Radar Thermodynamic And Wind Profiling

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What should you expect to hear during this presentation?

- A discussion of wind and thermodynamic profiling methodologies with a focus on radar and wind profilers in particular
- What wind profilers provide in the way of dynamic and thermodynamic information
- Which parameters they not not so good at providing
- Which measurements are well suited to complement wind profiler observations
Strengths of Wind Profiling Radars

1. Provide continuous measurements of the atmosphere in all weather conditions over a large range of heights

2. Provide ‘gated’ observations (not just linearly integrated observations) with relatively good spatial and temporal resolution.

3. Capable of supporting atmospheric research in a wide range of topic areas

4. Have been in operation for many years at a variety of geographic locations, so plenty of opportunities for data mining.
Wind Profilers
Coherent Clear-Air Scatter

For the case of Bragg scatter from clear-air turbulence, it is customary to assume that

\[ P = C \frac{\eta}{r^2} \]

\[ \eta = 0.379 \frac{C_n^2}{\lambda^{1/3}} \]

Here it has been assumed that the turbulence is:
- Homogeneous,
- Isotropic,
- Volume-filling, and
- Within the inertial subrange
Structure Function Parameters

The structure function parameter is given by

\[ C_n^2 = \frac{\left\langle |n(r) - n(r + \Delta)|^2 \right\rangle}{\Delta^{2/3}} \]

\[ n - 1 = 77.6 \times 10^{-6} \frac{p}{T} + 0.3733 \frac{e}{T^2} \]

where

- \( p \) is pressure in hPa
- \( T \) is temperature in K
- \( e \) is water vapor pressure in hPa

Neutral Atmosphere
Coherent Clear-Air Scatter

For the case of Bragg scatter from clear-air turbulence, one can also write

$$\eta = a L_o^{4/3} \frac{M^2}{\lambda^{1/3}}$$

$$M = \frac{dn}{dz} = \frac{\partial n}{\partial \Theta} \frac{d\Theta}{dz} + \frac{\partial n}{\partial q} \frac{dq}{dz}$$

Where
- $M$ is the mean gradient of potential refractive index
- $a$ is close to unity for our application
- $L_o$ is the outer scale of turbulence
Kolmogorov Energy Cascade

Wavenumber of turbulence scale given by $\kappa$

Energy-containing range

Buoyancy Subrange

Inertial Subrange

Viscous Subrange

Outer Scale: $L_o$

Inner Scale: $l_o$

$\log E(\kappa)$

$slope = -5/3$
Fresnel Scatter and Reflection

Röttger & Larsen, 1990
Doppler Beam Swinging

- Beam is rapidly steered to three or more directions (phased array antenna)
- Radial velocity measured for each beam
- Wind field reconstructed from the radial velocities
- Wind field assumed uniform over the sampling volume
Doppler Beam Swinging

It is assumed that the wind field is uniform in space and time across the sampling volume.
Spaced Antenna

- Radio waves transmitted and the backscattered signals recorded on three or more spatially separated antennas (or groups of antennas)
- The backscattered signals form a diffraction pattern that moves across the ground
- The speed of the diffraction pattern is measured and related to the wind speed
Interferometry

- Radio waves transmitted and the backscattered signals recorded on three or more spatially separated antennas (or groups of antennas)
- Assume that the backscatter primarily comes from a few scattering centers
- Use the time evolution of the phase differences between the echo power at the various receiver locations to measure the wind
Modular 449-MHz Profiler

UHF Wind Profiler being developed
By NCAR EOL
Radio Acoustic Sounding System (RASS)

- Use radar to measure the propagation speed of sound
- Use an acoustic carrier frequency that produces structures that are Bragg matched with the radar
- Provides profiles of the virtual temperature
Radio Acoustic Sounding System (RASS)

Wind and temperature data collected by NOAA ESRL of the California coast
Multiple Receiver and Frequency Techniques
Atmospheric Radar Imaging
Atmospheric Radar Imaging

