The PCAPS Profilers

How they work
and what they tell us

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PCAPS ISS Wind Profiler Site

915 MHz wind profiler
- Commercial system
- Winds and RASS

449 MHz wind profiler
- Experimental System
- Faster and higher winds
ISS Sounding Site

Soundings, surface met, **SODAR**, GPS Integrated Water Vapor, Profiling Microwave Radiometer, Webcam
NCAR Integrated Sounding System – 915 MHz Wind Profiler

Metek SODAR (with RASS)

Vaisala Ceilometer

Wind profiler with RASS speakers

Utah’s HALO lidar

http://halo-photonics.com/Galion_LiDAR_system.htm

NCAR is supported by the National Science Foundation.
Outline

• Radar wind profilers (mostly)
  ❖ Concepts
  ❖ Applications
  ❖ What can go wrong

• Radio Acoustic Sounding (RASS)

• Sodars
Wind Profilers – A variety of sizes

Vaisala LAP-3000 915 MHz
2-m square

NPN 404-MHz (Ledbetter, TX)
12-m square. Soon 449 MHz
(photo courtesy of Brian Phillips, SRG, Inc.)

NOAA Profiler Network sites (32)

MU radar (Japan) 50-MHz
103-m diameter. 475 Yagi antennas
Surface Obs Through a Warm Front

What are they used for?...Lots!
Winds Aloft Through a the same warm Front

Note: wind barbs indicate horizontal wind
Fig. 4. Time vs height sections of 915 Doppler wind profiler parameters at vertical incidence: (a) signal-to-noise ratio (SNR, dB), (b) total vertical motion, $W = w + V_T$ (m s$^{-1}$), and (c) spectrum width (m s$^{-1}$).
Boundary Layer Observations and Model

Profilers are used to observe boundary layer evolution.

- Lidar backscatter (SABL)
- Lidar backscatter (HRDL)
- Vertical Velocity (HRDL)
- Wind profiler backscatter
- Diurnal cycle (after Stull 1988)
Radio Acoustic Sounding System (RASS)

Profilers are used to observe inversions.
A cold front during PCAPS 15 December 2010.

Surface station shows:
- T drops at 01Z and 05Z (13C to 3C)
- Wind shift from southerly to northerly between 01Z and 06Z.
Full troposphere profiling (45 MHz profiler)

60m x 60m 45 MHz VHF profiler
Laboratoire d’Aerologie (France)

http://www.aero.obs-mip.fr/specials/images_st.html
NCAR is supported by the National Science Foundation.

Reflectivity and winds during PCAPS IOP-3 05:15Z sounding (from ISS2 site)

Measurements from different observing systems are often complementary.

REAL-TIME DATA, NOT CHECKED FOR QUALITY
So how do profilers work?

Next:

- Scattering mechanisms
- Doppler processing
- Differences for precipitation
- Calculating horizontal wind
Glass: About 4% is reflected (at normal incidence)

$u = \frac{c}{n}$

$u =$ electromagnetic wave propagation speed
$c =$ speed of light in a vacuum
$n =$ refractive index
Refractive Index - determines the speed of light

\[ u = \frac{c}{n} \]

- \( u \) = electromagnetic wave propagation speed
- \( c \) = speed of light in a vacuum
- \( n \) = refractive index

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.0</td>
</tr>
<tr>
<td>Air</td>
<td>1.0 + ( N ) (slightly more than 1.0)</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Glass</td>
<td>1.45 – 1.48</td>
</tr>
<tr>
<td>Silicon</td>
<td>3.5</td>
</tr>
<tr>
<td>Germanium</td>
<td>4.0</td>
</tr>
</tbody>
</table>
The Refractive Index of Air

\[ N = n - 1 = 0.373 \frac{e}{T^2} + 77.6 \times 10^{-6} \frac{P}{T} \]

(+ free electrons term in the ionosphere)

\( n \) = refractive index of air
\( P \) = atmospheric pressure (hPa)
\( e \) = water vapor pressure (hPa)
\( T \) = atmospheric temperature (K)

Reflection depends on **gradients**
- Strong dependence on moisture (e)
- Secondary dependence on temperature (T)
- Also pressure (P) dependence, but pressure gradients are weak
Where do gradients come from?

Drawing based on a study of water formations by Leonardo da Vinci

REAL TIME DATA, NOT CHECKED FOR QUALITY
But gradients at the right scale (size)....

Turbulence

Big whorls have little whorls, Which feed on their velocity; And little whorls have lesser whorls, And so on to viscosity.

(Lewis Richardson, 1922)

Bragg Scatter

Half wavelength scales reinforce. All other scales cancel.

