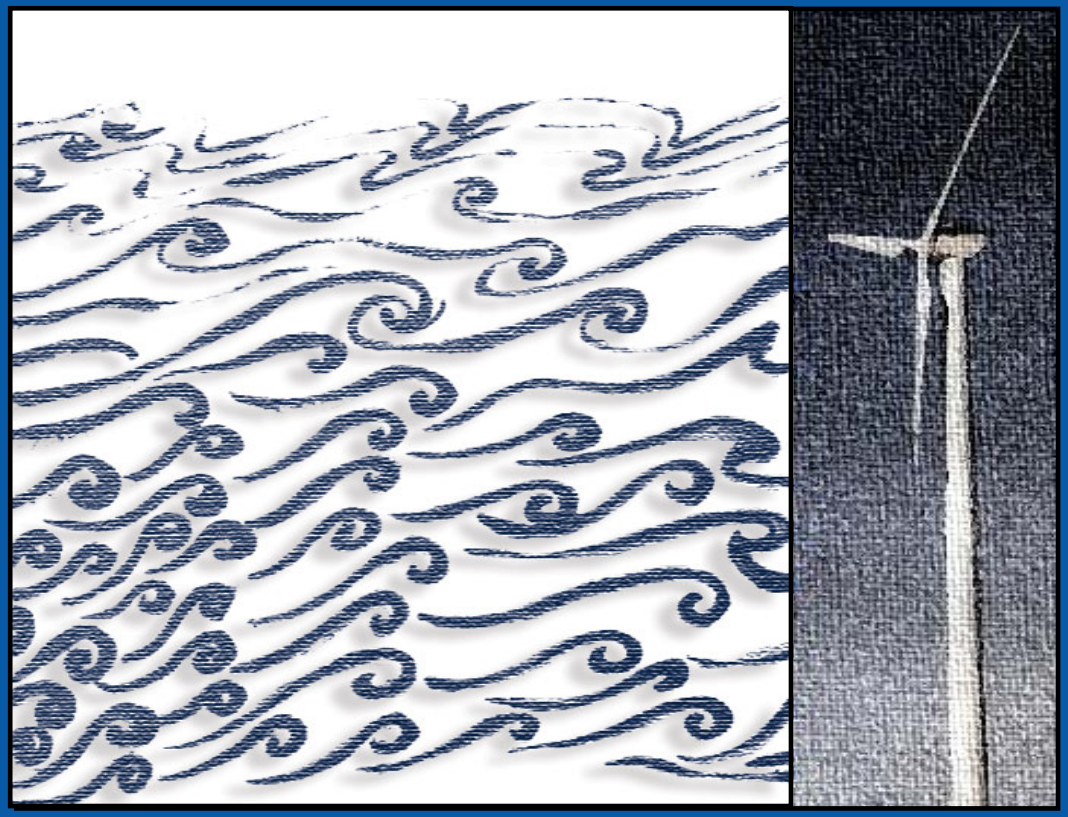
National Renewable Energy Laboratory
Innovation for Our Energy Future

The TurbSim Site-Specific Models



TurbSim Workshop
National Wind Technology Center

Bonnie Jonkman

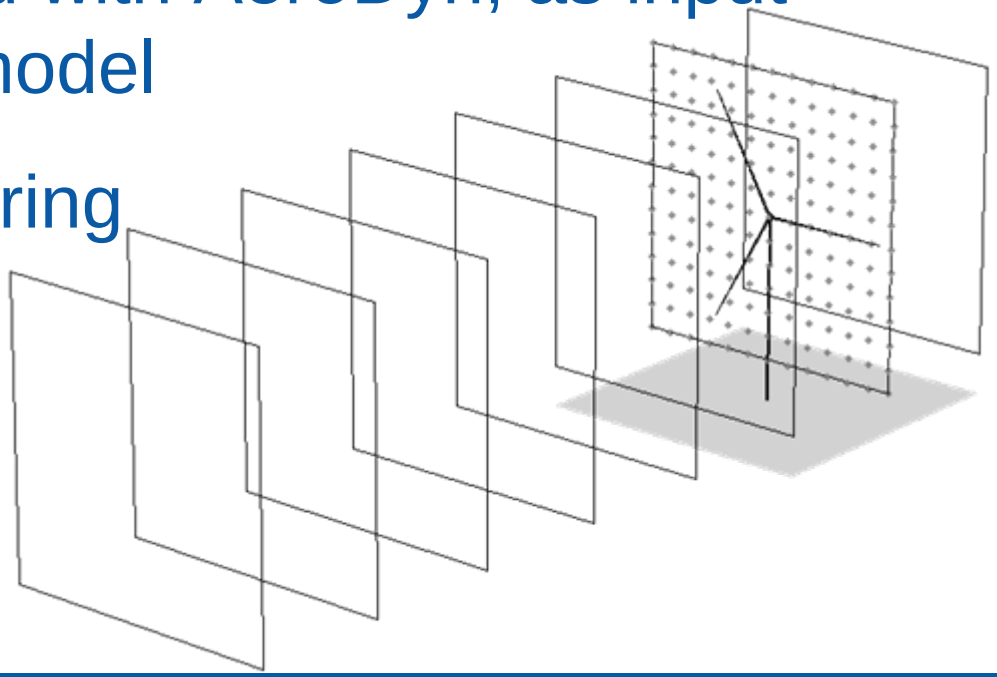
September 23, 2008

Presentation Outline

- TurbSim Overview
- History
- Simulation Method
  - Frequency Domain
  - Time Domain
  - Superimposed Coherent Structures
- Implementation in TurbSim
  - Velocity Spectra
  - Spatial Coherence
  - Wind Profiles
  - Coherent Structures

Overview

- TurbSim generates time series of 3-component winds on a rectangular 2-D (Y-Z) grid in space
- Intended to be used with AeroDyn, as input for a wind turbine model
- **Statistical** engineering simulation (not physics-based)



History

- SNLWIND (1988)
  - Developed by Paul Veers at Sandia National Laboratories
  - Simulated the *u*-component wind speed only
- SNLWIND-3D (1992)
  - Developed by Neil Kelley at NREL
  - Simulated all three wind components
  - Included additional spectral models
    - Wind farm models (WF_UPW, WF_07D, WF_14D)
    - Smooth-terrain model
    - IEC Kaimal and von Karman models

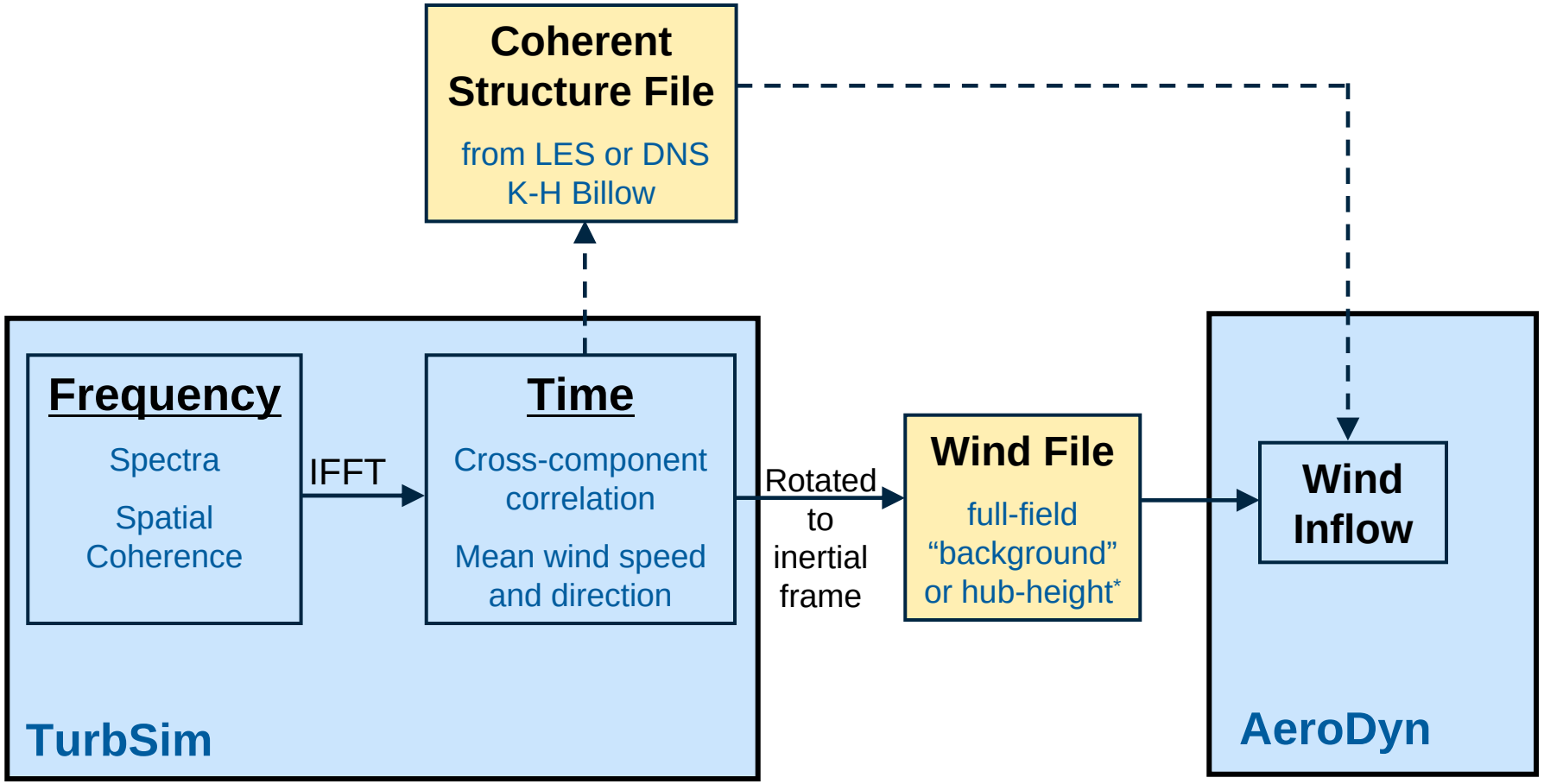
History

- SNwind (2000)
  - Code was modernized by Marshall Buhl
    - Written in Fortran 95 instead of FORTRAN 77
  - Contained only IEC Kaimal and von Karman models
- TurbSim (2004)
  - Written by Bonnie Jonkman
  - Includes all features of SNLWIND-3D and SNwind
  - Added ability to generate superimposed coherent structures
  - Added additional site-specific models
    - NWTCUP, based on NWTC-LIST Project data
    - GP_LLJ, based on Lamar Low-Level Jet Project data

Current Models

- Three general spectral models
  - IECKAI: Neutral Kaimal (defined in IEC 61400-1)
  - IECVKM: Neutral von Karman (defined in 61400-1)
  - SMOOTH: Smooth Terrain
- Five site-specific spectral models
  - GP_LLJ: Great Plains Low-Level Jet
  - NWTCUP: NWTC (downwind of Rocky Mountains)
  - WF_UPW: Wind Farm, Upwind
  - WF_14D: Wind Farm, 14 Rotor-Diameters Downwind
  - WF_07D: Wind Farm, 7 Rotor-Diameter Spacing

Simulation Method



* Coherent structure files require full-field "background" wind files (*.wnd). They will not work with hub-height files (*.hh).

Simulation Method

- Frequency Domain
  - Power spectral density, *S*, is defined for each of three independent wind components
  - Coherence, Coh_{jk}, is defined between *points j* and *k* in space for each component (not between *components*)
  - Cross-spectral density, S_{jk}, is calculated using the auto-spectral densities and coherence:

$$S_{jk} = Coh_{jk} \sqrt{S_j \, S_k}$$

Simulation Method

- Fourier Transformation
  - The spectral matrix is transformed using a Cholesky decomposition:

$$S_{jk} = HH^T$$

  - Fourier coefficients are calculated:

$$V_j\left(f_m\right) = \sum_{k=1}^{j} H_{jk}\left(f_m\right) e^{i\theta_{km}}$$

  - Independent, zero-mean, wind speed time series are obtained by an inverse FFT

Simulation Method

- Time Domain
  - The three independent wind speed components, *u*, *v*, and *w*, are correlated at each point, *j*:

$$u_{j,cor} = u_{j,indep}$$

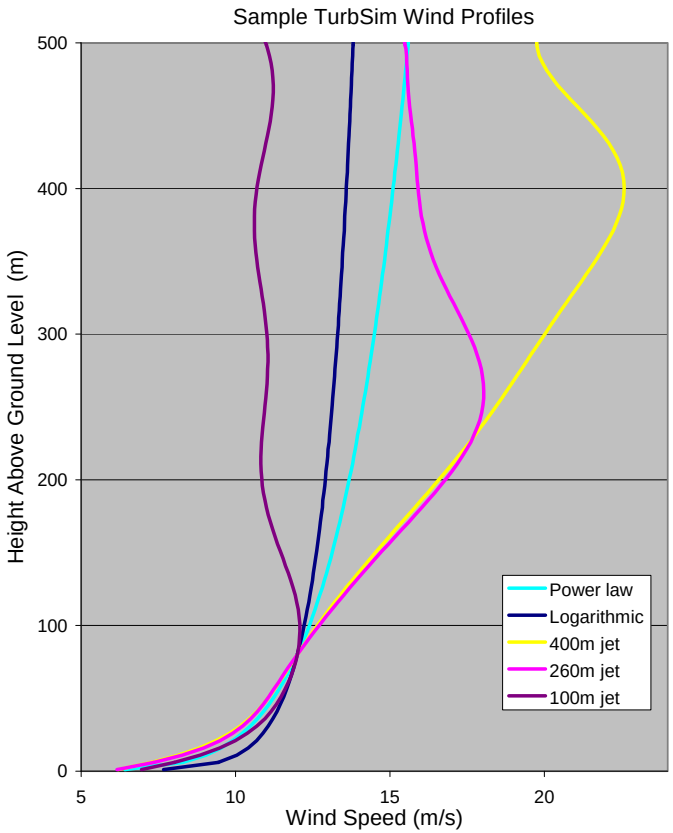
$$v_{j,cor} = \alpha_{uv} u_{j,indep} + v_{j,indep} + \alpha_{vw} w_{j,indep}$$

$$w_{j,cor} = \alpha_{uw} u_{j,indep} + w_{j,indep}$$

    - The α coefficients are chosen so that the input hub-point Reynolds stresses are achieved
    - The α coefficients are zero for the IEC spectral models

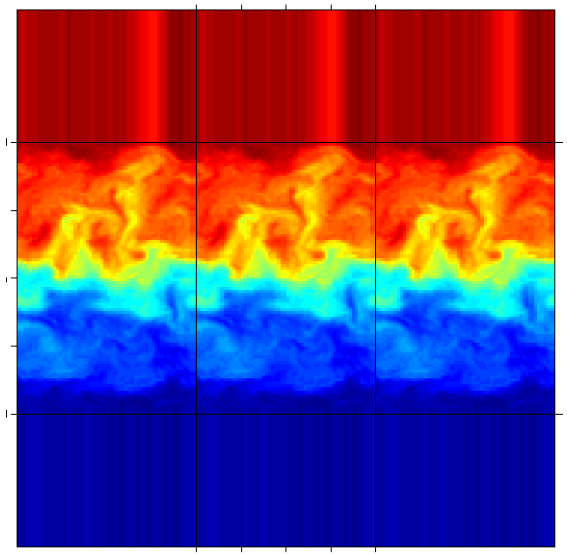
Simulation Method

- Time Domain (continued)
  - The mean wind speed profile is added
  - Horizontal and vertical flow angles are applied
    - Data is transformed from coordinate system aligned with the mean flow to inertial reference frame
  - Time series are summarized and written to output files