CRI (2D in angles)  RIM (1D in range)  3D Imaging
Atmospheric Radar Imaging

- Coherent Radar Imaging (CRI)
  - Multiple Receivers (Single Frequency)
    - Angular (2D)
- Range Imaging (RIM/FII)
  - Multiple Frequencies (Single Receiver)
    - Range (1D)
- 3-Dimensional Imaging (3D Imaging)
  - Multiple Receivers and Multiple Frequencies
    - Angular and Range (3D)
The formation of *multiple receive beams* by digitizing the output of the receiving array elements and forming beams by means of a digital processor.

$$s(n) = \begin{bmatrix} s(\vec{D}_1,n) & s(\vec{D}_2,n) & \cdots & s(\vec{D}_N,n) \end{bmatrix}$$

$$y(n) = w^H s(n)$$
Range Imaging (RIM)

Sum signals from multiple frequencies coherently

RIM input signals
\[ s(n) = [ s(k_1, n) \ s(k_2, n) \ \cdots \ s(k_M, n) ] \]

RIM output signals
\[ y(n) = w^H s(n) \]

Weighted sum !!

1. Fourier RIM:
\[ w = \begin{bmatrix} e^{j2k_1r_1} & e^{j2k_2r_1} & \cdots & e^{j2k_Mr_1} \end{bmatrix}^T \]

2. Capon adaptive RIM:
\[ w = \frac{\hat{V}^{-1}e}{e^H \hat{V}^{-1}e} \]

\[ \hat{P}_r(r_t) = w^H \hat{V}w \]

\[ \hat{V}_{ij} = \hat{R}(\vec{D}_0, k_m, \vec{D}_0, k_n, \tau = 0) = \hat{R}(\Delta k) \]
S-Band FMCW Radar
FMCW

- 2.94 GHz single pol.
- 2.4 m parabolic antennas
- 250 W peak/average TWTA
- 60 MHz bandwidth
- >2.5 m range resolution
- Primary targets: insects and refractive index turbulence
- Tradeoff between range resolution, velocity range, and max range
Planetary Boundary Layer

- Can exhibit extremely complex flow on account of interactions with the Earth’s surface
- Despite its relative proximity to the Earth, still difficult to monitor
Planetary Boundary Layer
In-Situ Instrumentation for PBL Research

- Radiosondes
- Towers
- Tethersondes
- Piloted Aircraft
SMARTSonde's maiden flight on March 15, 2009
March 6\textsuperscript{th} Morning Transition Observations
Sunrise: 6:53
March 6\textsuperscript{th} Morning Transition Observations

Sunrise: 6:53

Wind Profile on 03/06/11

- Height (m)
- Wind Speed (m/s)
- Wind Direction (degrees)

Legend:
- 07:18
- 07:50
- 08:25
- 08:59
- OUN
Large Eddy Simulation

- Assign dynamic and thermodynamic variables to each grid cell
- Parameterize the turbulence within each grid cell
- Use prognostic equations to describe dynamics and thermodynamics at larger scales
- Initialize the LES based on measured values
- “Nudge” the LES based on measured values
LES Thermodynamic Fields

Potential Temperature (K)

Specific Humidity (g kg⁻¹)
Example of one possible SMARTSonde and Radar profiling technique.

- **Radio Waves**
- **Stable Layer**
- **Vertical Transport of Air & Constituents**
- **Turbulent Layer**
- **VHF Radar**
- **SMARTSonde**
- **Flight Path**
Observations at Esrange, Sweden
Swedish Space Corporation
Measurements of $C_n^2$

23 Aug 2012: Height = 900m AGL

24 Aug 2012: Height = 900m AGL
Measurements of $M^2$
Additional Complementary Methods

- Microwave Radiometry
- Infrared Radiometry
- Lidar
- Dual-wavelength radar
- Global Navigation Satellite Systems
- Refractivity Methods
- Others …
Summary

• Wind profilers are well suited for wind retrievals and to some extent can be used for direct and indirect estimation of thermodynamic parameters.

• The prospects of thermodynamic retrieval is enhanced when complementary observations from other sources are used.

• Thermodynamic Profiling Technologies Workshop held in Boulder, CO (April 2011)

NCAR/TN-488+STR NCAR Technical Note
“Thermodynamic Profiling Technologies Workshop Report to the National Science Foundation and the National Weather Service”

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