Drawing based on a study of water formations by Leonardo da Vinci
How does this become a velocity? **Doppler Processing**

- Phase at receiver
- Fourier transform

NCAR is supported by the National Science Foundation.
Doppler Spectrum (averaged)

Clear air only

Signal Power (S)
Radial velocity ($V_r$)
Spectral Width ($\sigma_w$)

$$v_r = \frac{\Delta f \lambda}{2}$$
Doppler Spectrum (averaged)

Signal Power ($S$)
Radial velocity ($V_r$)
Spectral Width ($\sigma_w$)

\[ v_r = \frac{\Delta f \lambda}{2} \]
Reflectivity, Fallspeed, Spectral Width

Clear air example

Snow example
<table>
<thead>
<tr>
<th>Dependencies...</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bragg Scatter</strong> (clear air)</td>
</tr>
</tbody>
</table>
\[ \eta(\lambda) = 0.38 C_n^2 \lambda^{-1/3} \]  
Tatarskii; for scales in the inertial subrange  
\[ C_n^2 = 5.45 (\Delta n)^2 L_0^{-2/3} \]  
(\(\Delta n\)^2 = mean square fluctuations of n  
\(L_0\) = turbulence outer (larger) scale  

**Rayleigh Scatter** (rain, birds, ...)  
\[ \eta(\lambda) \propto \lambda^{-4} D^6 \]  
(D is the drop diameter)  

\[ \eta(\lambda) = \text{radar reflectivity as a function of wavelength (\(\lambda\))} \]  
\[ C_n^2 = \text{refractive index structure constant (independent of \(\lambda\))} \]  
\[ \lambda = \text{radar wavelength} \]
Finding the horizontal wind
Radial component seen with the East tilted beam

\[ v_{rE} = v_h \sin(\varphi_E + \beta) + v_z \cos \theta \]
\[ v_{rW} = v_h \sin(\varphi_E + \beta + \pi) + v_z \cos \theta \]

Horizontal wind: \( v_h \), \( \beta \)
Vertical wind: \( v_z \)
Beam direction (azimuth, zenith): \( \varphi \), \( \theta \)
Observed radial speed (east beam): \( v_{rE} \)
\[ v_{rE} = v_h \sin(\varphi_E + \beta) + v_z \cos \theta \]
\[ v_{rW} = v_h \sin(\varphi_E + \beta + \pi) + v_z \cos \theta \]

\[ v_E + v_W = 2v_z \cos \theta \]
\[ v_z = \frac{v_E + v_W}{2 \cos \theta} \]

\[ v_E - v_W = 2v_h \sin(\varphi_E + \beta) \]

(similar for \( V_N \) and \( V_S \) to get horizontal wind speed and dir)
What can go wrong?

Mechanical beam steering failures *(rare)*

Non-atmospheric targets/clutter *(common!)*
  - Ground clutter *(near the surface)* *(NIMA helps)*
  - Radio interference *(vertical stripes)* *(NIMA helps)*
  - Bird/plane clutter *(broad, high reflectivity)* *(statistical averaging helps)*

*All of these show up in the Doppler spectra*

**Atmospheric Effects**

- Weak signal strength in dry and cold conditions
- Assumes spatial homogeneity over beam swing distance
- Assumes temporal stationarity over consensus *(averaging) time*
**NIMA** *(NCAR Improved Moments Algorithm) (Cornman et al. 1998)*

- Uses fuzzy logic to identify features in Doppler spectra
- Removes ground clutter and RFI (helps with birds too)
- Produces a “confidence” measure

NCAR will provide NIMA processed moments for the 915 MHz PCAPS dataset
A digression to the prototype 449 MHz profiler and Spaced Antenna Winds
MAPR (915 MHz) or
Prototype 449 MHz

- Advanced wind profiler
devolved at EOL
- Uses spaced antenna
technique
- Subdivided antenna
- Track motion over radar
- Wind measurement every
1 – 5 minutes \textit{(not 30 min)}
- Vertical measurement
every \textit{\~1 minute (not 5 min)}

\textbf{Assumes:} homogeneous, stationary scatterers over \textbf{300 m} \textbf{and} \textbf{30 sec}
\textbf{Measures:} wind in inhomogeneous atmospheric conditions
large-scale turbulence intensity

Limited use in low SNR; sensitive to clutter
MAPR: Antenna and Deployment as an ISS

MAPR Antenna

Antenna with clutter screen, and RASS

Integrated Sounding System
Benefits of the Spaced Antenna Technique

- Less error from spatial and temporal wind variations.
- Continuous measurements within a pulse volume
- Horizontal wind with very good time resolution.
- Monitor vertical air and precipitation motions with high time resolution.
  - Vertical velocity and variance (turbulent energy)
  - Precipitation characteristics (riming, particle size, rainrate)

But...
Needs high signal strength, and Interference is harder to handle
MAPR and tower observations of an Arctic front

Note the brief updraft (red) in clear-air ahead of the front

30-second MAPR winds
449 MHz Spaced Antenna Profiler Prototype at PCAPS

Altitude coverage

449
915 High
915 Low

PCAPS 10 Dec 2010 – 7 Feb 2011

Worked great!
Modular Profiler Concept (Advanced 449-MHz Wind Profiler)