Simulation Method

- Superimposed Coherent Structures
  - Structures are sections of LES and DNS realizations of a Kelvin-Helmholtz billow
  - TurbSim calculates (randomly) where structures should be added and how they should be scaled
  - Structures are superimposed on the TurbSim-generated time series in AeroDyn during turbine simulations

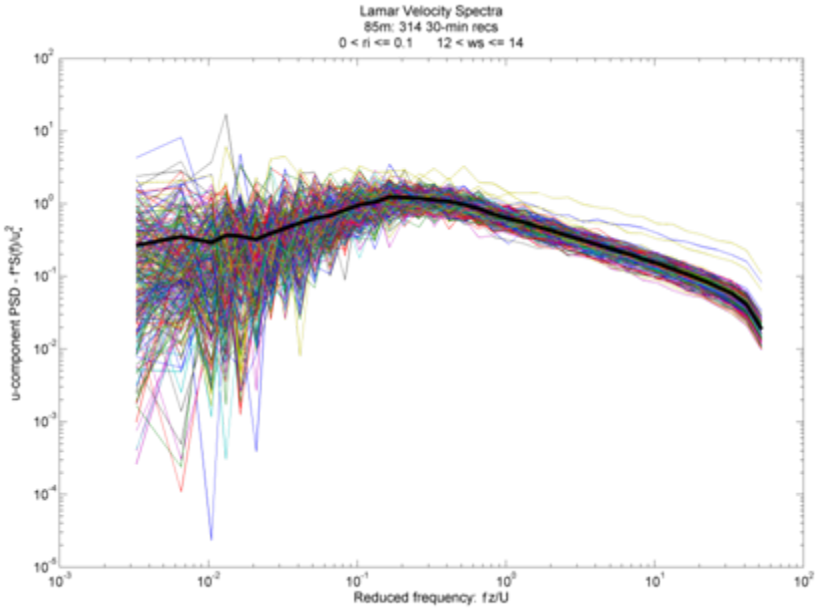


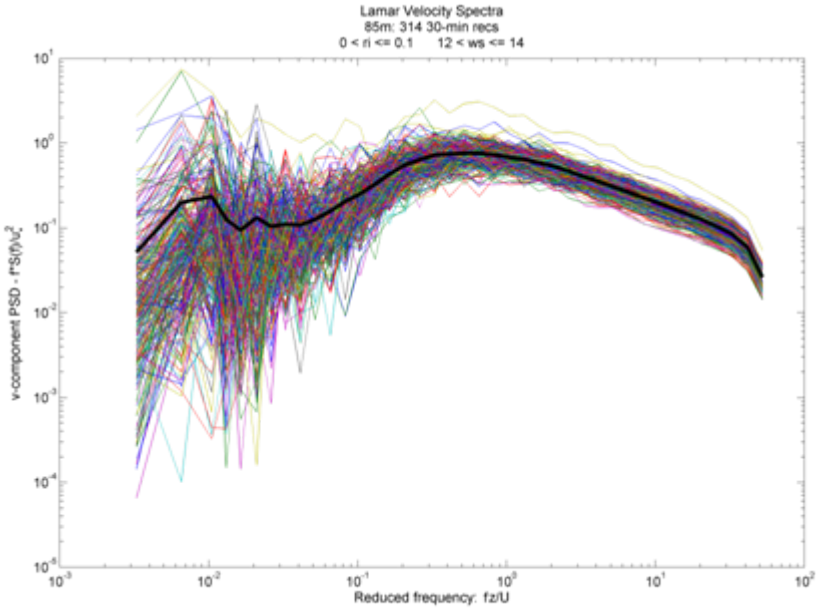
Types of Coherence in TurbSim

	Spatial Frequency Domain	Cross-Component Time Domain	Coherent Structures "Merged" in AeroDyn
IEC models	Coherence between u_j and u_k		
All other models	Coherence between u_j and u_k, v_j and v_k, and w_j and w_k	Coherence between u_j, v_j, and w_j	Pieces of an LES or DNS KH billow superimposed

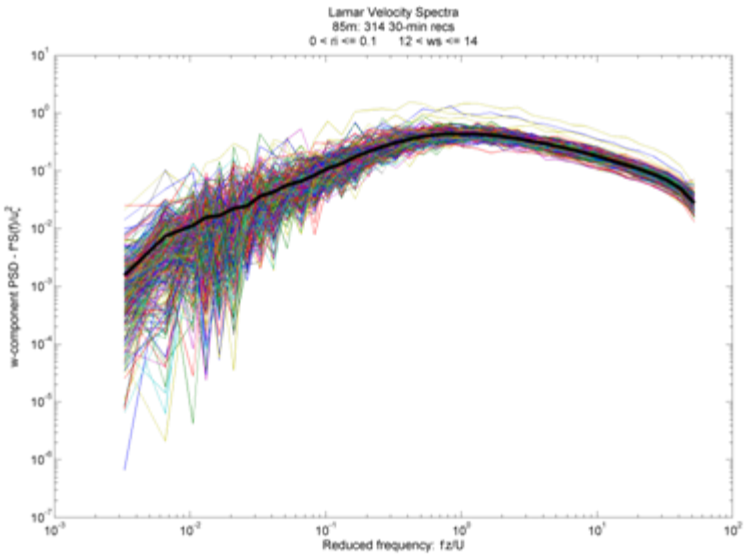
Velocity Spectra

Modeling Velocity Spectra for Site-Specific Models





Modeling Spectra: Method



- Data binned by stability and wind speed categories
  - 2-m/s wind-speed bins
  - 5 stability bins based on Richardson number (2 unstable, 3 stable)
- 30-minute logarithmic spectra averaged in each category bin
- Average spectrum in each bin modeled as a sum of spectral peaks, based on form of SMOOTH model (spectra developed by Risø authors Højstrup, Olesen, and Larsen)
- Scaling parameters of spectral peaks fit to exponential and power functions, based on mean of category

Modeling Spectra: Datasets

- GP_LLJ model → Lamar dataset
  - 20 Hz data
  - Sonic anemometers at 54, 67, 85, and 116 m
    - Each anemometer had 1,152 – 3,633 thirty-minute spectra
- NWTCUP model → NWTC/LIST dataset
  - 40 Hz data
  - Sonic anemometers at 15, 37, and 58 m on central tower and at 37 m on two outside towers
    - Each anemometer had 405 – 668 thirty-minute spectra

Modeling Spectra: Datasets

- WF_UPW model → San Gorgonio Inflow dataset
  - 50 Hz data
  - Sonic anemometer at 23 m
- WF_14D → model San Gorgonio Outflow dataset
  - 50 Hz data
  - Sonic anemometer at 23 m
- WF_07D model → Thin Airfoil Row 37 dataset
  - 16 Hz data
  - Sonic anemometer at 23 m

Modeling Stable Spectra

- Neutral/Stable SMOOTH model[1]
  - Basis function for modeling site-specific spectra for stable boundary conditions

$$\frac{f\,S_{SMOOTH,c}(f)}{u_*^{\,2}} = \frac{s_{1,c}\left(\dfrac{fz}{u\phi_M}\right)\left(\dfrac{\phi_E}{\phi_M}\right)^{2/3}}{1.0 + s_{2,c}\left(\dfrac{fz}{u\phi_M}\right)^{5/3}}$$

$$\phi_M = 1.0 + 4.7\,{}^{z}\!/_{L}$$

$$\phi_E = \left(1 + 2.5\left({}^{z}\!/_{L}\right)^{0.6}\right)^{3/2}$$

$$\langle s_1, s_2 \rangle = \begin{cases} \langle 79.0, 263.0 \rangle & u\text{-component} \\ \langle 13.0, 32.0 \rangle & v\text{-component} \\ \langle 3.5, 8.6 \rangle & w\text{-component} \end{cases}$$

[1] Olesen, H.R.; Larsen, S.E.; and Højstrup, J. (July 1984) "Modeling Velocity Spectra in the Lower Part of the Planetary Boundary Layer." *Boundary-Layer Meteorology,* Vol. 29.

Modeling Stable Spectra

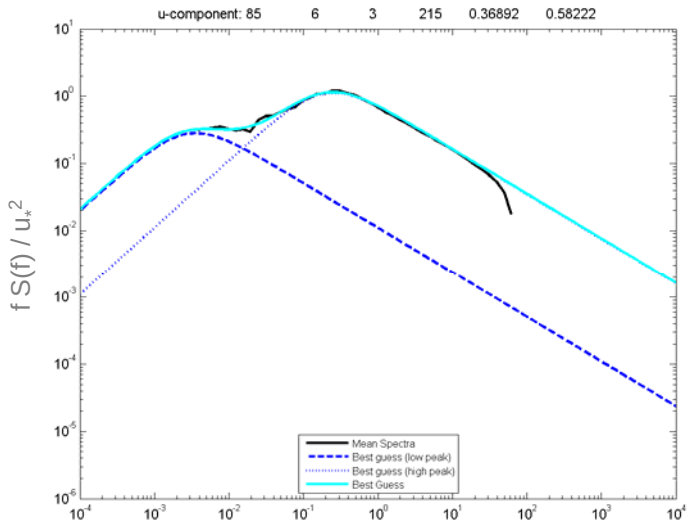
- Neutral/Stable Site-Specific Models:

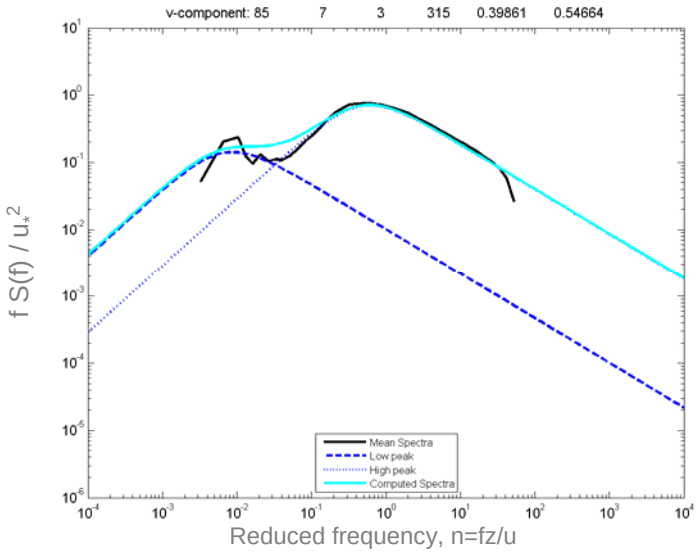
$$S_{site-spec}(f) = \sum_{i=1}^{NumPeaks} \widetilde{p_i} S_{SMOOTH}\left(\frac{f}{\widetilde{f_i}}\right)$$

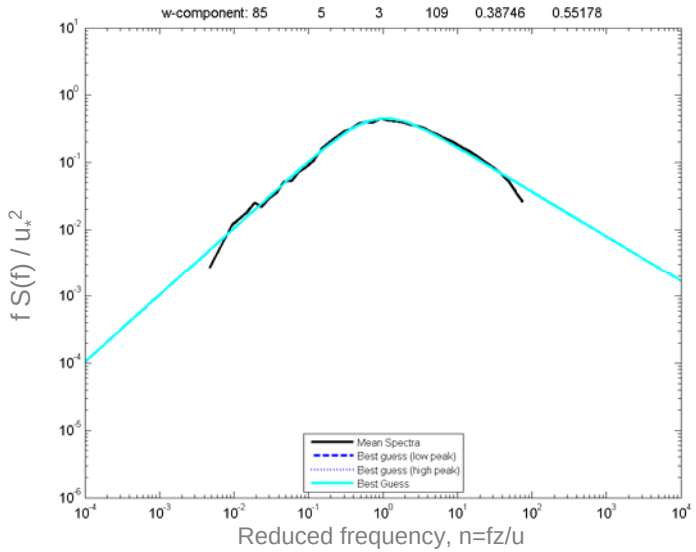
Number of Stable Spectral Peaks in TurbSim Models

	u	v	w
SMOOTH	1	1	1
GP_LLJ	2	2	1
NWTCUP	2	2	2
WF_UPW	2	2	2
WF_14D/ WF_07D	2	2	2

GP_LLJ Stable Spectra



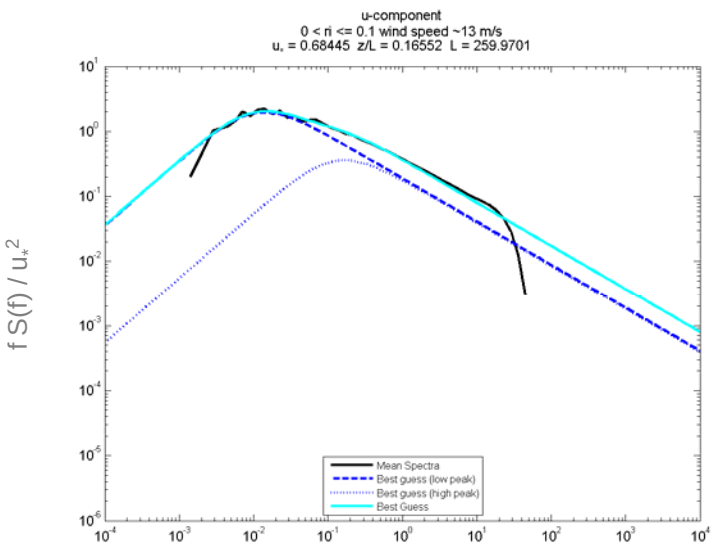


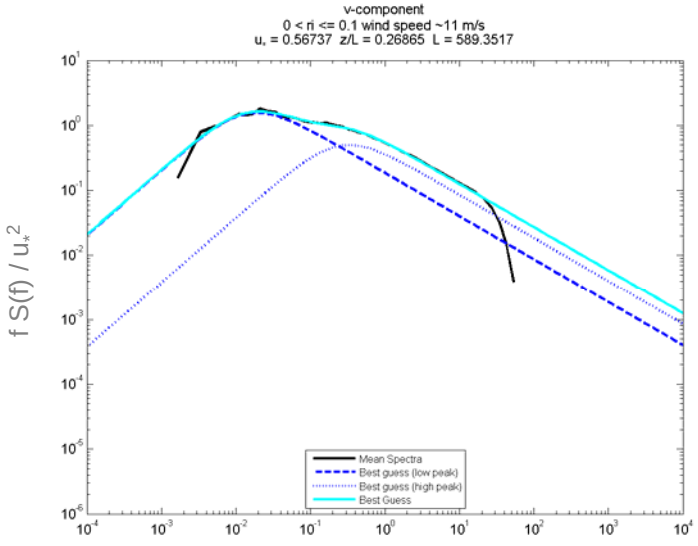


$$\widetilde{f_{i,c}} = \alpha_{1,i,c} \, {}^{z}\!/_{L_{local}}{}^{\alpha_{2,i,c}} \, u_{*_{local}}{}^{\alpha_{3,i,c}} \cdot \exp\left(\alpha_{4,i,c} \, {}^{z}\!/_{L_{local}} + \alpha_{5,i,c} u_{*_{local}}\right)$$

