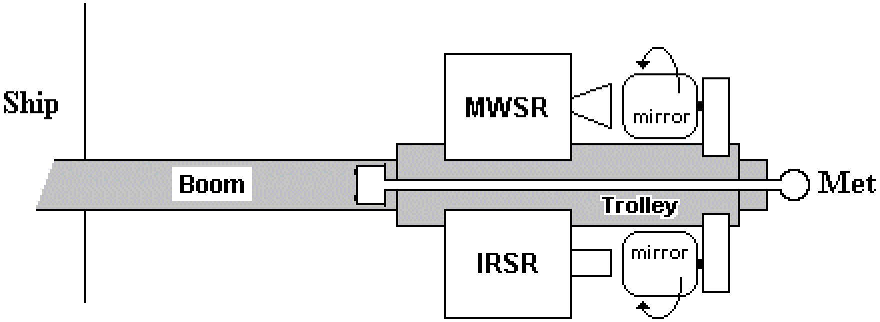




- RMS between Radisonde & HATPRO lower than 1 K below 1 km
- slightly depends on wind direction
- lower inversion strength of is well detected
- 6 angle retrieval performs much better than 5

SCANNING O2 60 GHz Radiometer (pictured here for ocean deployment)
Developed by V. Leuski (NOAA) and V. Kadygrov (ATTEX)
Now sold commercially by Kipp&Zonen





Center Frequency	60 GHz
Band Width	4 GHz
Sensitivity @ 1 s	0.02 K
Beam Width	6.5 deg
Scan Rate	0.55 Hz

PRODUCTS

Air-Sea Temperature Diff.	0.1K rms
T Profile to 500 m	0.5 K rms

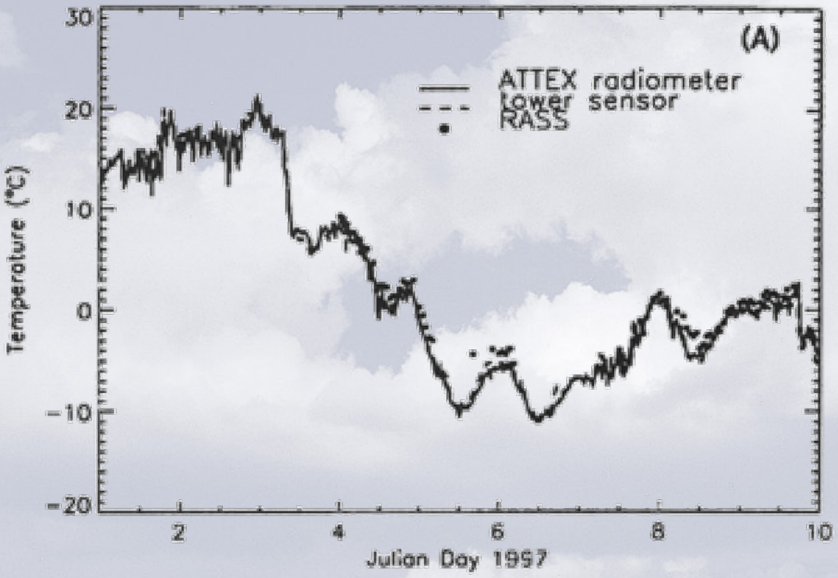
FIELD CAMPAIGNS
JUSREX 1992
COPE 1995
BAO 1997
SGP 1996
NAURU 1999
NSA 1999

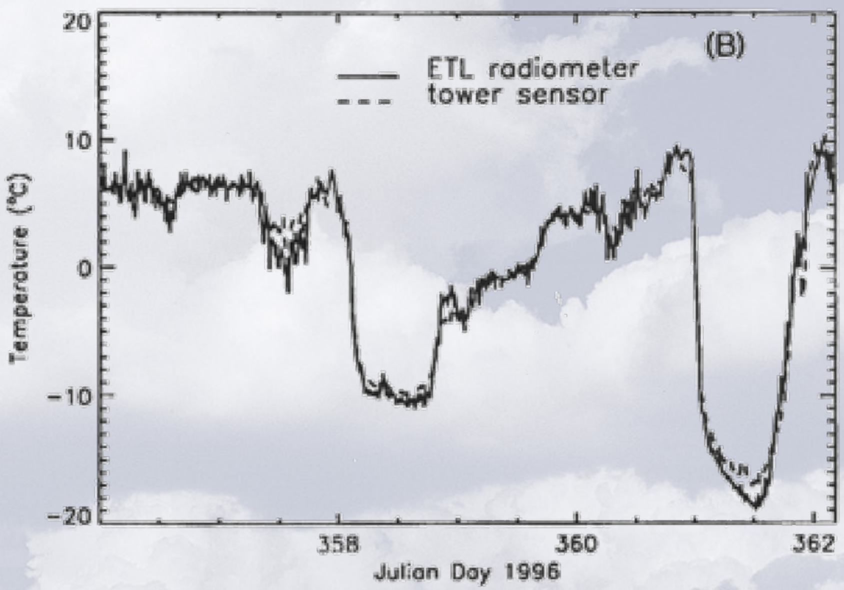
Courtesy of Ed Westwater

(A) A 10-day time series of temperature at 200 m as measured by the ATTEX radiometer, by the in situ measurement on the tower, and by a Radio Acoustic Sounding System (RASS). January 1–10, 1997.

(B) A 6-day time series of temperature at 200 m as measured by the ETL radiometer and by the in situ measurement on the tower. December 21–27, 1996.

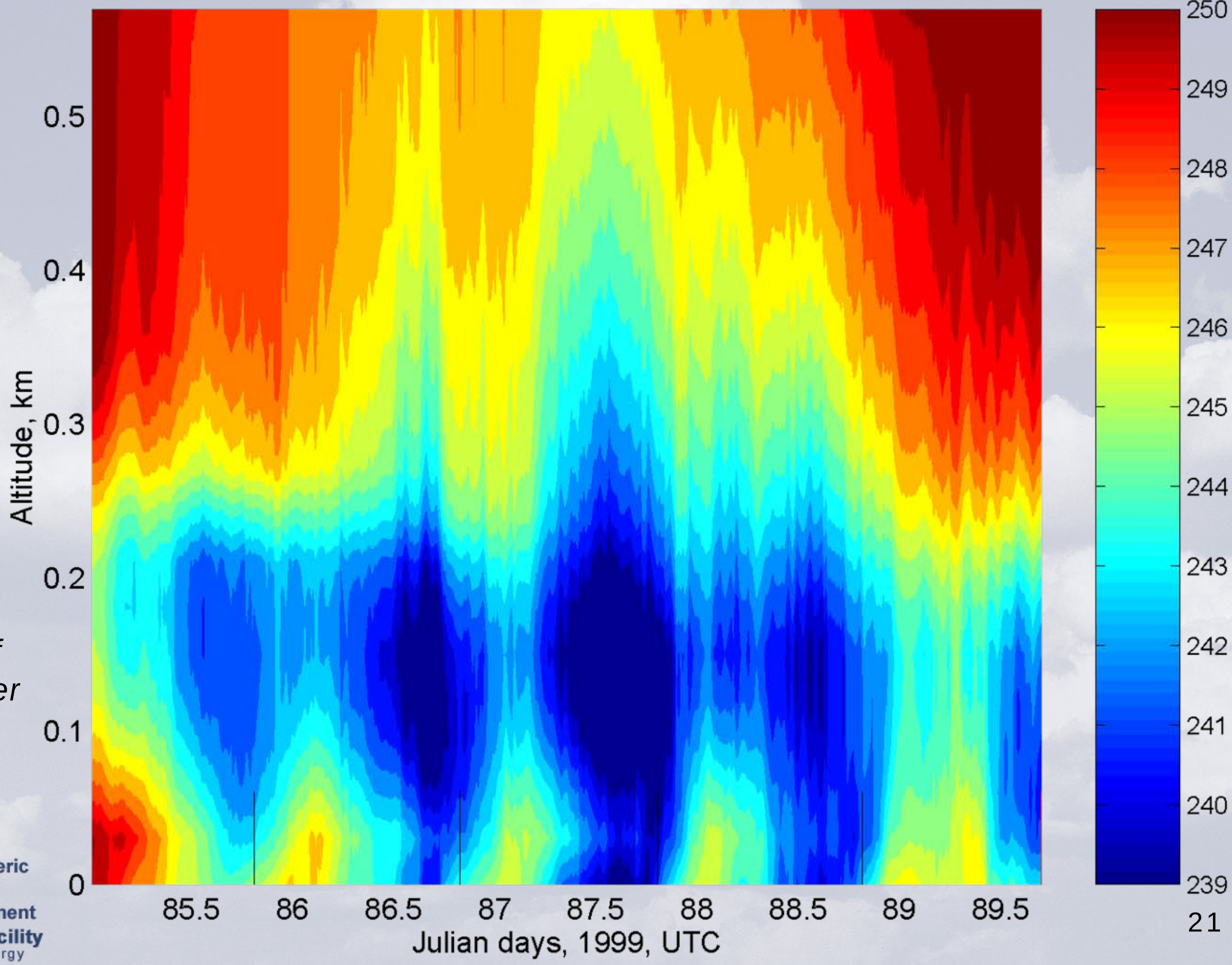
After Westwater et al., JAOT, 16(7), 805-818, 1999