Boundary Layer Config
3 antenna modules
Network of 6

Mid-Tropospheric Config
7 antenna modules
Network of 2

Lower Stratospheric Configuration
19 antenna modules

Range: 150 m – 4 km
Resolution: 30 m

Range: 200 m – 7 km
Resolution: 30-200 m

Range: 300 m – 15 km
Resolution: 100-200 m
What NOAA says:

<quote>
Researchers and forecasters use NPN profiler winds to identify features including

- Ridges and troughs
- Upper level and surface fronts
- Upper and low-level jets
- Vertical shear profiles associated with severe weather
- Mesoscale circulations associated with Mesoscale Convective Systems
- Layers of thermal advection (cold and warm air advection)
</quote>
Low level jet and upper level jet (NPN)
Vertical Shear associated with severe weather (NPN)
NPN Example: Precipitation measured by profilers
Radio Acoustic Sounding (RASS)

RASS Speaker and Shroud
How RASS works

Generate sound waves.
Use the profiler to measure the speed of those sound wave.

\[ C_a = 20.047 \sqrt[2]{T_v} \]

- \( C_a \) The speed of sound in air
- \( T_v \) Virtual temperature (adjusts for moisture content; density)

\( C_a \) is about 340 m/s so ground clutter is not an problem

BUT must adjust for vertical air motion, w
MU Radar Example

Ray-tracing of acoustic wave fronts

Figure 4.1: Acoustic wavefronts assuming constant gradient of acoustic velocity for parameters $C_0 = 331 \text{ m s}^{-1}$ and $C' = 0.0028 \text{ s}^{-1}$.

Figure 4.2: Acoustic wavefronts for parameters $C_0 = 331 \text{ m s}^{-1}$, $C' = 0.0028 \text{ s}^{-1}$, $U_w = 0 \text{ m s}^{-1}$ and $U' = 0.009 \text{ s}^{-1}$.

Figure 4.4: Shape of the backscatter region assuming constant gradients for acoustic and wind speed. (Upper) $C' = 0.0028 \text{ s}^{-1}$ and $U' = 0.00056 \text{ s}^{-1}$. (Lower) $C' = 0.0028 \text{ s}^{-1}$ and $U' = 0.0045 \text{ s}^{-1}$. The radar antenna is located a distance $r$ from the acoustic source.
Radio Acoustic Sounding System (RASS)

Evolution of an inversion – hourly RASS profiles
RASS Limitations and sources of error

• The acoustic shells must be at the Bragg spacing (choose T range)

• Sound can be advected out of the profiler’s view

• Strongly attenuated (915MHz: range < ~1.2 km)

• Correction for vertical air motion

• Minor correction for range weighting
CLIMODE
Gulf Stream
Boundary Layer

Profiler deployed on R/V Knorr in N. Atlantic
Boundary Layer response to Gulf Stream heating

Heat flux from warm ocean
• Similar operating principles as wind profiler/RASS.
  • Transmit sound. Backscatter from thermal and mechanical turbulence.
  • Measure Doppler shifted frequency
  • Uses beam steering.
• Coverage to ~300 (the mini-SODARs we have used)
• Fills in data gap near the surface.
• Resolution of SODAR data is good (15 – 30 m; 15-min)
SODAR

Good for measuring low levels winds and relatively cheap too!

This model: Winds to 300-400m, Reflectivity & turbulence, 15 min.
SODAR winds during an intermittent orographic flow event.

(Pinto et al.)
Correlated SODAR w (bottom) and backscatter lidar wave pattern. 4 Oct 2000. VTMX
SODAR Limitations and errors

- Degraded performance with background noise (e.g. nearby generator)
- Sound can be advected out of the profiler’s view (in high winds)
- Acoustic waves are strongly attenuated
- Limited height coverage
- Often do not work in rain
Final Thoughts

- Remote sensors are powerful tools! (with some subtle pitfalls)
- Can observe winds, temperature, precipitation, even turbulence.
- Fronts, inversions, jets, BL evolution, ocean-atmosphere flux signatures
- We hope PCAPS participants dig deeply into the remote sensor data. And keep in touch with us at NCAR/EOL.
NSF Facilities can be requested for Scientific Campaigns and Educational Uses

Aircraft and instruments:
- C-130, G-V jet, King Air
- Dropsondes from many aircraft

Airborne and Ground based radars:
- ELDORA airborne Doppler radar
- Airborne cloud radar and lidar
- S-POLka and CHILL S/Ka-band radar

Surface remote and in-situ sensors:
- ISS - fixed / mobile profilers and more
- ISFS – surface flux network and more
- Radiosondes (GPS GAUS)

NCAR also as visitor programs and postdoc programs

Go to http://www.eol.ucar.edu/requestfacilities
Bragg Scatter
Constructive interference from reflections spaced a half-wavelength apart

Half wavelength scales reinforce. All other scales cancel.

That’s how we get enough energy back to detect.
RASS Example – Cooling near the surface. Inversion above