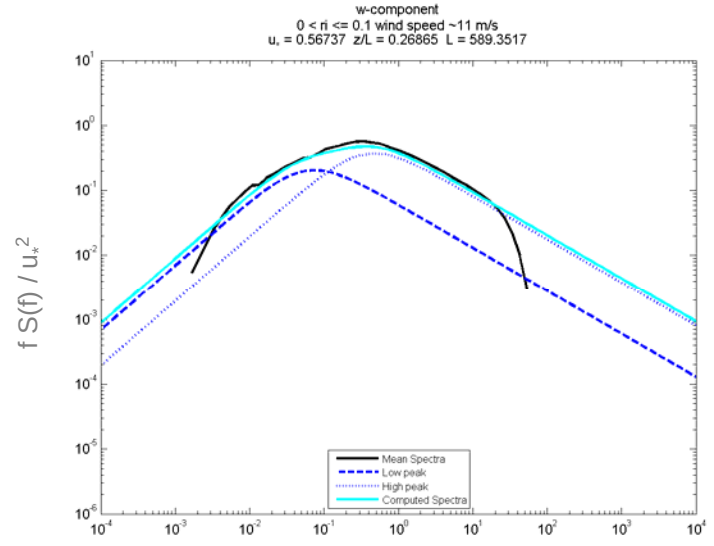
$$\widetilde{P_{i,c}} = \beta_{1,i,c} \, {}^{z}\!/_{L_{local}}{}^{\beta_{2,i,c}} \, u_{*_{local}}{}^{\beta_{3,i,c}} \cdot \exp\left(\beta_{4,i,c} \, {}^{z}\!/_{L_{local}} + \beta_{5,i,c} u_{*_{local}}\right)$$

NWTCUP Stable Spectra





Reduced frequency, n=fz/u

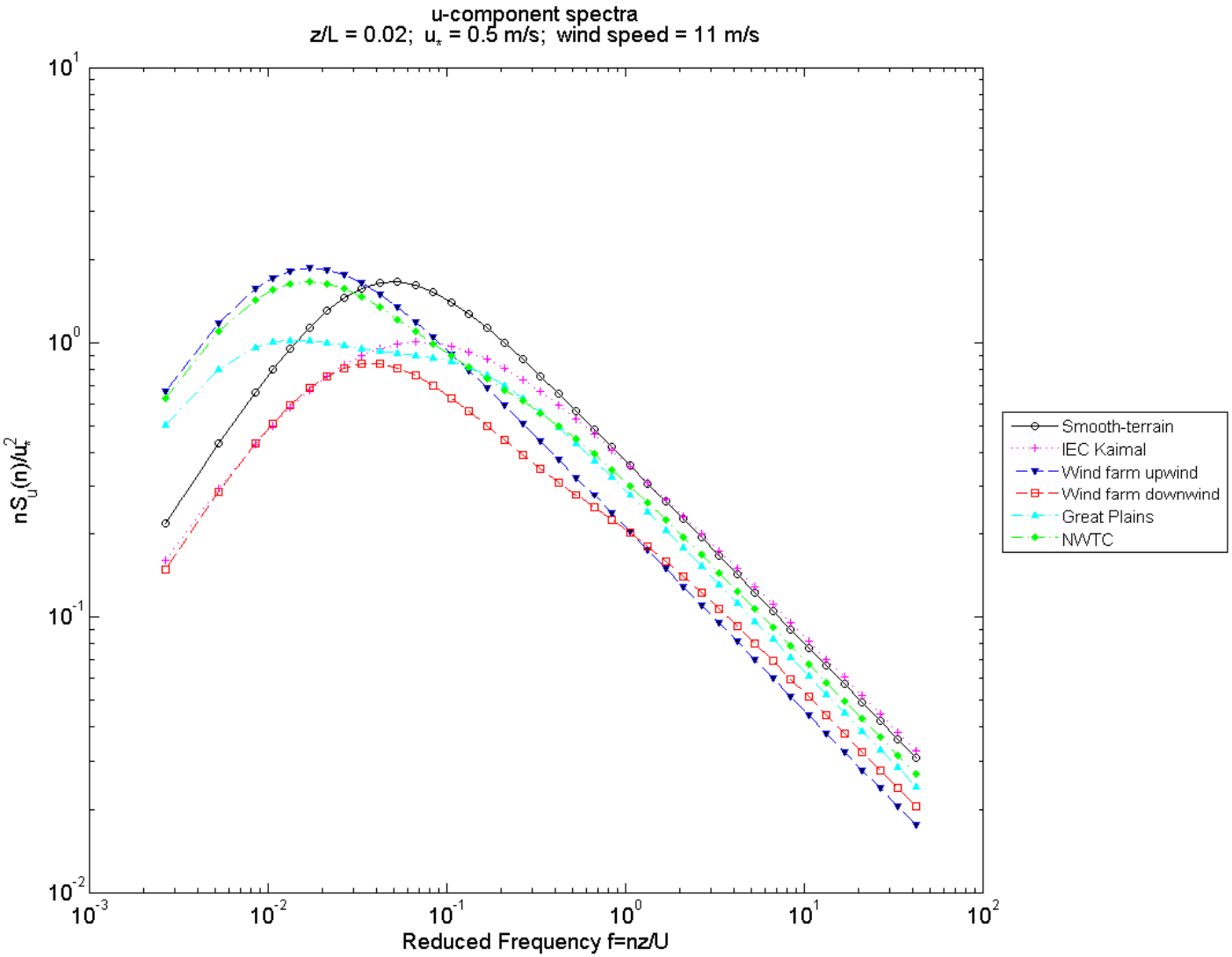


Reduced frequency, n=fz/u

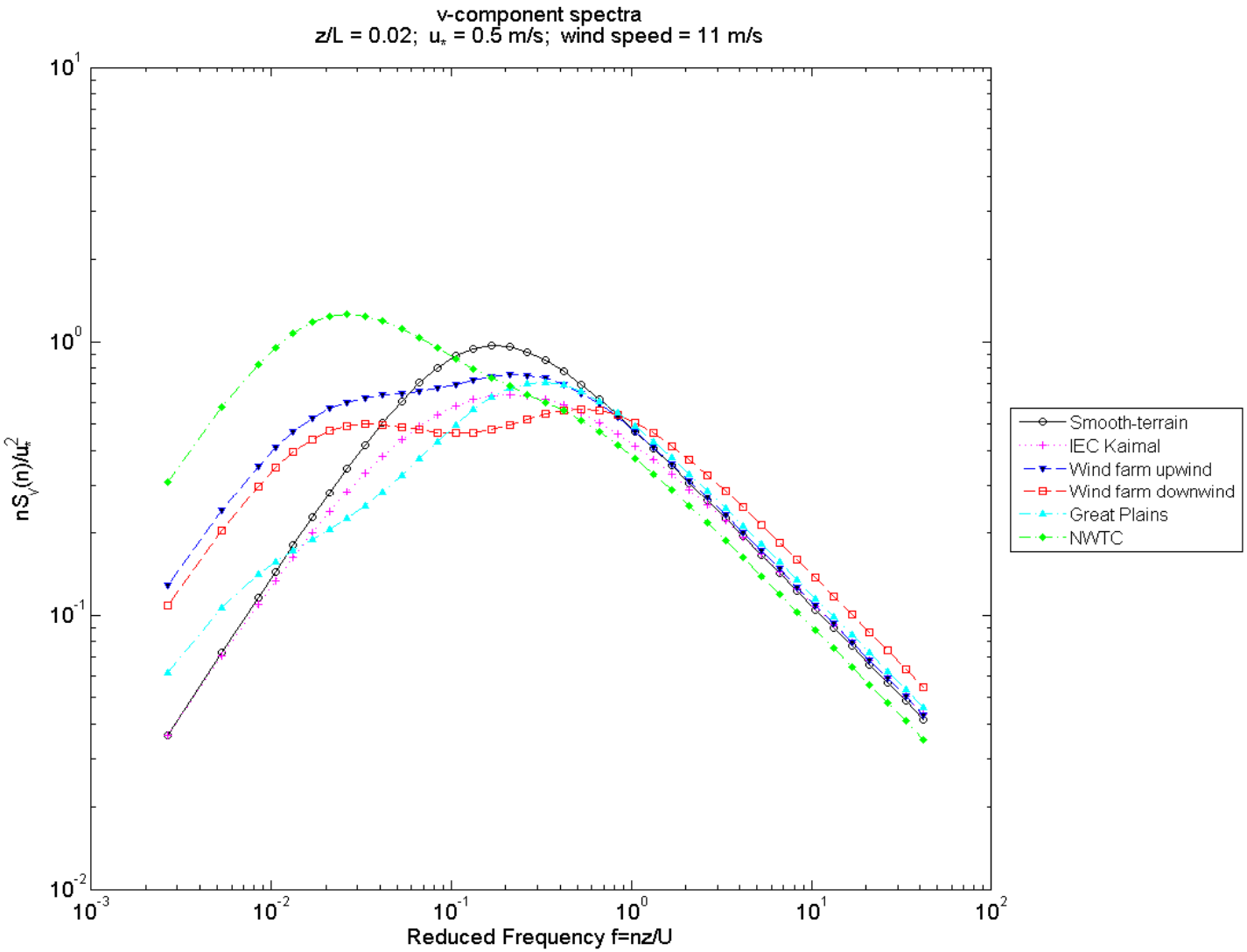
$$\widetilde{f_{i,c}} = \alpha_{1,i,c}\, z/L^{\alpha_{2,i,c}} \exp\left(\alpha_{3,i,c}\, z/L\right)$$

$$\widetilde{P_{i,c}} = \beta_{1,i,c}\, z/L^{\beta_{2,i,c}} \exp\left(\beta_{3,i,c}\, z/L\right)$$

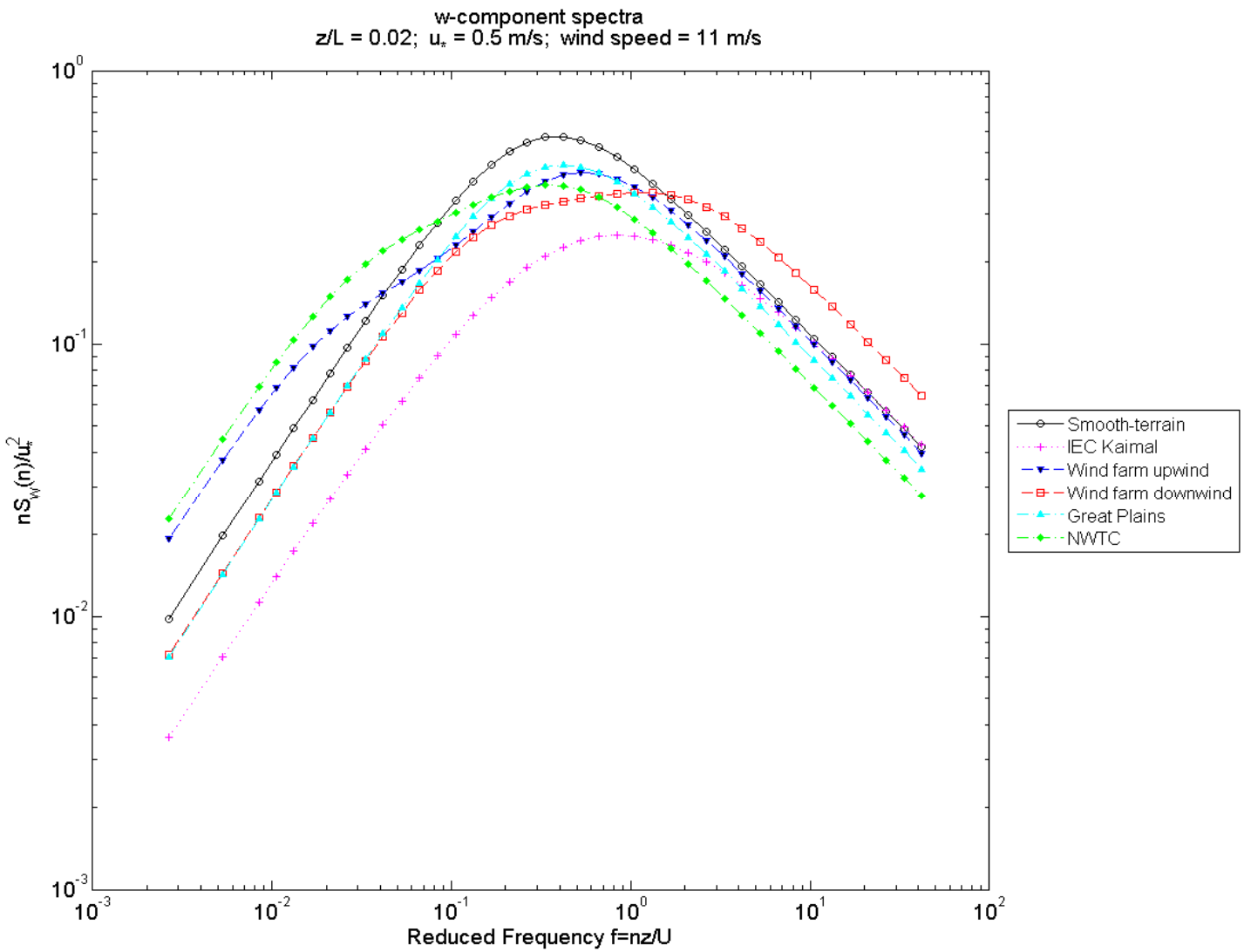
Stable u-Component Spectra



Stable v-Component Spectra



Stable w-Component Spectra



Modeling Unstable Spectra

- Unstable SMOOTH model[2]
  - Basis function for modeling site-specific spectra for unstable boundary conditions

$$\frac{f\,S_{SMOOTH,c}(f)}{u_*^{\,2}} = P_{L,c}(f) + P_{H,c}(f)$$

$$P_{L,c} = \frac{s_{1,c}\,\frac{f\,z_i}{u}}{1 + s_{2,c}\left(\frac{f\,z_i}{u}\right)^{5/3}}\left(\frac{z_i}{-L}\right)^{2/3} F_c$$

$$F_c = \begin{cases} 1, & u,\,v \\ \left(\dfrac{\left(\frac{f\,z}{u}\right)^2 + \left(0.3\,z/z_i\right)^2}{\left(\frac{f\,z}{u}\right)^2 + \left(0.15\right)^2}\right)^{1/2}, & w \end{cases}$$

$$P_{H,c} = \frac{s_{1,c}\,\frac{f\,z}{u\left(1+s_{3,c}\,z/z_i\right)}\left(1 - z/z_i\right)^2}{\left(1 + s_{2,c}\,\frac{f\,z}{u\left(1+s_{3,c}\,z/z_i\right)}\right)^{5/3}\left(1 + s_{3,c}\,z/z_i\right)^{2/3}}$$

[2] Højstrup, J. (October 1982) "Velocity Spectra in the Unstable Planetary Boundary Layer." *Journal of the Atmospheric Sciences*, Vol. 39.