Courtesy of Ed Westwater

5-day time series of air temperature profile retrieved from 10 min averaged scanning microwave upward looking scan; Barrow, Alaska, 1999. Julian day 85 is 03/26/1999. After Racette et al., JAOT, Vol. 22, No. 4, pp. 317 - 337, April 2005.



Courtesy of Ed Westwater

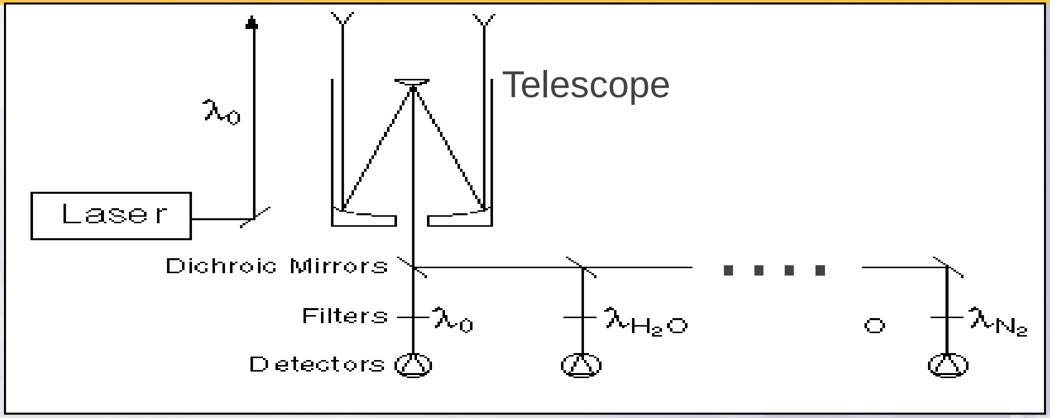
Atmospheric Radiation Measurement
Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

Passive Microwave

- **Wavelength/frequency:** 22-31 GHz (water vapor), 50-60 GHz (temperature)
- **Vertical Range:** 0-10 km
- **Vertical Reporting Interval:** 100 m (sfc to 1 km), 250 m (1-10 km)
- **Vertical Resolution:** varies with height
- **Temporal Resolution:** 5 minutes
- **Accuracy:** < 1 K bias for temperature; < 0.5 g/kg bias for water vapor mixing ratio compared with radiosondes (T_B accuracy ~0.5 K in K-band, 1 K in V-band)
- **Accuracy constraints:** spectroscopy, calibration
- **Precision:** ~1-3 K RMS for temperature; varies with height for water vapor mixing ratio
- **Precision constraints:** dwell time, cycle time
- **Calibration:** one blackbody reference (ambient); periodic LN_2 calibration required
- **Weather constraints:** no valid water vapor measurements during precipitation
- **Shelter requirements:** no shelter needed; controlled environment for computer
- **Initial cost:** $175,000 (RPG HATPRO), $250,000 (Radiometrics TP/WVP-3000)
- **Operating cost:** $9,000/year (MWRP+MWR: tunable synthesizer, gunn diode oscillators, circuit boards (age, lightning, blizzard), polycarbonate foam radomes)

Active Remote Sensing: Raman lidar



- Transmits laser pulse of energy λ_0
- Detects backscattered energy at λ_0 and the wavelengths associated with Raman shifts of molecules of interest as a function of range
- Ratios of various channels provide desired parameters
- Derives profiles of water vapor, aerosol, depolarization, liquid/ice water content and temperature
- Derives integrated products precipitable water vapor and aerosol optical thickness
- Designed for continuous, autonomous (24/7) operation
- Has been operational since 1998 (~50-60% uptime)
- Data available via ftp from ARM (http://www.arm.gov)

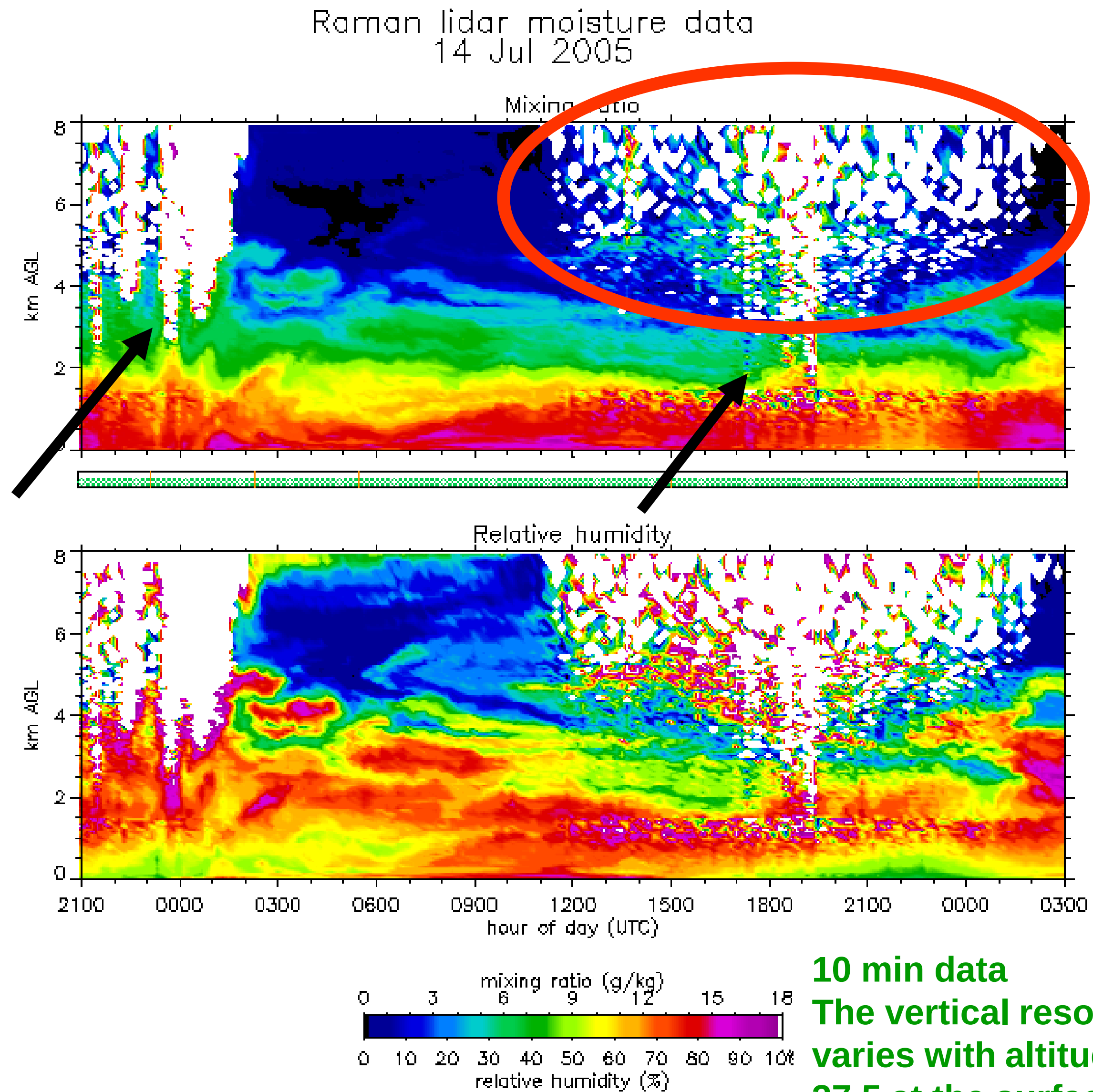
λ nm	detected
353	rot. N_2&O_2
354	rot. N_2&O_2
355	λ_0
387	N_2
403	liq. H_2O
408	H_2O vapor

