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

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- 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
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
Spectral Regions used in AERI Retrieval

AERI Radiance Channel 1 and 2

* Note spectral microwindows used for emissivity values are throughout the spectrum, consult Table 2 for exact locations.

Courtesy of Wayne Feltz
Comparison with Radiosondes

3 June 2003 0230 UTC

Hillsboro

Vici

Lamont

Morris

Purcell

Courtesy of Wayne Feltz
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

![Graph showing absorption vs. frequency for different conditions at different altitudes and temperatures.](image)

- **Surface (978 mb)**
  - Temperature: 300 K
  - **ρ_vapor** = 16 g/m^3

- **2 km (800 mb)**
  - Temperature: 283 K
  - **ρ_vapor** = 4.5 g/m^3

- **Cloud at 2 km**
  - Temperature: 283 K
  - **ρ_liquid** = 0.5 g/m^3
Temperature Combined with GOES

\[ C(z_0, z) = \frac{\sum [Y(z_0) - Y_{sonde}(z_0)] [Y(z) - Y_{sonde}(z)]}{\sqrt{\sum [Y(z_0) - Y_{sonde}(z_0)]^2 \sum [Y(z) - Y_{sonde}(z)]^2}} \]
Water Vapor Combined with GOES

Bias

Standard Deviation

Vapor Density

Vapor Density Difference [g/m³]

Height [km]

Bias

Standard Deviation

Vapor Density

Resolution [km]

MWRP

GOES

GOES+MWRP

GOES+AERI
Comparison with Radiosonde

- sgp C1 20030702 113000

- $p_{\text{vap}, \text{sonde}}$, $p_{\text{vap}, \text{profiler}}$, $100x p_{\text{H}_{2}O, \text{profiler}}$

- $\text{PW}_{\text{sonde}} = 3.902 \, \text{cm}$
- $\text{PW}_{\text{profiler}} = 4.032 \, \text{cm}$
- LWP = 0.008 mm
- Wet? N
Comparison with Radiosonde
Combined MWRP and GVR

Combined MWRP and GVR data showing vapor density and precipitable water vapor for two dates: 20051212 with PWV = 3.1 mm and 20060125 with PWV = 1.9 mm. The data includes measurements from Radiosonde, MWRP statistical, MWRP physical, and MWRP + GVR physical.

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
- 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

Courtesy of Ed Westwater
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 $\lambda_0$
- Detects backscattered energy at $\lambda_0$ 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)

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>353</td>
<td>rot. N$_2$&amp;O$_2$</td>
</tr>
<tr>
<td>354</td>
<td>rot. N$_2$&amp;O$_2$</td>
</tr>
<tr>
<td>355</td>
<td>$\lambda_0$</td>
</tr>
<tr>
<td>387</td>
<td>N$_2$</td>
</tr>
<tr>
<td>403</td>
<td>liq. H$_2$O</td>
</tr>
<tr>
<td>408</td>
<td>H$_2$O vapor</td>
</tr>
</tbody>
</table>

Courtesy of Diana Petty
Comparison of the water vapor mixing ratio

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

Sonde, Raman lidar

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

Preliminary results

Sonde
Raman lidar

Courtesy of Zhien Wang
Raman Lidar Temperature Profiles

Preliminary results

Courtesy of Zhien Wang

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

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

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

Plots from ALIVE courtesy of Connor Flynn
ARM Cloud Radars

- 35, 95 GHz Doppler radars
- Reflectivity, moments, co-pol and cross-pol spectra recorded
- Cloud boundaries (bottoms, tops)
- Cloud constituent velocities

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

Images courtesy of Vic Morris
Sky Images at SGP with sun exposed

IRSI

TSI

10/19/2005 16:00:09

10/19/2005 16:00:00

Images courtesy of Vic Morris
Liquid Water Path

- **MWR**: 23.8, 31.4 GHz
  - Accuracy: 20-40 g/m² RMS
- **GVR**: 183.3±1, 3, 7, 14 GHz
  - Accuracy: 6 g/m² RMS

Courtesy of Maria Cadeddu
Radar Wind Profilers
Radio-Acoustic Sounding Systems

- 50 MHz
- 915 MHz
# Wind Profilers

<table>
<thead>
<tr>
<th></th>
<th>915 MHz</th>
<th>404/449 MHz</th>
<th>50 MHz</th>
<th>Sodar (1, 5 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum Height</strong></td>
<td>100 m</td>
<td>500 m</td>
<td>2000 m</td>
<td>50 (5-10 m)</td>
</tr>
<tr>
<td><strong>Maximum Height</strong></td>
<td>3.3-4.6 km (50%)</td>
<td>8-18 km (nom)</td>
<td>12 km (50%)</td>
<td>0.8-1.2 km</td>
</tr>
<tr>
<td><strong>Max Height Constraint</strong></td>
<td>Antenna size, output power, humidity, atmospheric stability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical Resolution</strong></td>
<td>300-600 m</td>
<td>320-900 m</td>
<td>60-100 m</td>
<td>50 (5-10 m)</td>
</tr>
<tr>
<td><strong>Temporal Resolution</strong></td>
<td>30-60 min consensus averages</td>
<td></td>
<td></td>
<td>5-6 min</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
</tr>
<tr>
<td><strong>Accuracy Constraints</strong></td>
<td>Sampling volume (vertical resolution), length of FFT (spectral resolution)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Precision</strong></td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
<td>0.5 m/s</td>
</tr>
<tr>
<td><strong>Precision Constraints</strong></td>
<td>SNR: sampling volume, interference (ground clutter, birds, precip.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weather Constraints</strong></td>
<td>Sensitive to rain, snow</td>
<td>Large rain drops, hail</td>
<td>Insensitive to precip.</td>
<td>Sensitive to rain, snow</td>
</tr>
<tr>
<td><strong>Shelter Requirements</strong></td>
<td></td>
<td>Electronics and computers require controlled environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Initial Cost</strong></td>
<td>$250,000-$370,000</td>
<td>?</td>
<td>?</td>
<td>$70,000-?</td>
</tr>
<tr>
<td><strong>Operation Cost</strong></td>
<td>$14,000/year</td>
<td>$10,000/year</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 (RWP)
  - LWP (MWRs)
  - Rainfall (ARBRFC radar product)
  - Surface met, radiation, sensible/latent heat fluxes
  - TOA radiation, clouds (GOES/Minnis)
Niamey, Niger

Thank you!