Modeling Unstable Spectra

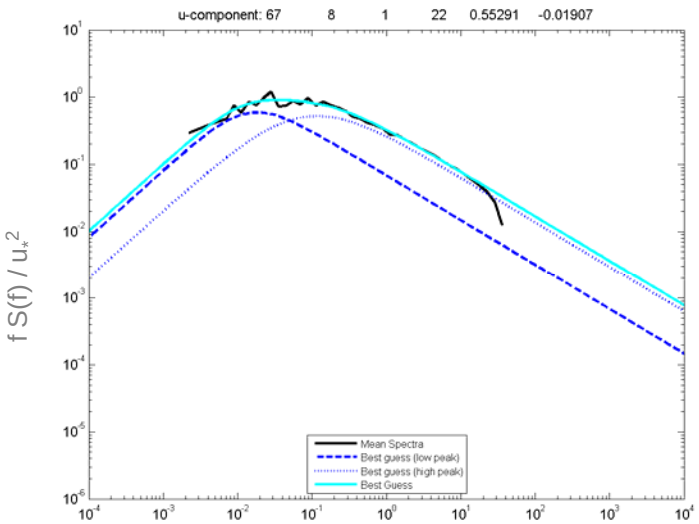
- Unstable Site-Specific Models

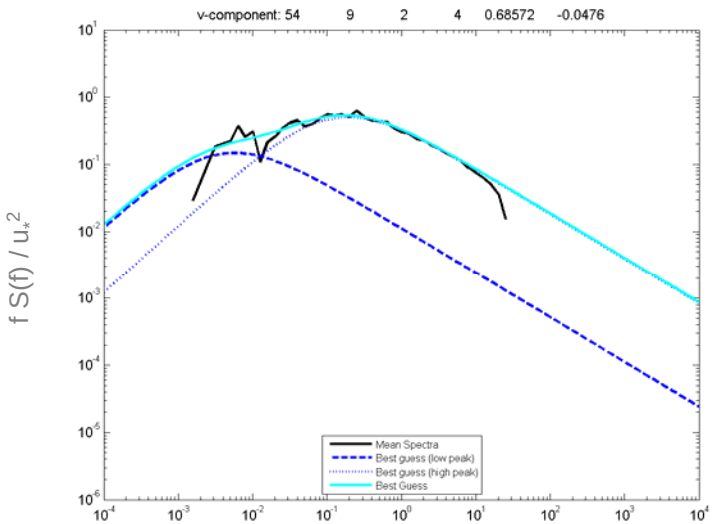
$$S_{site-spec}(f) = \widetilde{p_1} S_{SMOOTH,L}\left(\frac{f}{\widetilde{f_1}}\right) + \sum_{i=2}^{NumPeaks} \widetilde{p_i} S_{SMOOTH,H}\left(\frac{f}{\widetilde{f_i}}\right)$$

Number of Unstable Spectral Peaks in TurbSim Models

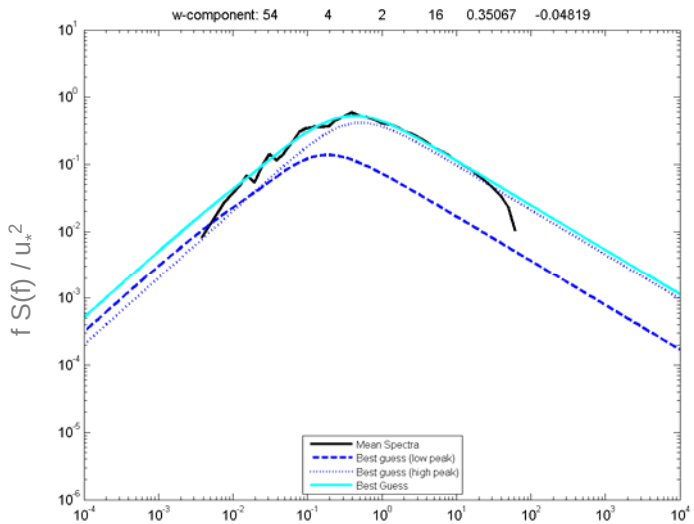
	u	v	w
SMOOTH/ GP_LLJ	2	2	2
NWTCUP	2	2	2
WF_UPW	2	2	2
WF_14D/ WF_07D	2	3	2

GP_LLJ Unstable Spectra





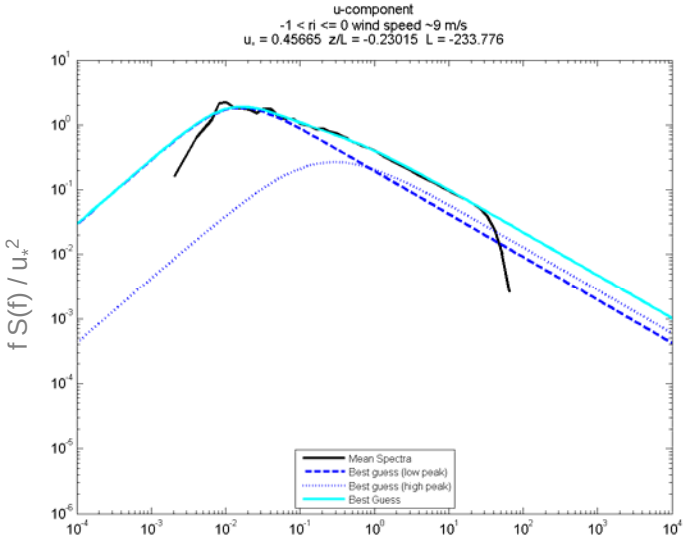
Reduced frequency, n=fz/u

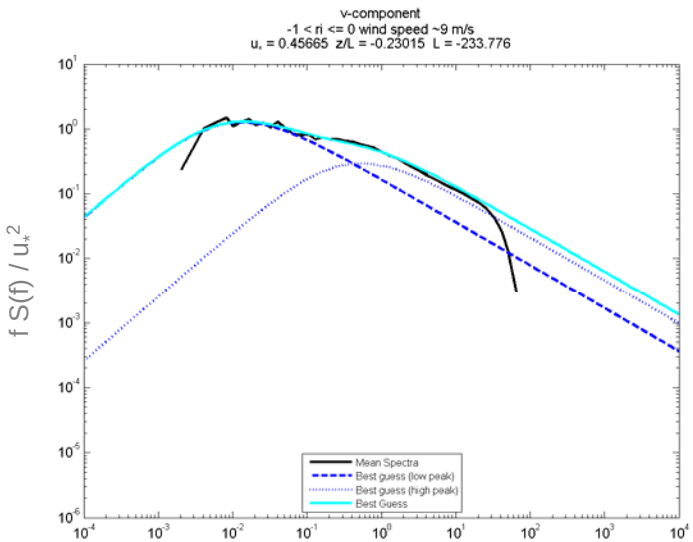


Reduced frequency, n=fz/u

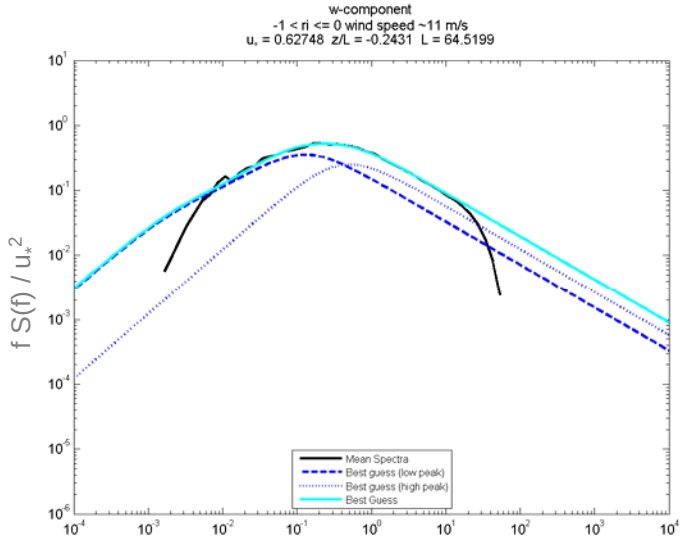
- Not enough data to fit scaling equations with confidence
- The unstable GP_LLJ spectra are the same as the unstable SMOOTH spectra in TurbSim

NWTCUP Unstable Spectra





Reduced frequency, n=fz/u

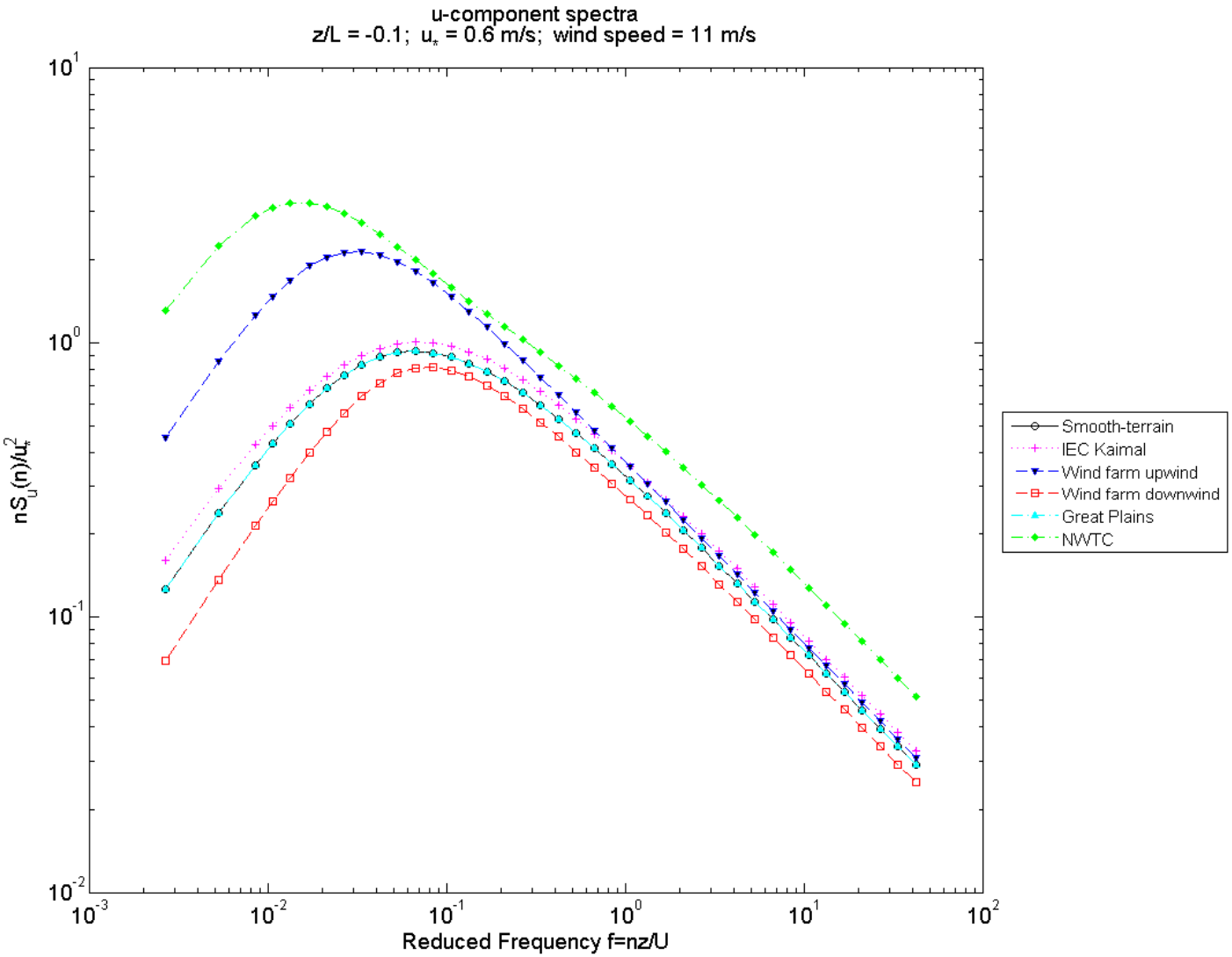


Reduced frequency, n=fz/u

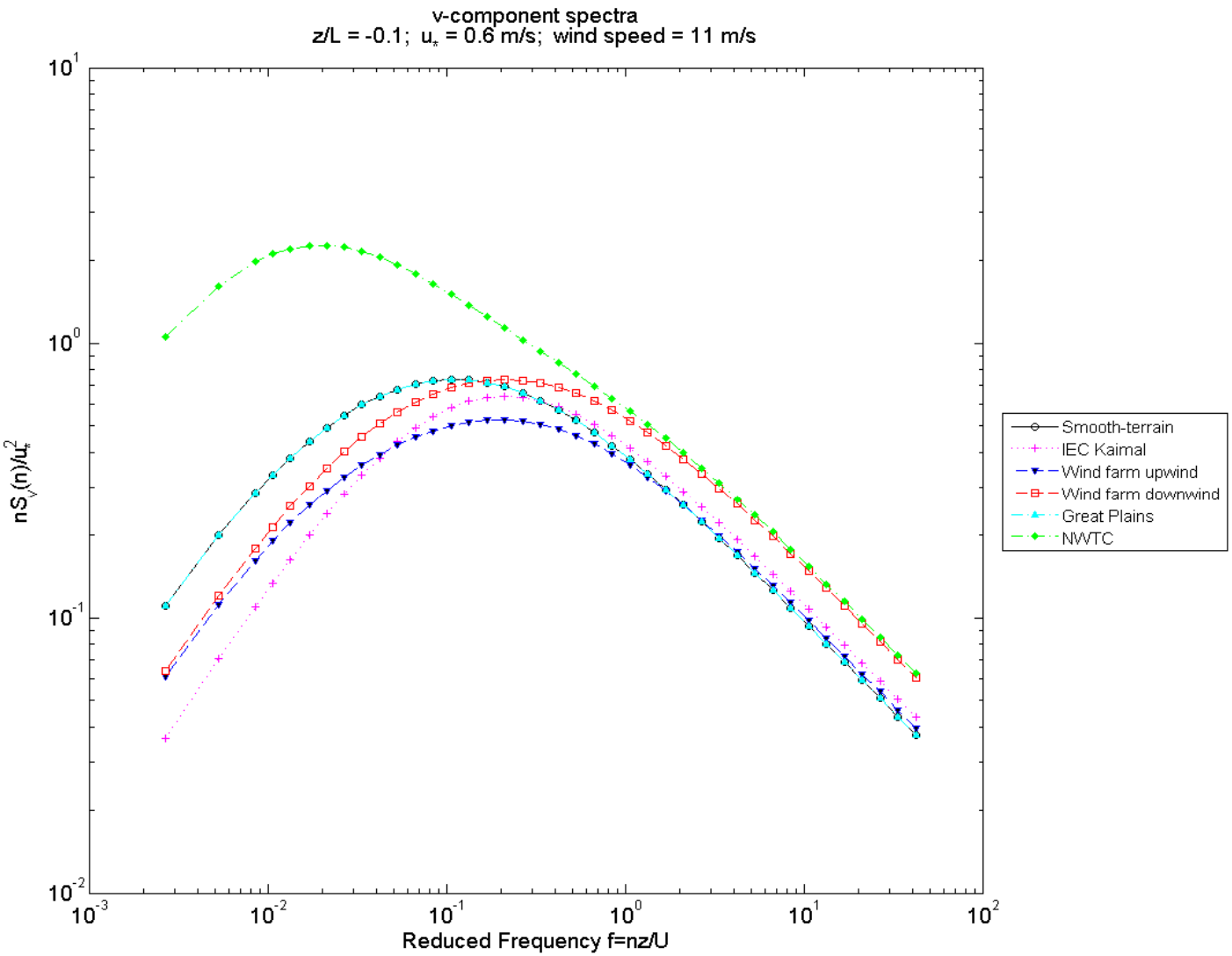
$$\widetilde{f_{i,c}} = \alpha_{1,i,c}\, z/L^{\alpha_{2,i,c}}\, u_*^{\alpha_{3,i,c}} \exp\left(\alpha_{4,i,c}\, z/L + \alpha_{5,i,c} u_*\right)$$

$$\widetilde{P_{i,c}} = \beta_{1,i,c}\, z/L^{\beta_{2,i,c}}\, u_*^{\beta_{3,i,c}} \exp\left(\beta_{4,i,c}\, z/L + \beta_{5,i,c} u_*\right)$$