Courtesy of Diana Petty

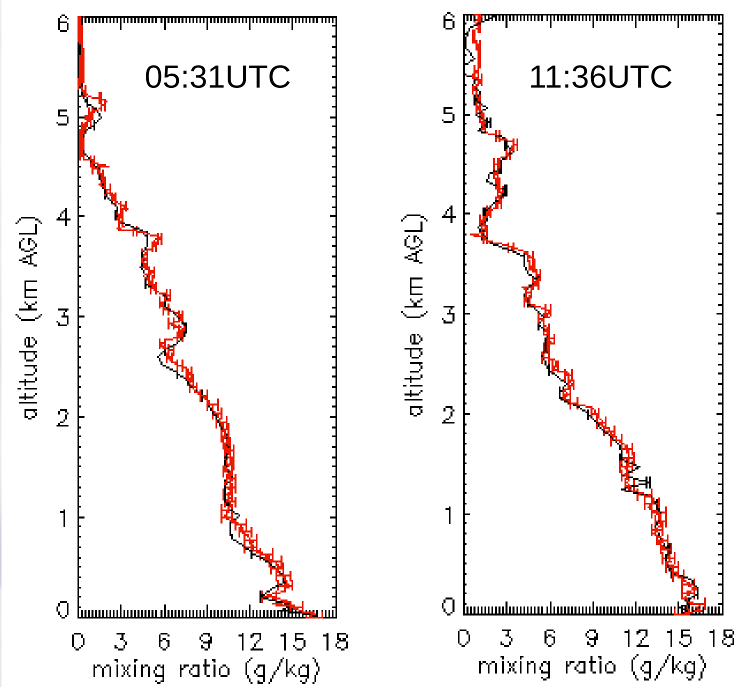
Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

Raman Lidar Water Vapor Mixing Ratio



Comparison of the water vapor mixing ratio



Sonde
Raman lidar

10 min data
The vertical resolution varies with altitude from 37.5 at the surface to up to 300m at 8 km

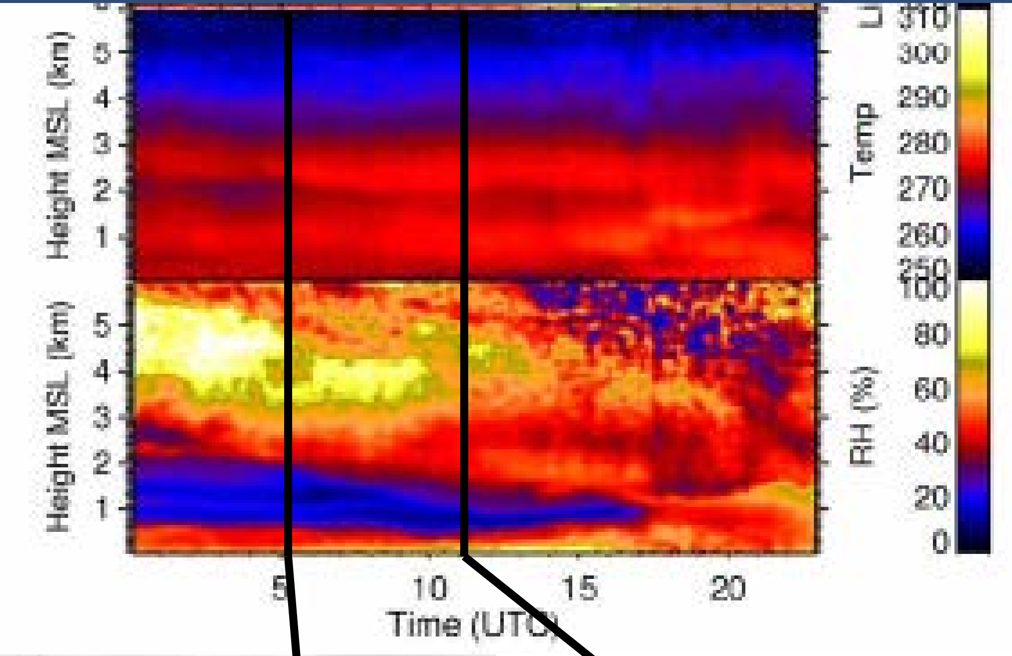
Courtesy of Diana Petty

Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

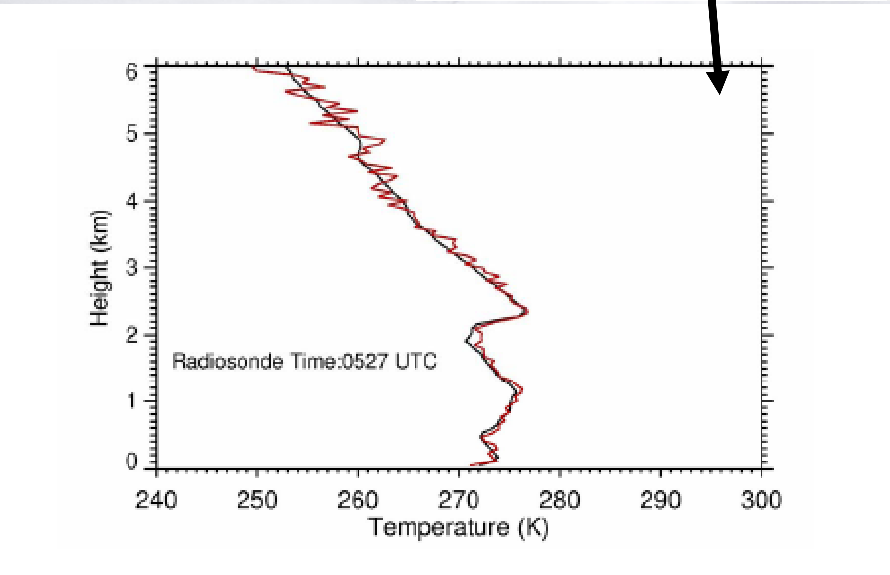
Raman Lidar Temperature Profiles

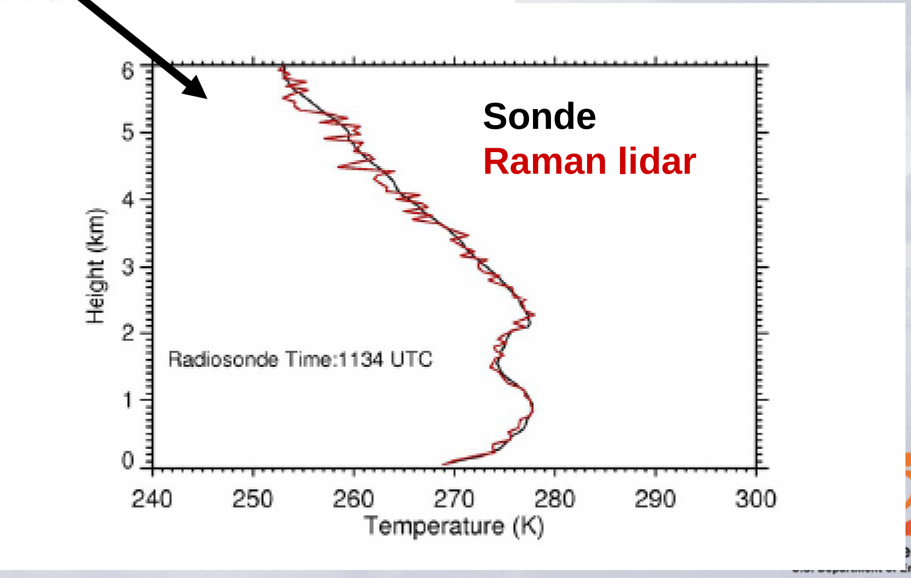
10 min averaged time-height cross section of temperature and relative humidity observed at the ARM SGP site on 2 Nov 2005.



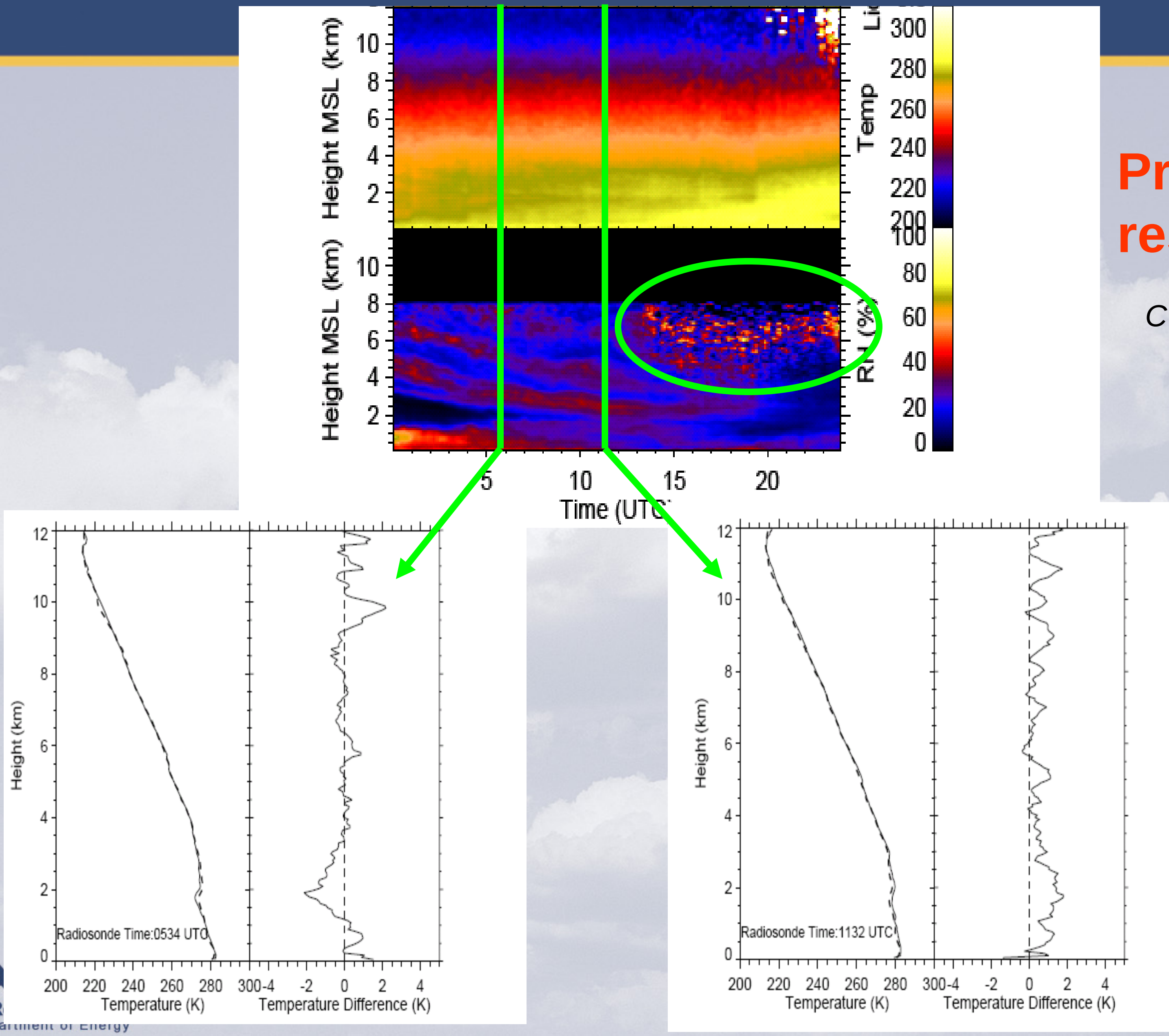
Preliminary results

Courtesy of Zhien Wang





Raman Lidar Temperature Profiles



Preliminary results

Courtesy of Zhien Wang

Sonde
CARL
Time averaging is 1.2 hour
Vertical resolution is 60 m

Raman Lidar

- **Wavelength/frequency:** 355 nm (outgoing)
- **Maximum Height:** 4-5 km (day), 15 km (night)
- **Vertical Resolution:** 37.5 m @ sfc to 300 m @ 8 km (7.5 m possible)
- **Temporal Resolution:** 10 minutes (10 sec possible)
- **Accuracy:** ~5% for water vapor mixing ratio (compared with radiosondes)
- **Accuracy constraints:** calibration
- **Precision:** depends on vertical, temporal averaging time
- **Precision constraints:** vertical, temporal averaging (SNR)
- **Calibration:** mixing ratio: PWV from MWR
- **Weather constraints:** signal significantly attenuated by clouds, rain
- **Shelter requirements:** controlled environment required for optics and electronics
- **Initial cost:** ~$1M
- **Operating cost:** $50,000/year (flash lamps, THG crystals, laser cladding, pockel cell)