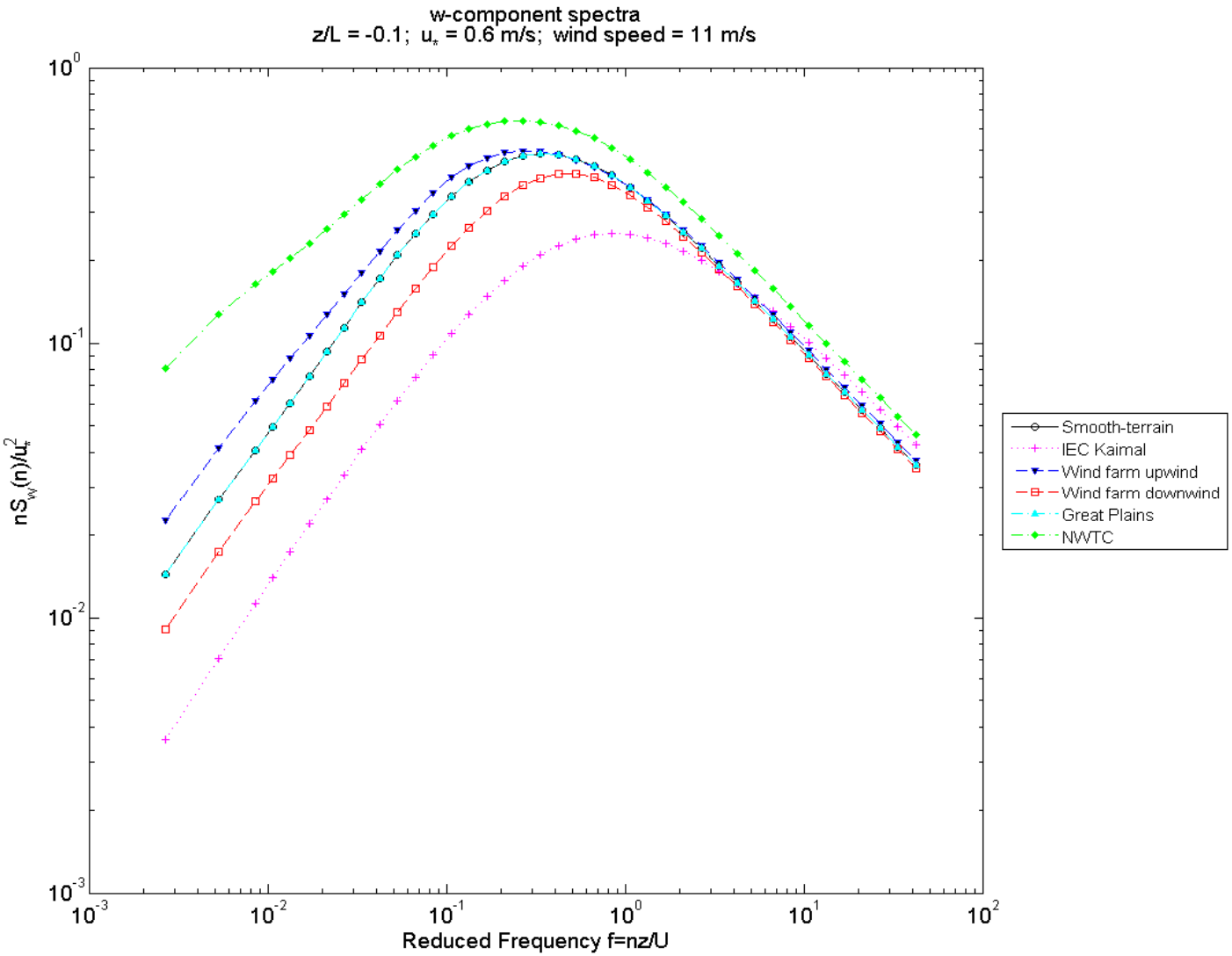
Unstable u-Component Spectra



Unstable v-Component Spectra

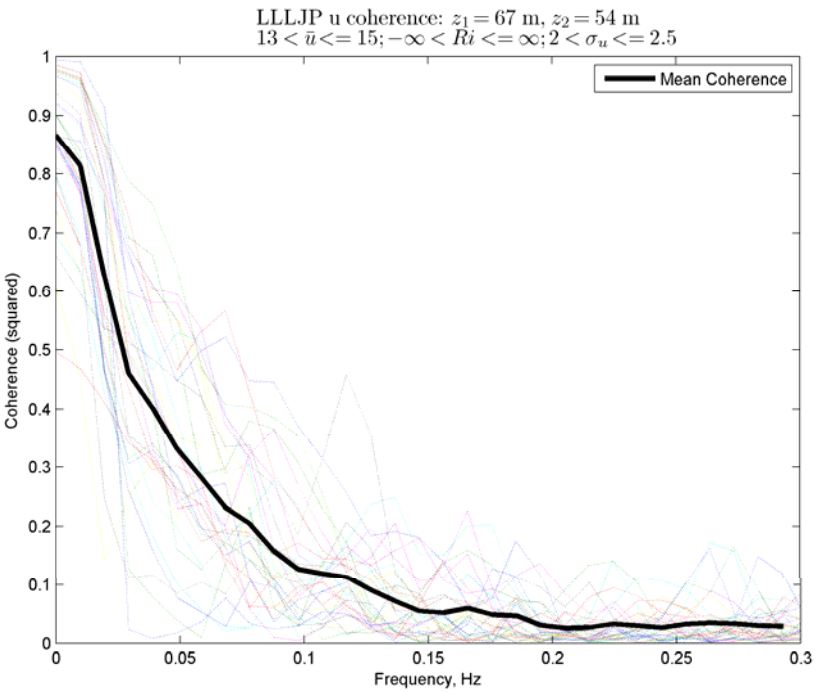


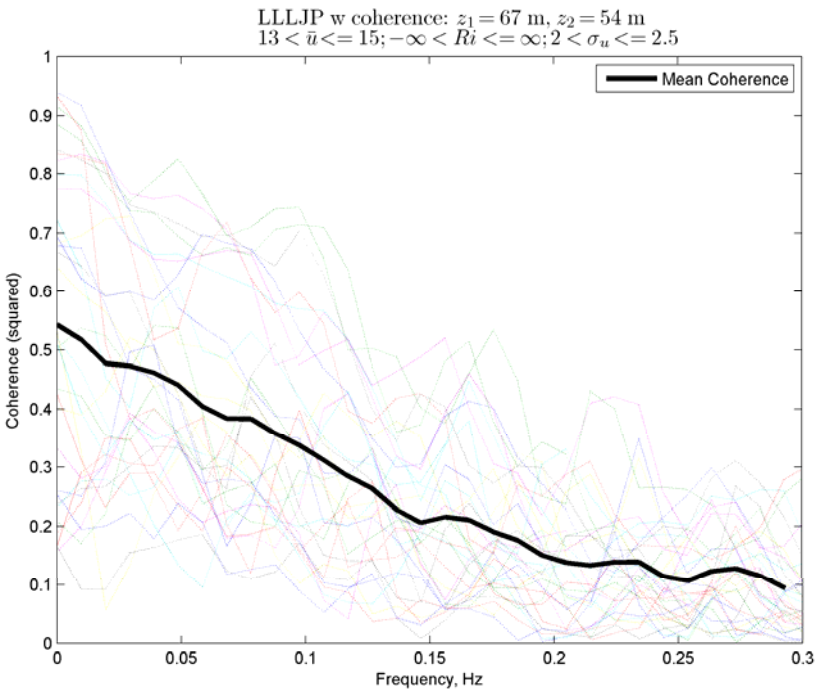
Unstable w-Component Spectra



Spatial Coherence

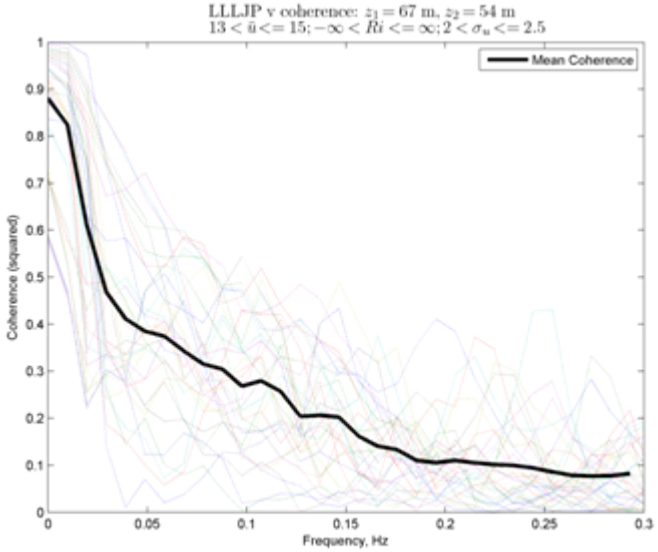
Modeling Vertical Coherence for Site-Specific Models





Modeling Coherence: Method

- Data binned by wind speed, standard deviation of wind speed, and stability categories
  - 2-m/s wind-speed bins
  - 0.5-m/s standard deviation bins
  - 5 stability bins based on Richardson number (2 unstable, 3 stable)



- Magnitude-squared coherence estimate from 30-minute time series averaged for each separation distance in each bin

$$\gamma^2(f) = \frac{\left|S_{pq}(f)\right|^2}{S_{pp}(f)S_{qq}(f)}$$

Modeling Coherence: Method

- Average coherence fit with exponential coherence equation developed by Thresher *et al*[3] , with free variables “a” and “b/L” :

$$Coh_{j,k} = \exp\left(-a\sqrt{\left(\frac{f\,r}{U_m}\right)^2 + \left(\frac{b}{L}r\right)^2}\right)$$

- Coherence specified by IEC 61400-1 standard uses same form, with $U_m = U_{hub}$ and parameters specified as

$$a_u = \begin{cases} 12.0, & \text{Ed. 3} \\ 8.8, & \text{Ed. 2} \end{cases} \qquad \frac{b}{L_u} = \begin{cases} \dfrac{0.021}{\min\left(z_{hub}, 60\text{ m}\right)}, & \text{Ed. 3} \\ \dfrac{0.049}{\min\left(z_{hub}, 30\text{ m}\right)}, & \text{Ed. 2} \end{cases}$$

[3] Thresher, R.W.; Holley, W.E.; Smith, C.E.; Jafarey, N.; and Lin, S.-R.; (August 1981) “Modeling the Response of Wind Turbines to Atmospheric Turbulence.” Report No. RL0/2227-81/2, Department of Mechanical Engineering, Oregon State University, OR.

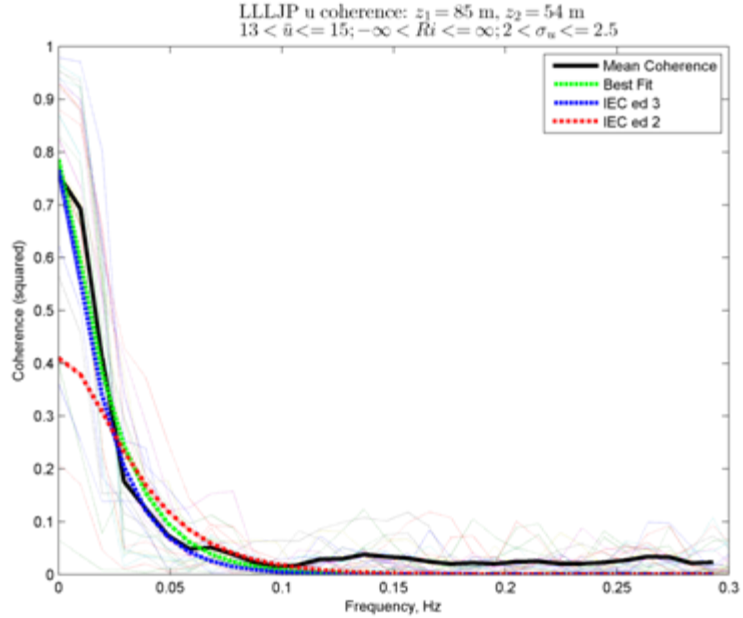
Modeling Coherence: Datasets

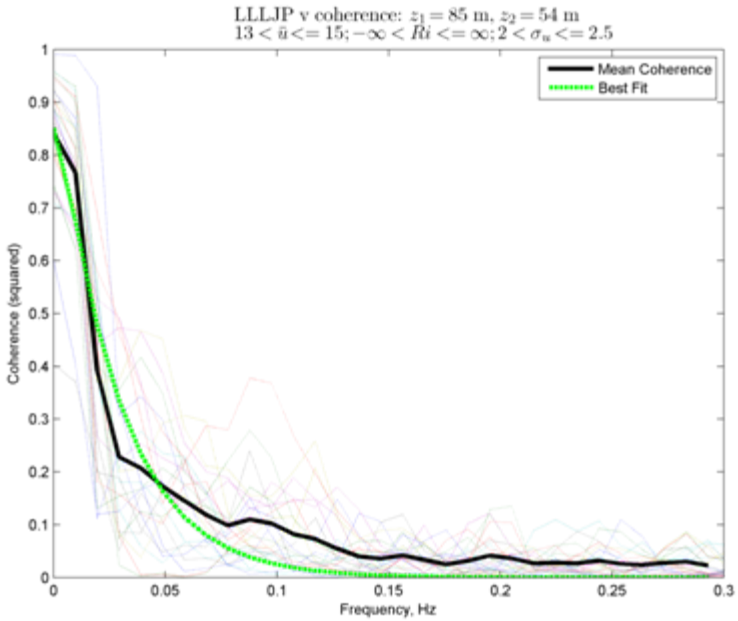
- GP_LLJ model → Lamar dataset
  - 20 Hz data
  - Sonic anemometers at 54, 67, 85, and 116 m
    - Coherence for all three wind components
- NWTCUP model → NWTC/LIST dataset
  - 40 Hz data
  - Sonic anemometers at 15, 37, and 58 m on central tower
    - Coherence for all three wind components

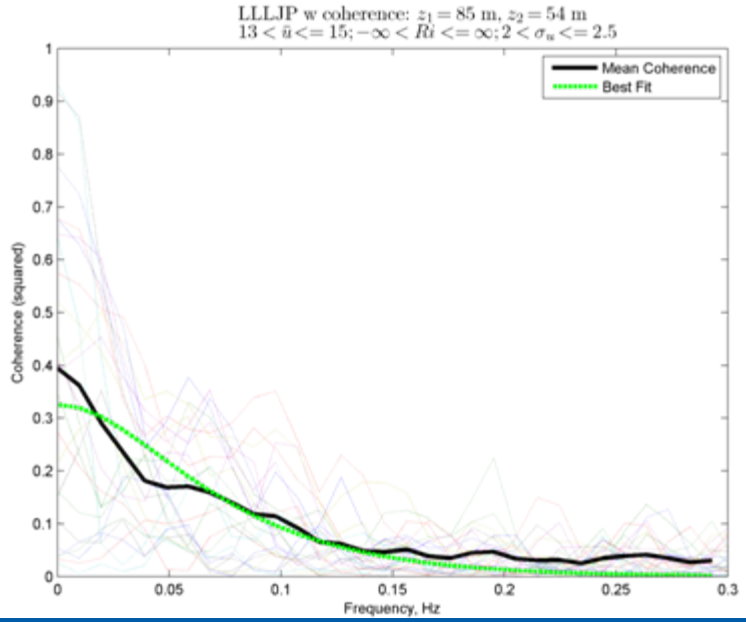
Modeling Coherence: Datasets

- WF_UPW model → San Gorgonio Inflow dataset
  - 5 Hz data
  - Cup anemometers at 5, 10, 20, and 50 m
    - Coherence for *u* and *v* wind components
- WF_14D and WF_07D models → San Gorgonio Outflow dataset
  - 5 Hz data
  - Cup anemometers at 5, 10, 20, and 50 m
    - Coherence for *u* and *v* wind components