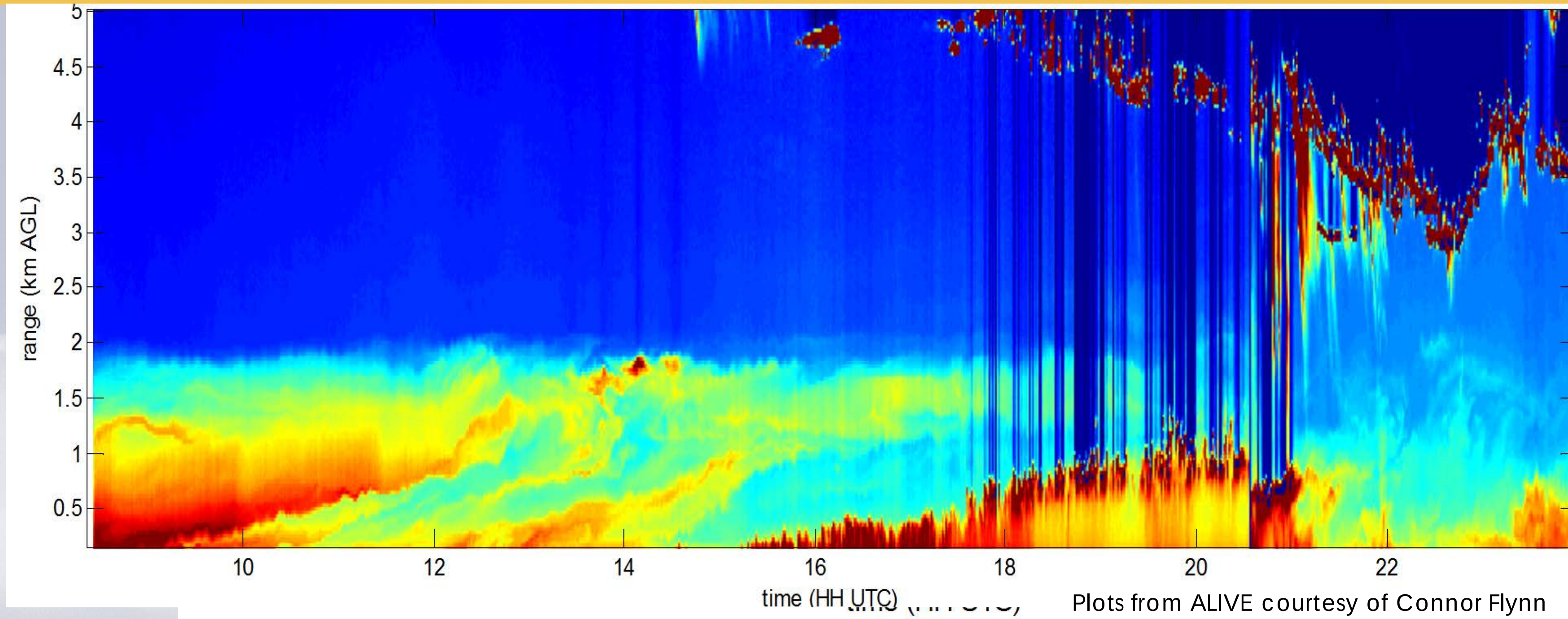
Cloud Properties

- Cloud Base Height
  - Ceilometer (e.g. Vaisala CT25, CL31, LD40)
  - Micro-Pulse Lidar
  - Radar (35 GHz, 95 GHz)
- Cloud Amount (% Cover)
  - Visible and Infrared Imagers
- Cloud Liquid Water Path
  - Microwave radiometer (23.8/31.4, 90/150 GHz)
  - Infrared/visible measurements for thin clouds

Lidars: Cloud Base Height

	Ceilometer (CT25)	Micro-Pulse Lidar
Wavelength	905 nm	532 nm
Vertical Range	7.5 km	~25 km
Vertical Resolution	15 m	15, 30, 75 m
Temporal Resolution	15-120 s	selectable
Accuracy		
Accuracy Constraints	CBH algorithm	CBH algorithm
Precision		
Precision Constraints	Averaging time	Averaging time, vert. res.
Calibration	N/A	N/A
Weather Constraints	Affected by precipitation	Affected by precipitation
Shelter Requirements	none	20-25°C, view port to sky
Initial Cost	$40,000	$125,000 (w/polarization)
Operating Cost	<$5,000/year (transceiver repair, fiber optic couplers)	$65,000/year (laser diode power supply)

Micro-Pulse Lidar

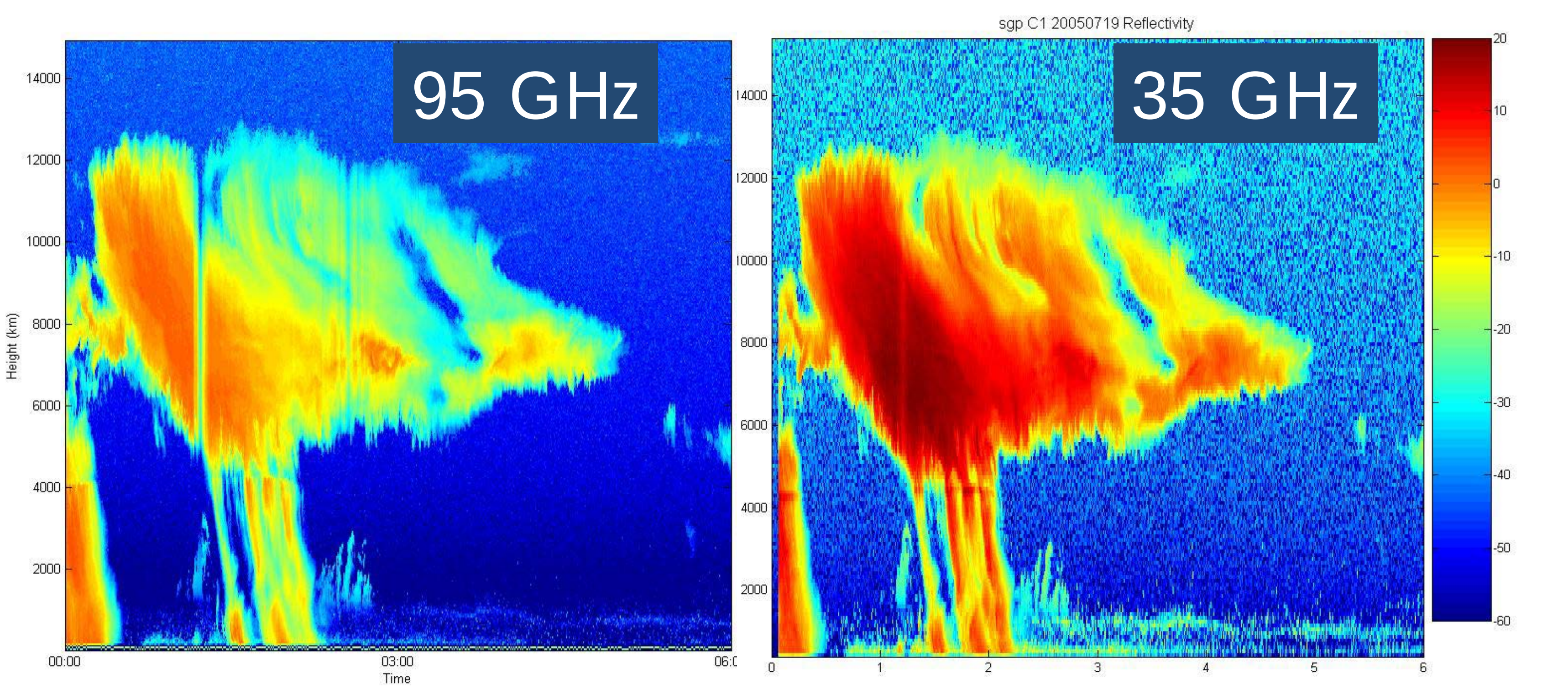


Plots from ALIVE courtesy of Connor Flynn

- Backscatter at 30 m resolution, ~25 km range
- Cloud boundaries
- Aerosol extinction profiles (VAP in development)
- SGP, TWP(3), NSA, AMF

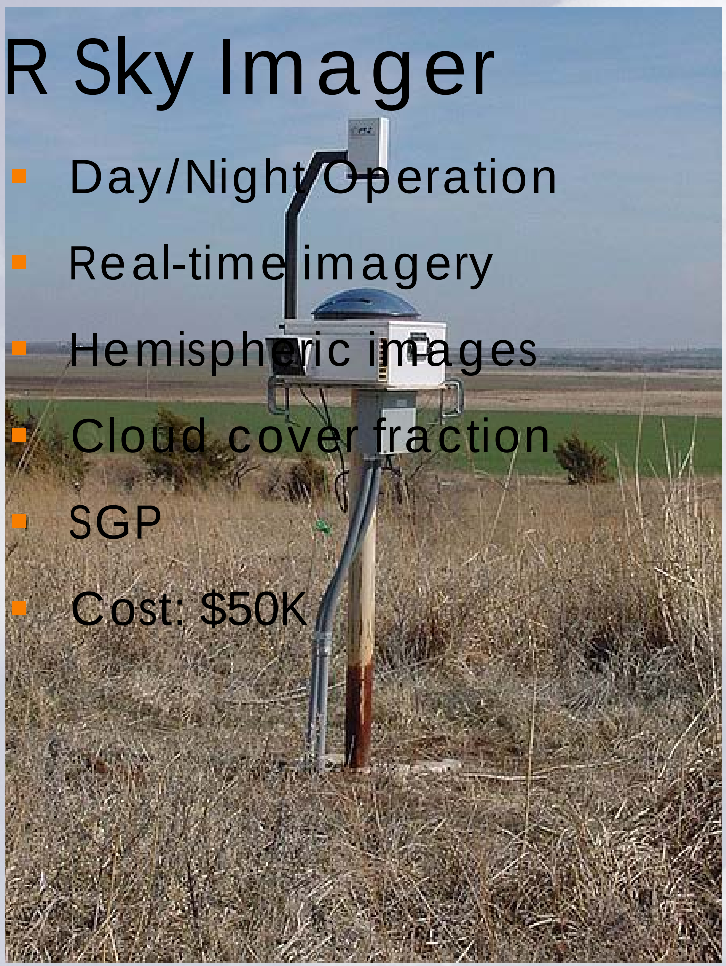
ARM Cloud Radars

- 35, 95 GHz Doppler radars

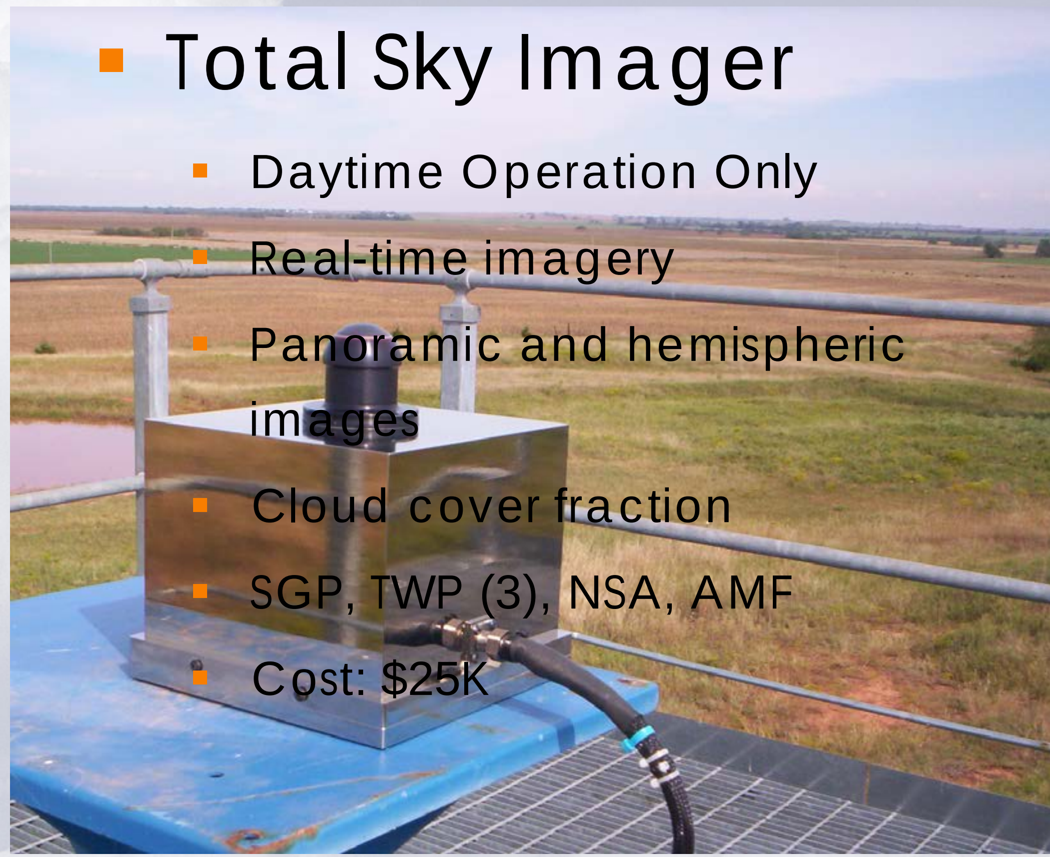


Images courtesy of Kevin Widener

Sky Imagers



- IR Sky Imager
  - Day/Night Operation
  - Real-time imagery
  - Hemispheric images
  - Cloud cover fraction
  - SGP
  - Cost: $50K

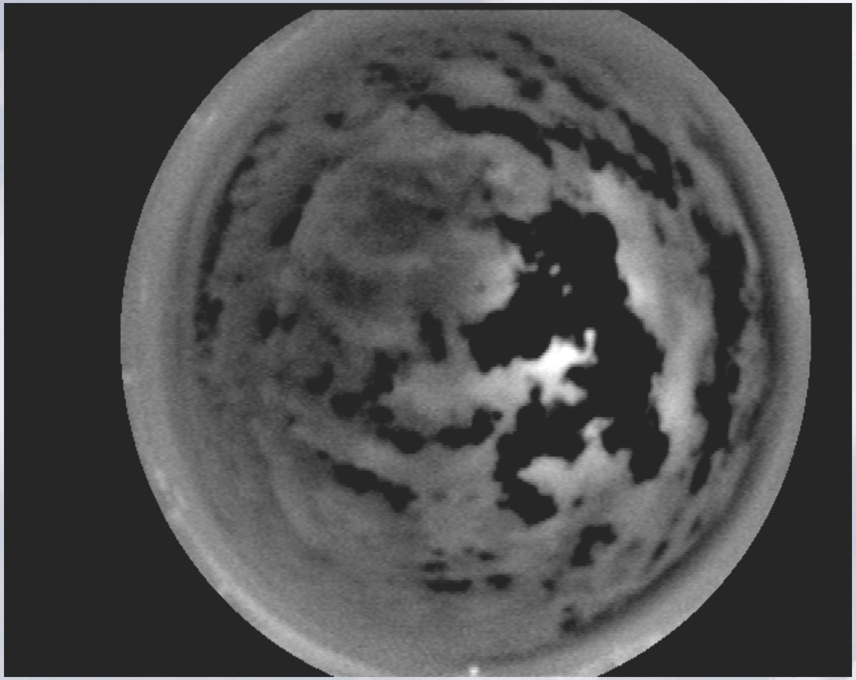


- Total Sky Imager
  - Daytime Operation Only
  - Real-time imagery
  - Panoramic and hemispheric images
  - Cloud cover fraction
  - SGP, TWP (3), NSA, AMF
  - Cost: $25K