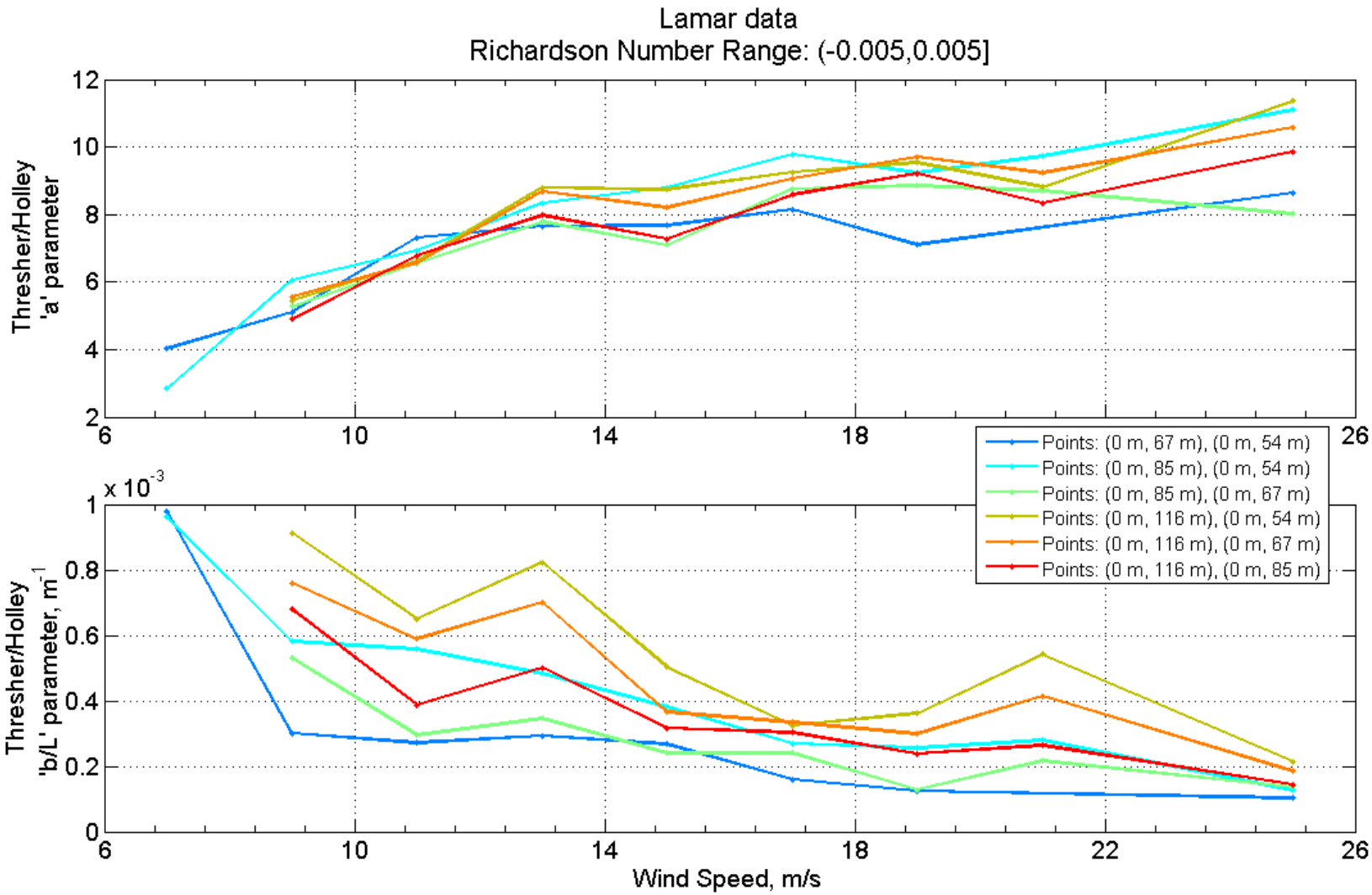
GP_LLJ Coherence



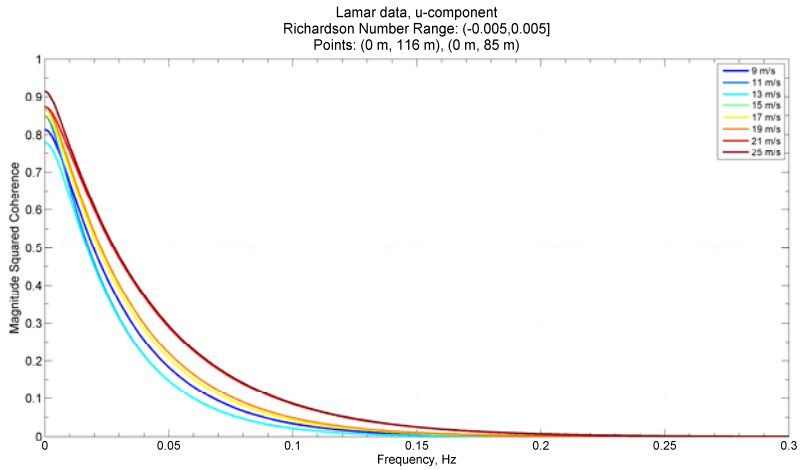


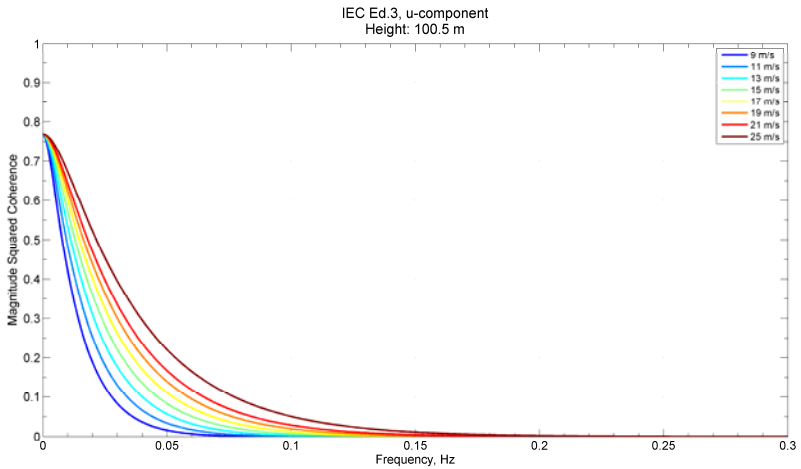


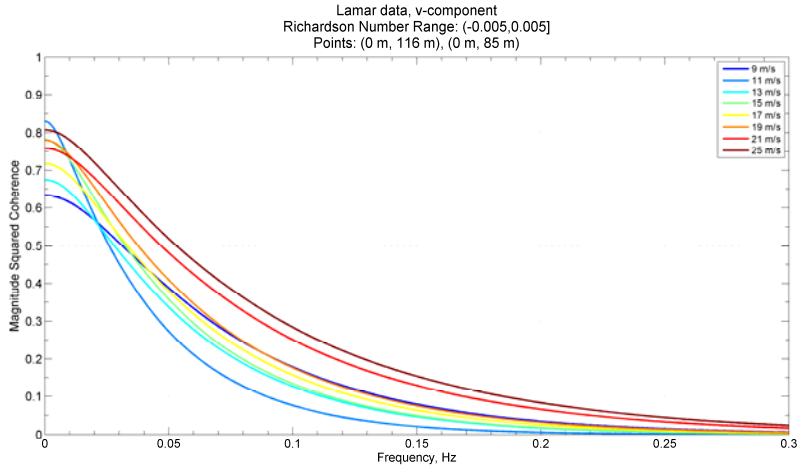
GP_LLJ Coherence: Neutral, *u*-Component