Images courtesy of Vic Morris

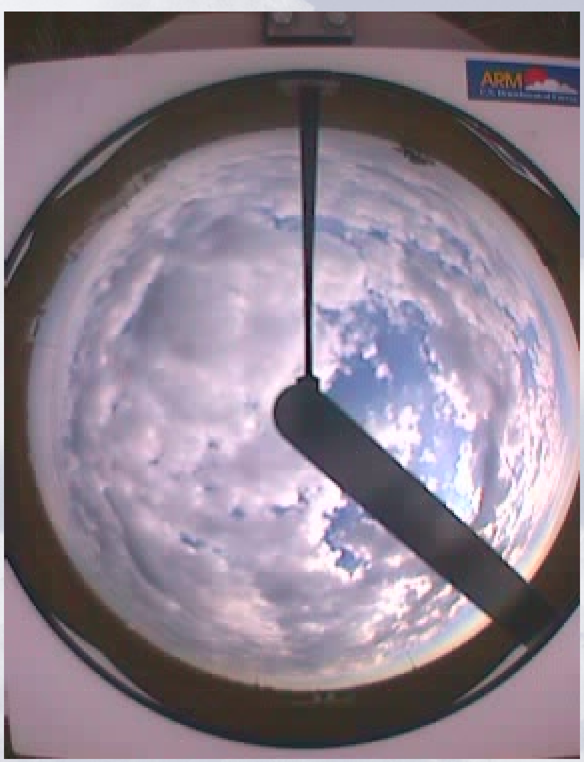
Sky Images at SGP
with sun covered by clouds

IRSI



10/19/2005 15:31:39

TSI

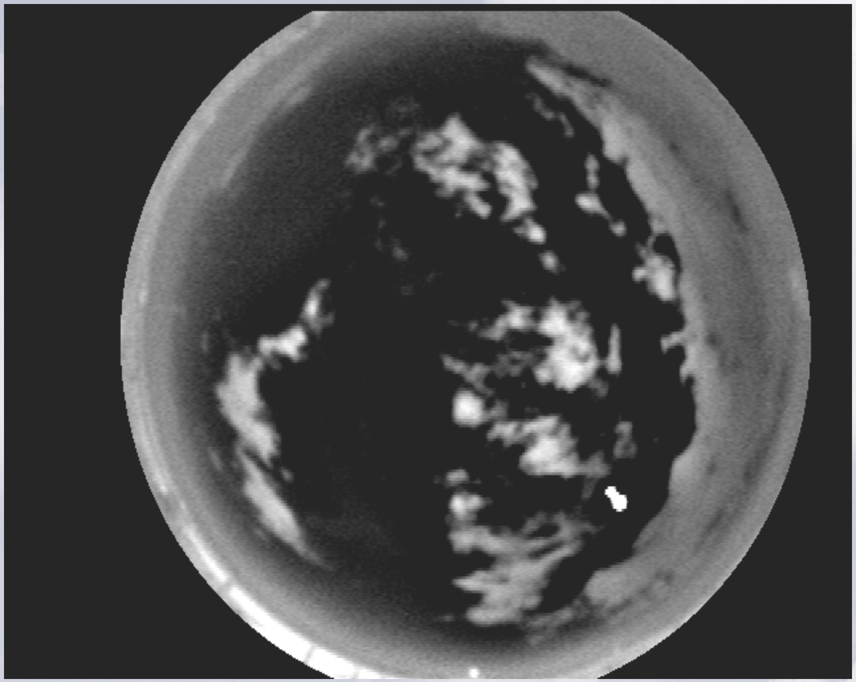


10/19/2005 15:31:30

Images courtesy of Vic Morris

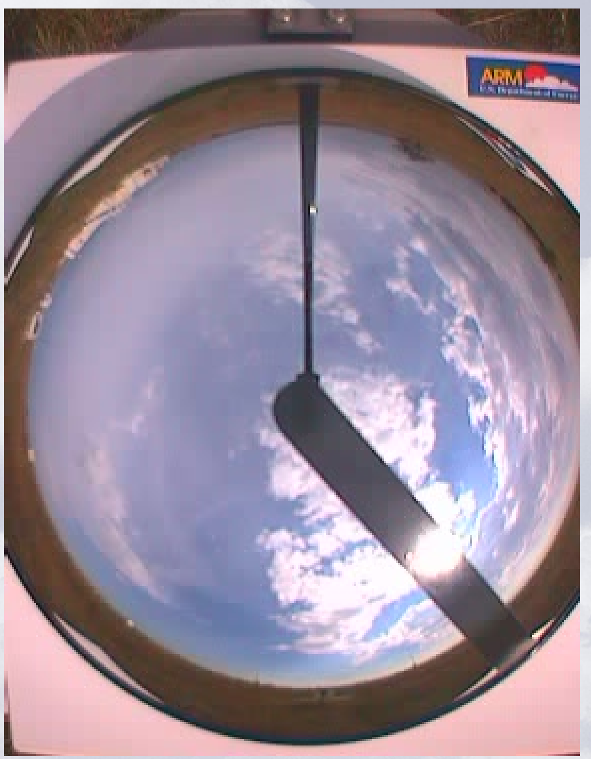
Sky Images at SGP
with sun exposed

IRSI



10/19/2005 16:00:09

TSI



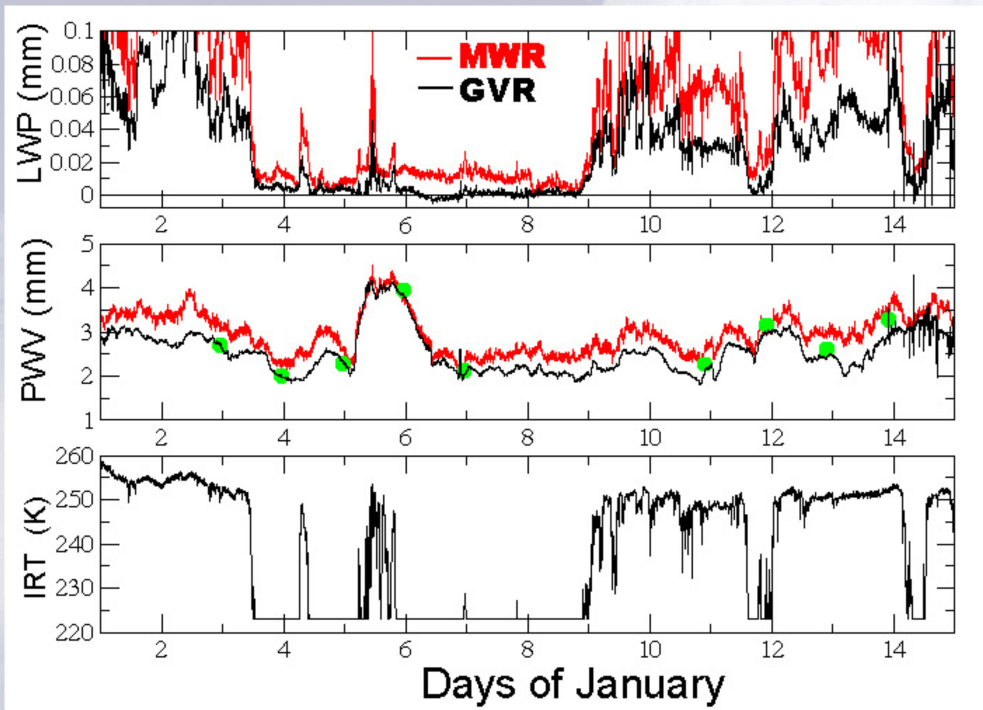
10/19/2005 16:00:00

Images courtesy of Vic Morris

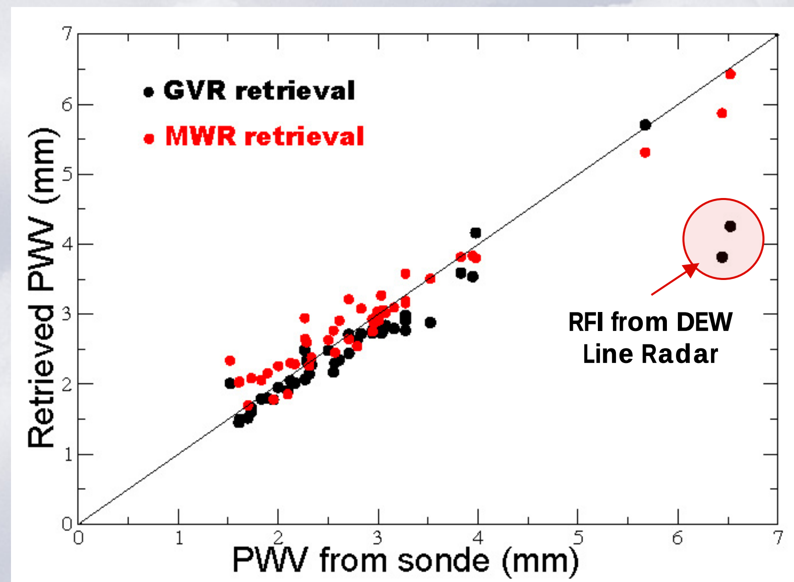
Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy

Liquid Water Path



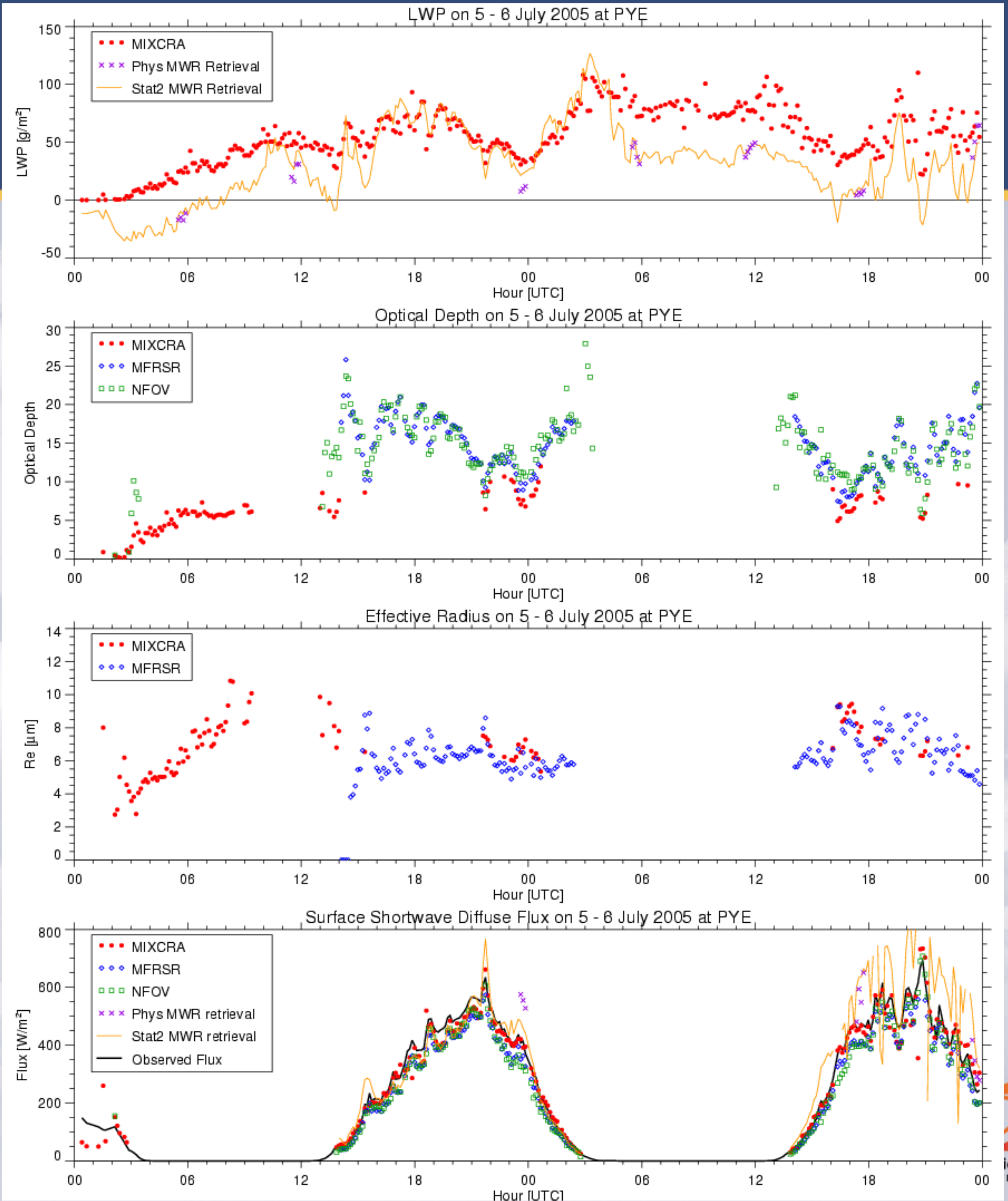
- MWR: 23.8, 31.4 GHz
  - Accuracy: 20-40 g/m^2 RMS
- GVR: 183.3±1, 3, 7, 14 GHz
  - Accuracy: 6 g/m^2 RMS



Courtesy of Maria Cadeddu

Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Office of Science
U.S. Department of Energy



Courtesy of Dave Turner

Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Radar Wind Profilers
Radio-Acoustic Sounding Systems

- 50 MHz

- 915 MHz

Wind Profilers

	915 MHz	404/449 MHz	50 MHz	Sodar (1, 5 kHz)
Minimum Height	100 m	500 m	2000 m	50 , 5-10 m
Maximum Height	3.3-4.6 km (50%)	8-18 km (nom)	12 km (50%)	0.8-1.2 km
Max Height Constraint	Antenna size, output power, humidity, atmospheric stability			
Vertical Resolution	300-600 m	320-900 m	60-100 m	50, 5-10 m
Temporal Resolution	30-60 min consensus averages			5-6 min
Accuracy	0.5 m/s	0.5 m/s	0.5 m/s	0.5 m/s
Accuracy Constraints	Sampling volume (vertical resolution), length of FFT (spectral resolution)			
Precision	0.5 m/s	0.5 m/s	0.5 m/s	0.5 m/s
Precision Constraints	SNR: sampling volume, interference (ground clutter, birds, precip.)			
Weather Constraints	Sensitive to rain, snow	Large rain drops, hail	Insensitive to precip.	Sensitive to rain, snow
Shelter Requirements	Electronics and computers require controlled environment			
Initial Cost	$250,000-$370,000	?	?	$70,000-?
[illegible]	$14,000/year		$10,000/year	

Constrained Variational Analysis

- Zhang and Lin (1997), Zhang et al. (2001)
  - Conserve mass, moisture, static energy, and momentum
- To provide inputs for SCMs, CRMs
  - Large-scale state variables (P, T, q, u, v)
  - Large-scale vertical velocity
  - Advective tendencies of state variables
- Input Measurements
  - *State variables:* P, T, q (radiosondes, RUC model), u, v (RWPs)
  - LWP (MWRs)
  - Rainfall (ARBRFC radar product)
  - Surface met, radiation, sensible/latent heat fluxes
  - TOA radiation, clouds (GOES/Minnis)

Niamey, Niger