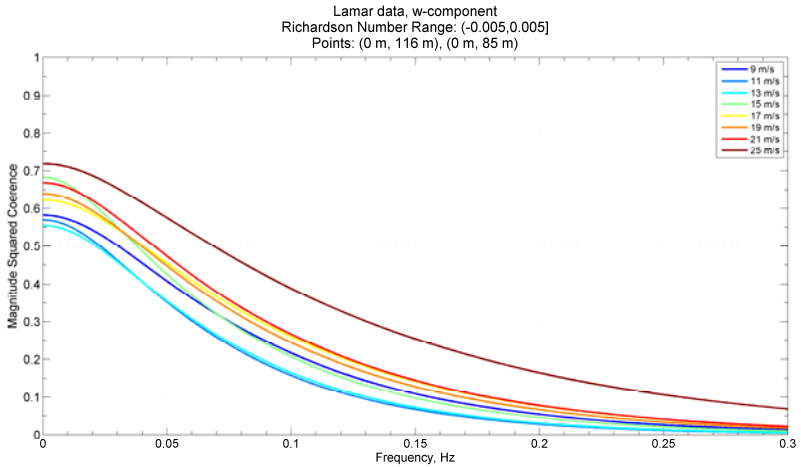


GP_LLJ Coherence: Neutral

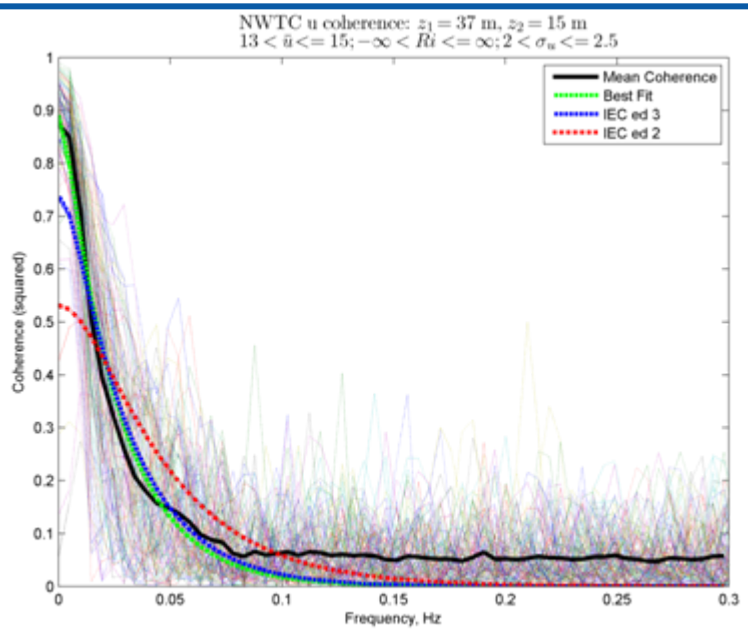


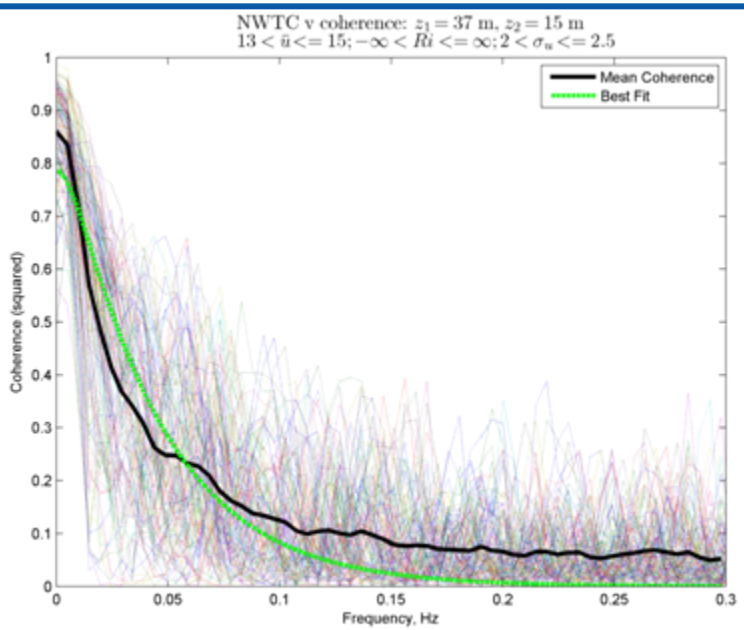


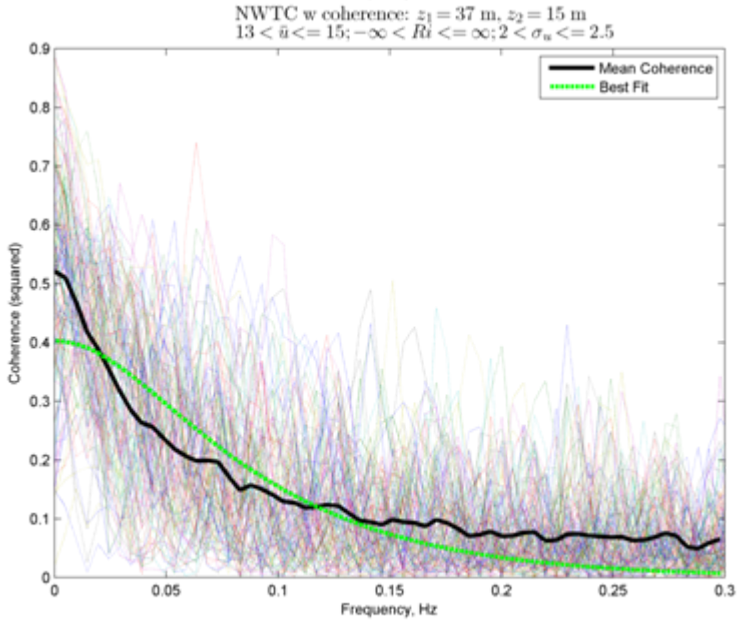




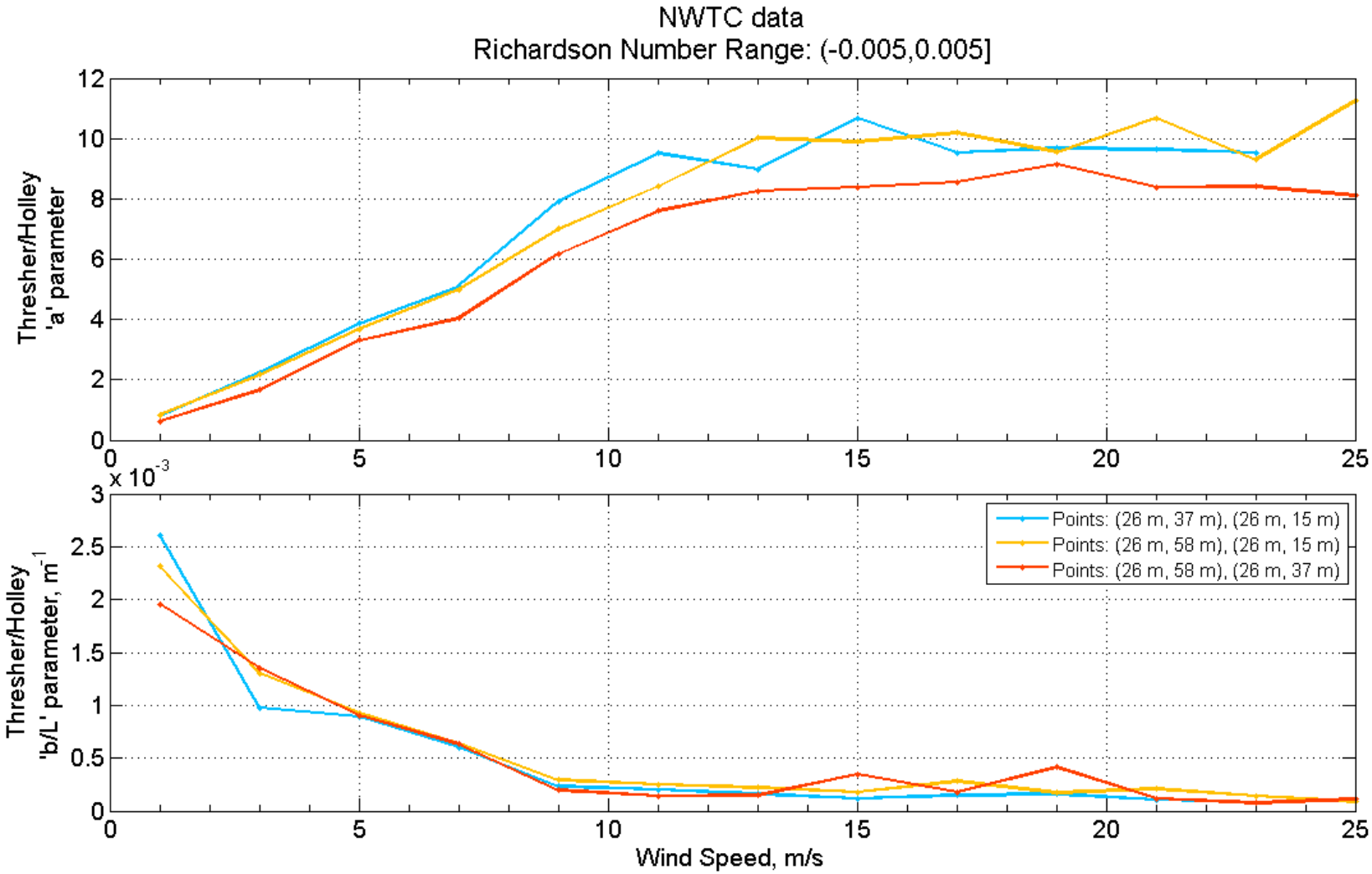
NWTCUP Coherence



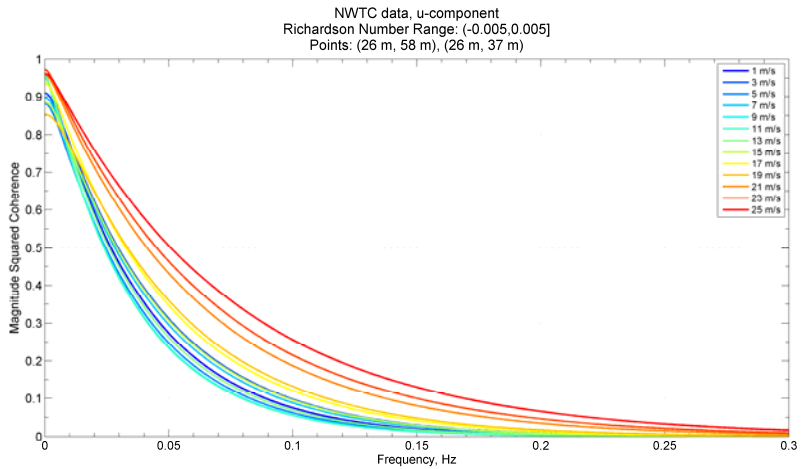


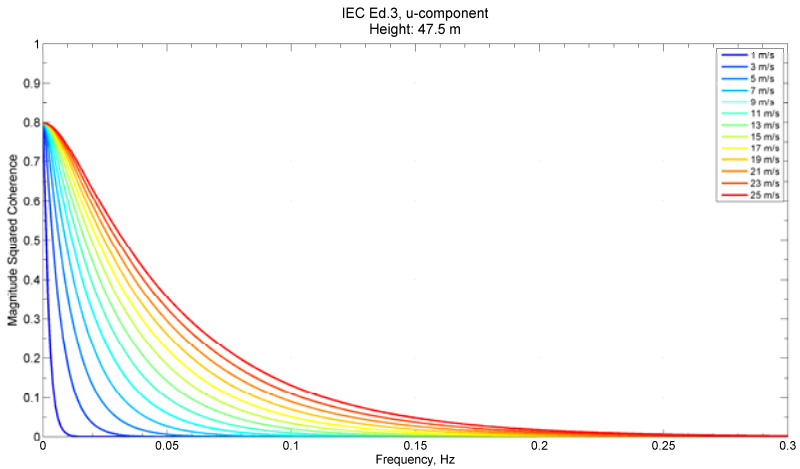


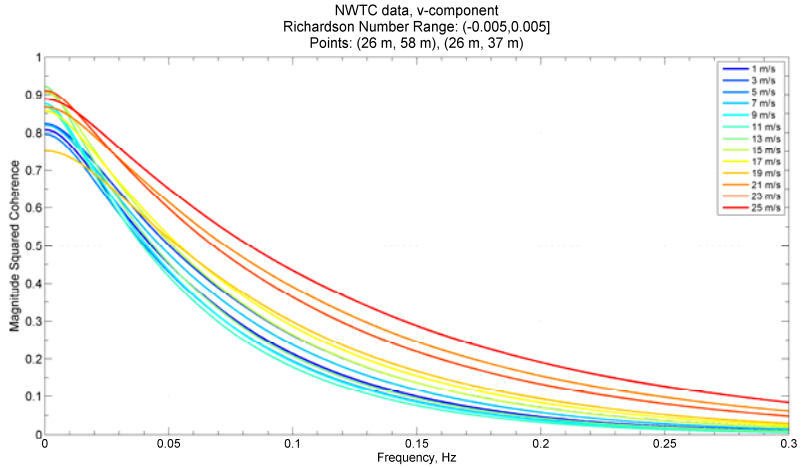
NWTCUP Coherence: Neutral, *u*-Component

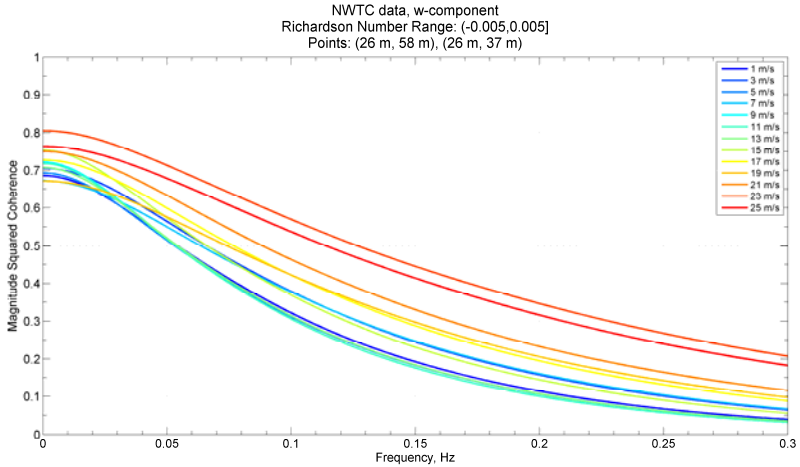


NWTCUP Coherence: Neutral









Modeling Coherence: Results

- For all site-specific models, the "*a*" parameter is modeled as a function of wind speed, height, and stability:

$$a_c = f\left(u_{hub}, Ri, z_{hub}\right)$$

- The "*b/L*" parameter is modeled as a function of wind speed for all site-specific models, as well as stability for the NWTCUP and GP_LLJ models:

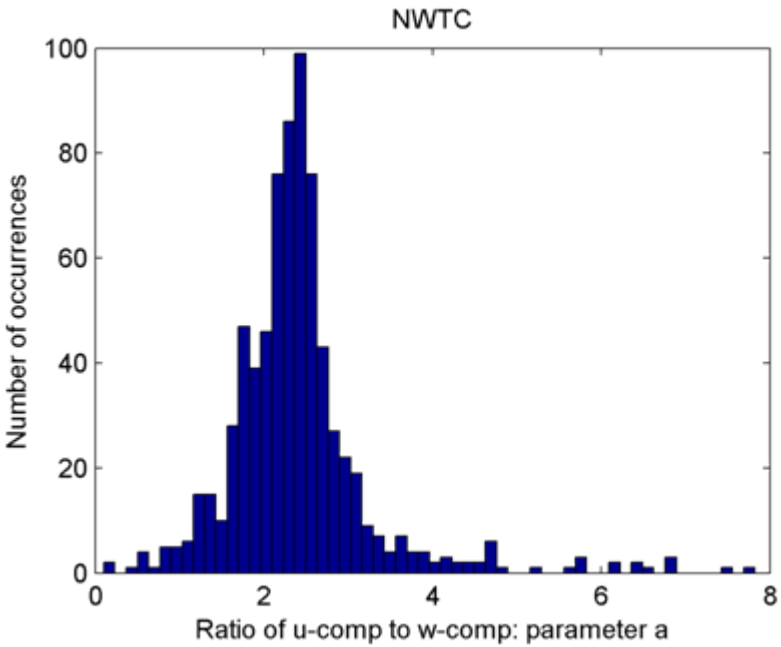
$$\frac{b}{L_c} = \begin{cases} f\left(u_{hub}, Ri\right), & \text{GP_LLJ and NWTCUP} \\ f\left(u_{hub}\right), & \text{WF_***} \end{cases}$$

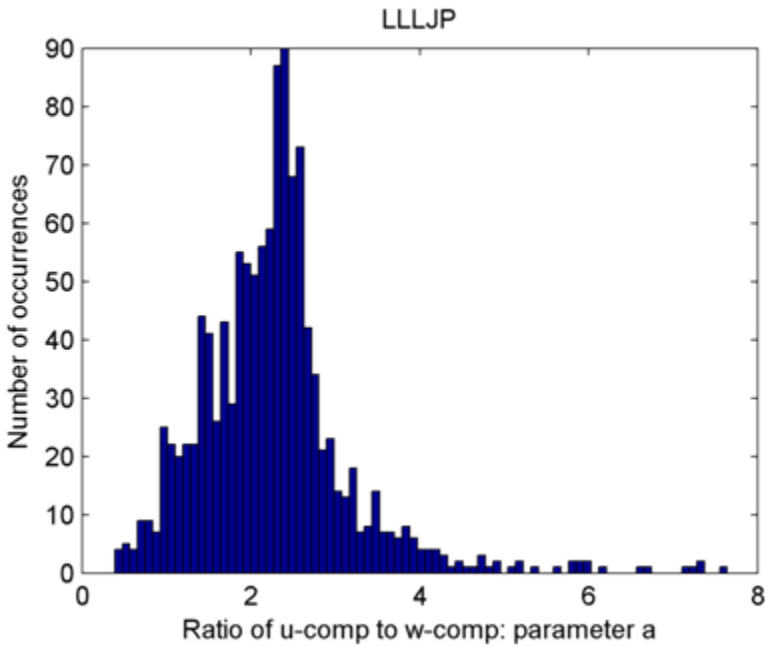
Modeling Coherence: Results

- The wind farm models (WF_***) did not have time series to analyze for *w*-component coherence (data came from cup anemometers)
- To model *w*, we compared ratios of the parameters of the *u*-component coherence to the *w*-component coherence in the NWTCUP and GP_LLJ models

Modeling Coherence: Results

- The ratio of the "*a*" decrement parameters:

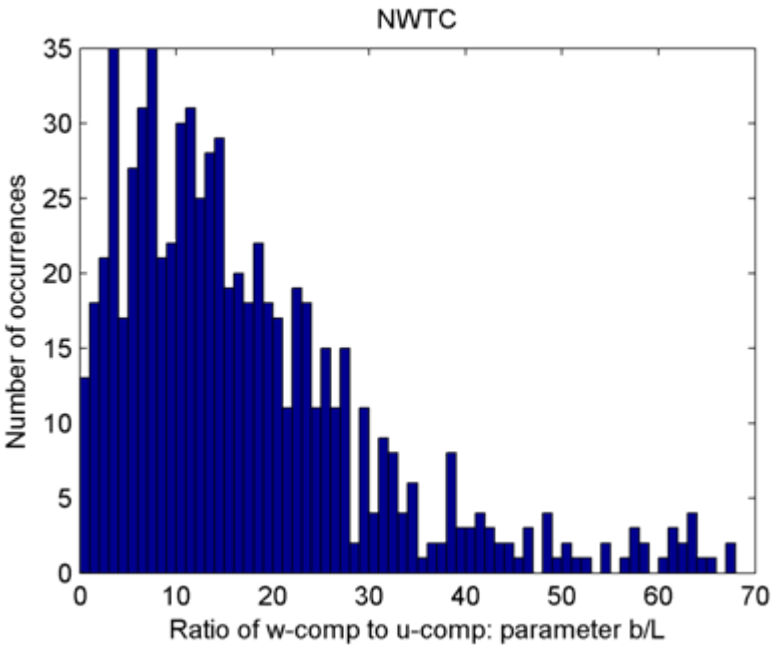


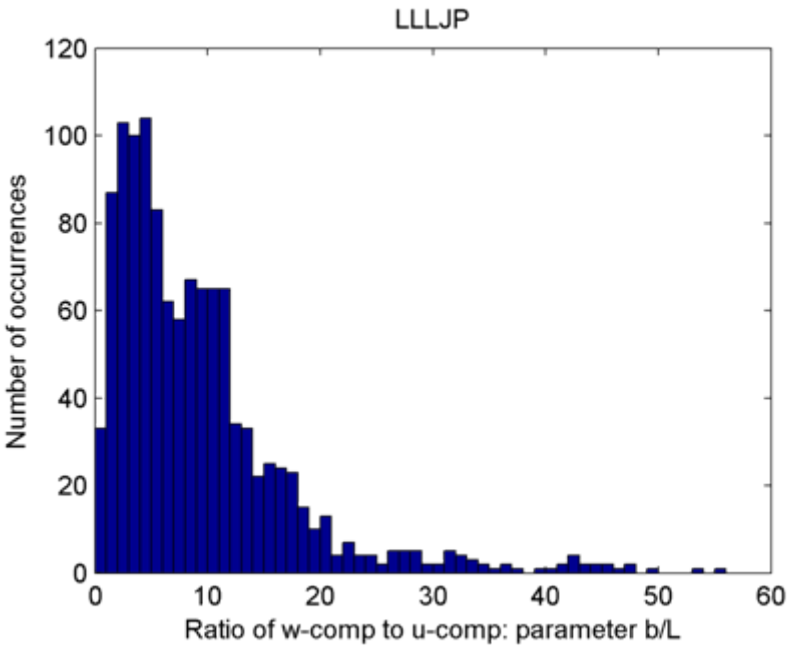


- WF_*** coherence modeled in TurbSim: $a_w = 0.4 a_u$

Modeling Coherence: Results

- The ratio of "*b/L*" parameters:

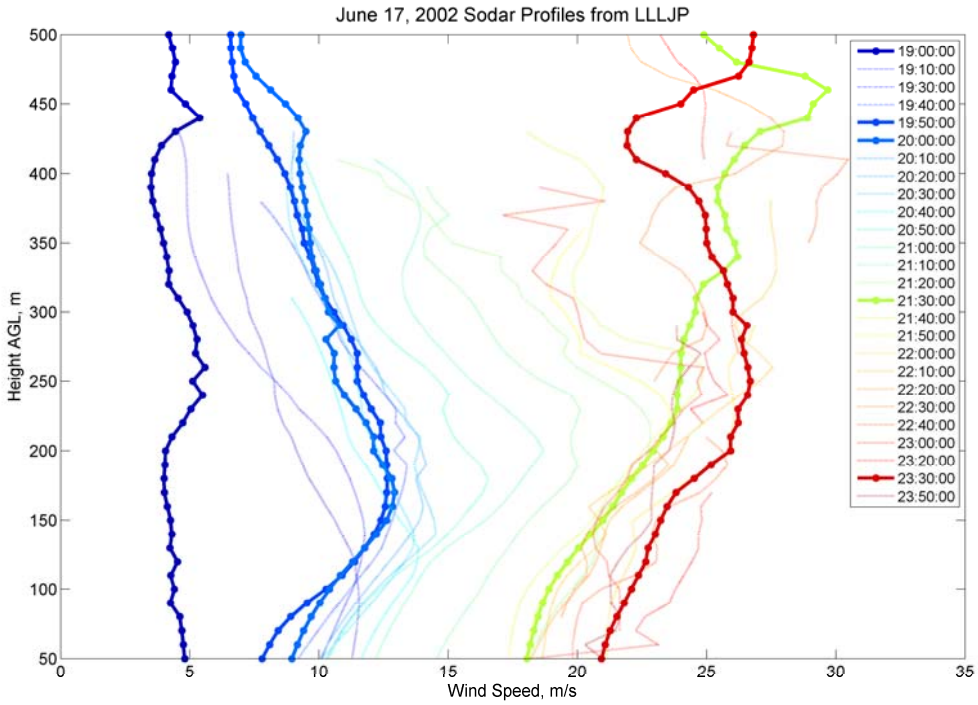




- WF_*** coherence modeled in TurbSim: $\frac{b}{L_w} = 10\frac{b}{L_u}$

Wind Profiles

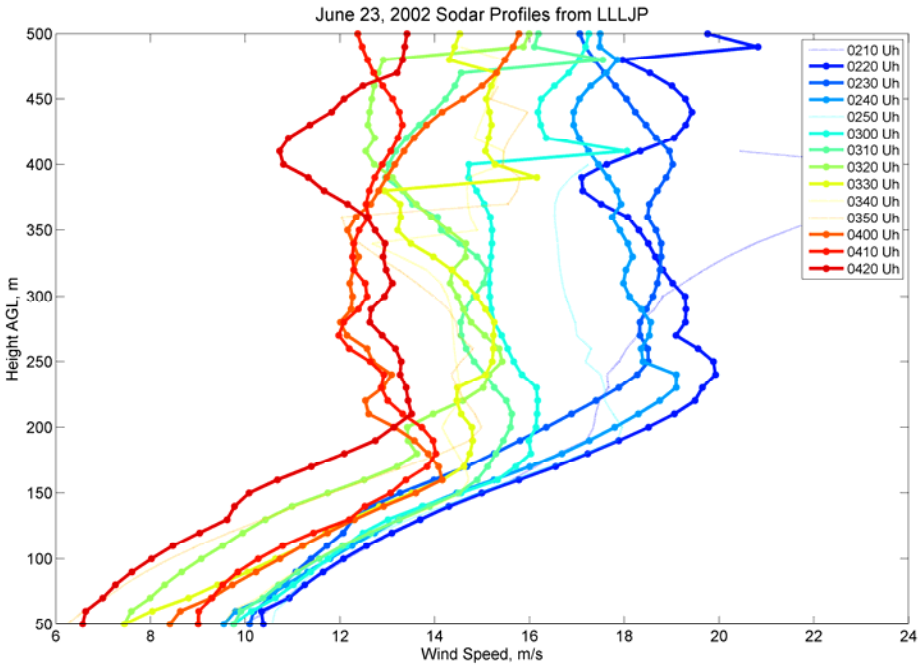
Modeling Wind Profiles for Site-Specific Models

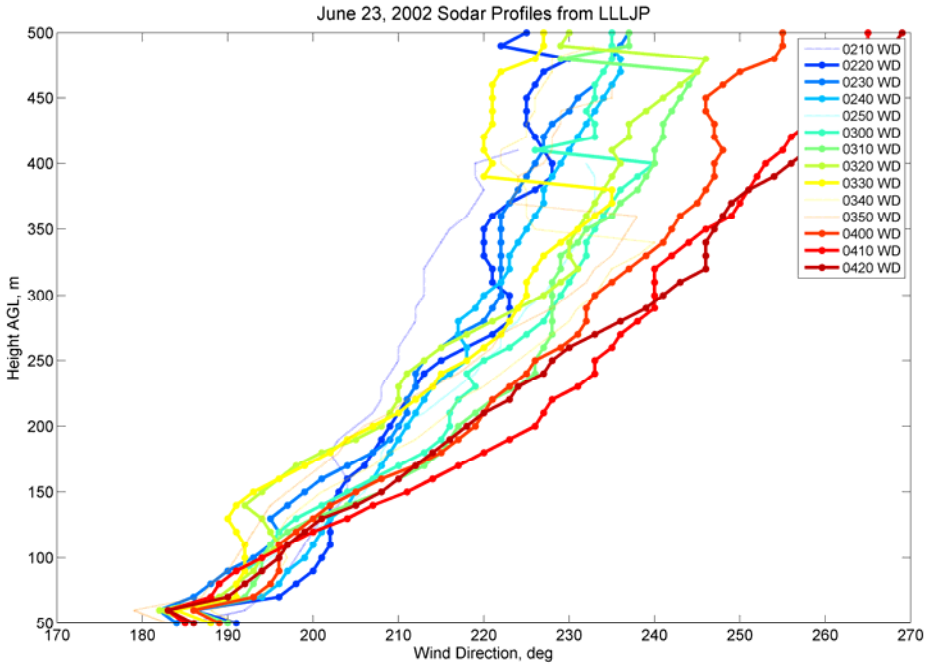


Modeling Wind Profiles: Method

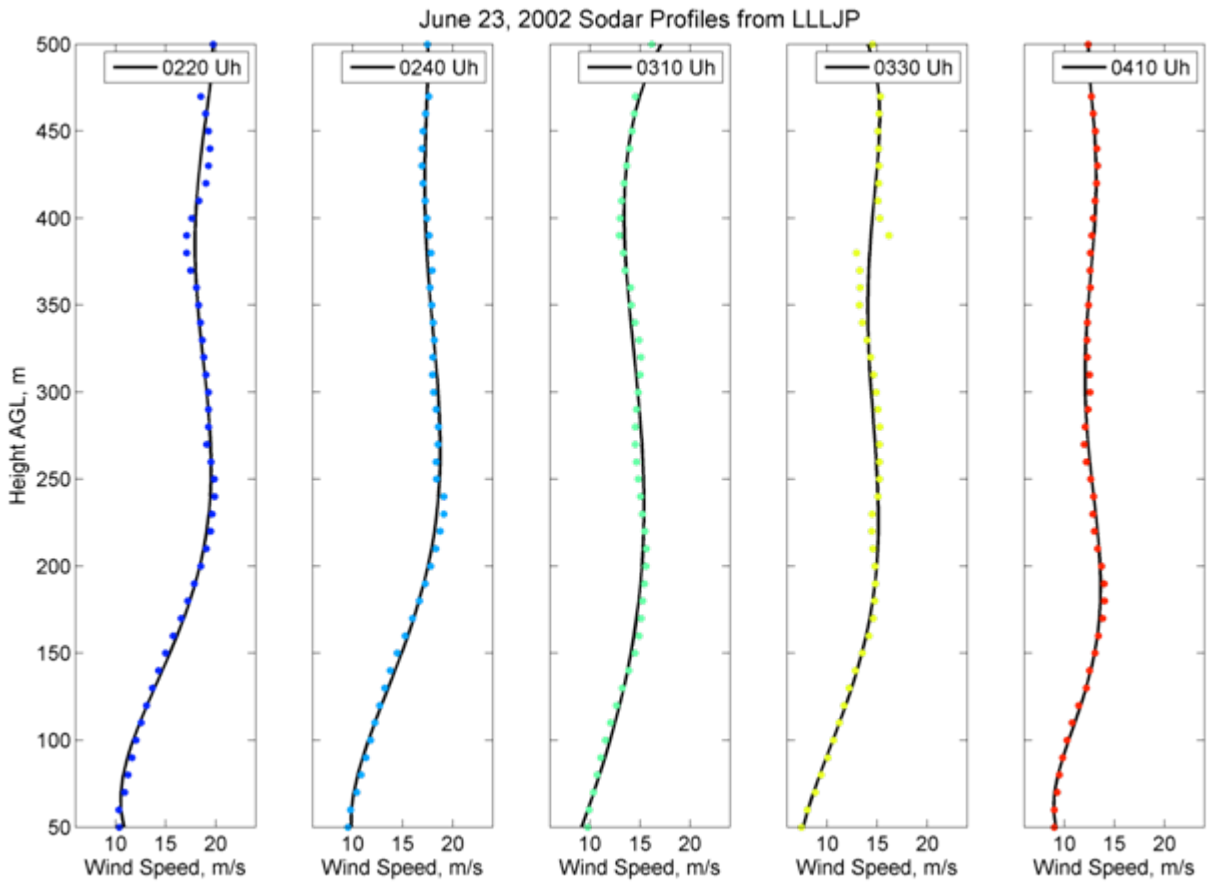
- Most models (all but GP_LLJ) assume power-law wind profile
  - Power-law exponent based on SeaWest Inflow and Outflow measurements
- Wind speed and direction profiles for GP_LLJ based on SODAR measurements from Lamar LLJ project
  - Used “high confidence” profiles with continuous data up to 500 meters
  - Each profile was fit with Chebyshev polynomials of the first kind
  - Coefficients of each polynomial were analyzed against scaling parameters (stability, jet wind speed, friction velocity, etc.)

Modeling Coherence: Jets





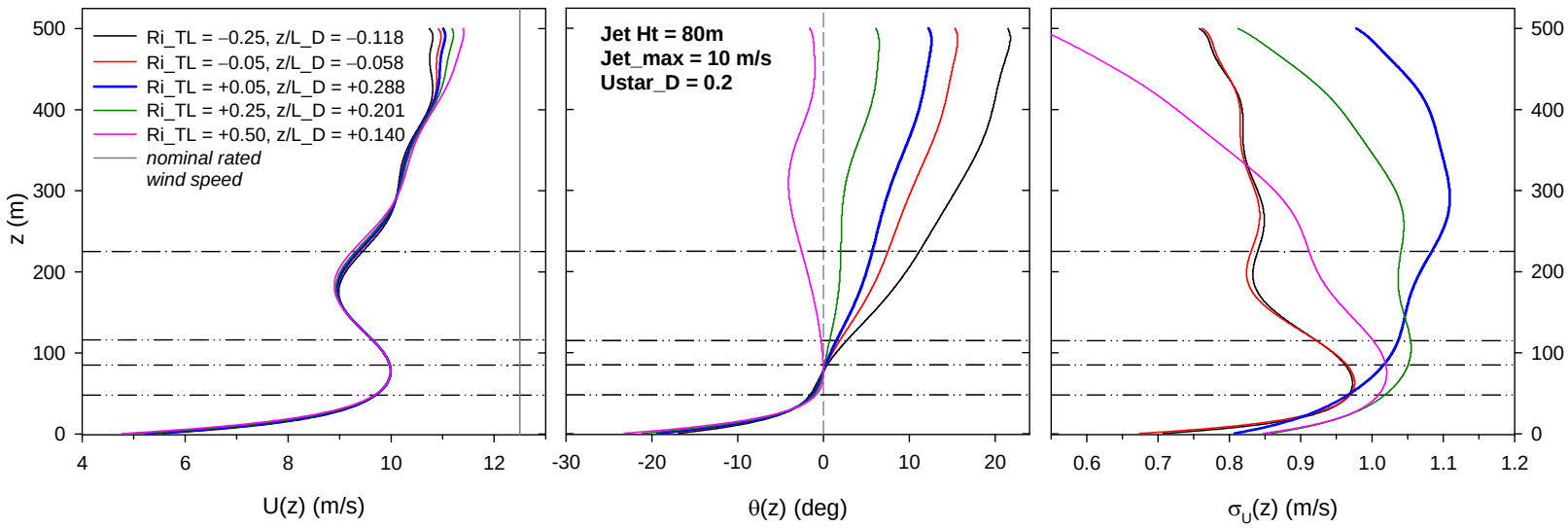
- Wind speed (left) and direction (right) profiles from the LLLJP measured by SODAR on June 23, 2002

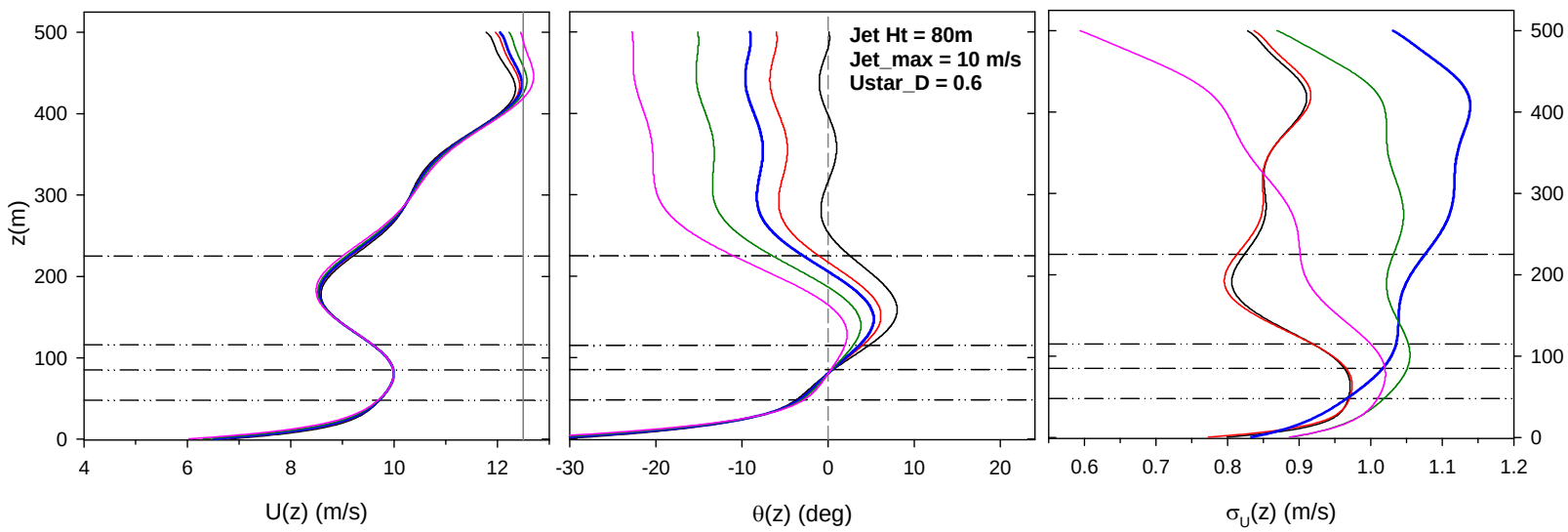


Chebyshev coefficients calculated and analyzed to produce models based on TurbSim input parameters

$$u(z) = \sum_{i=0}^{10} a_i \left(u_*, u_{jet}, z_{jet}, Ri \right) T_i(z)$$

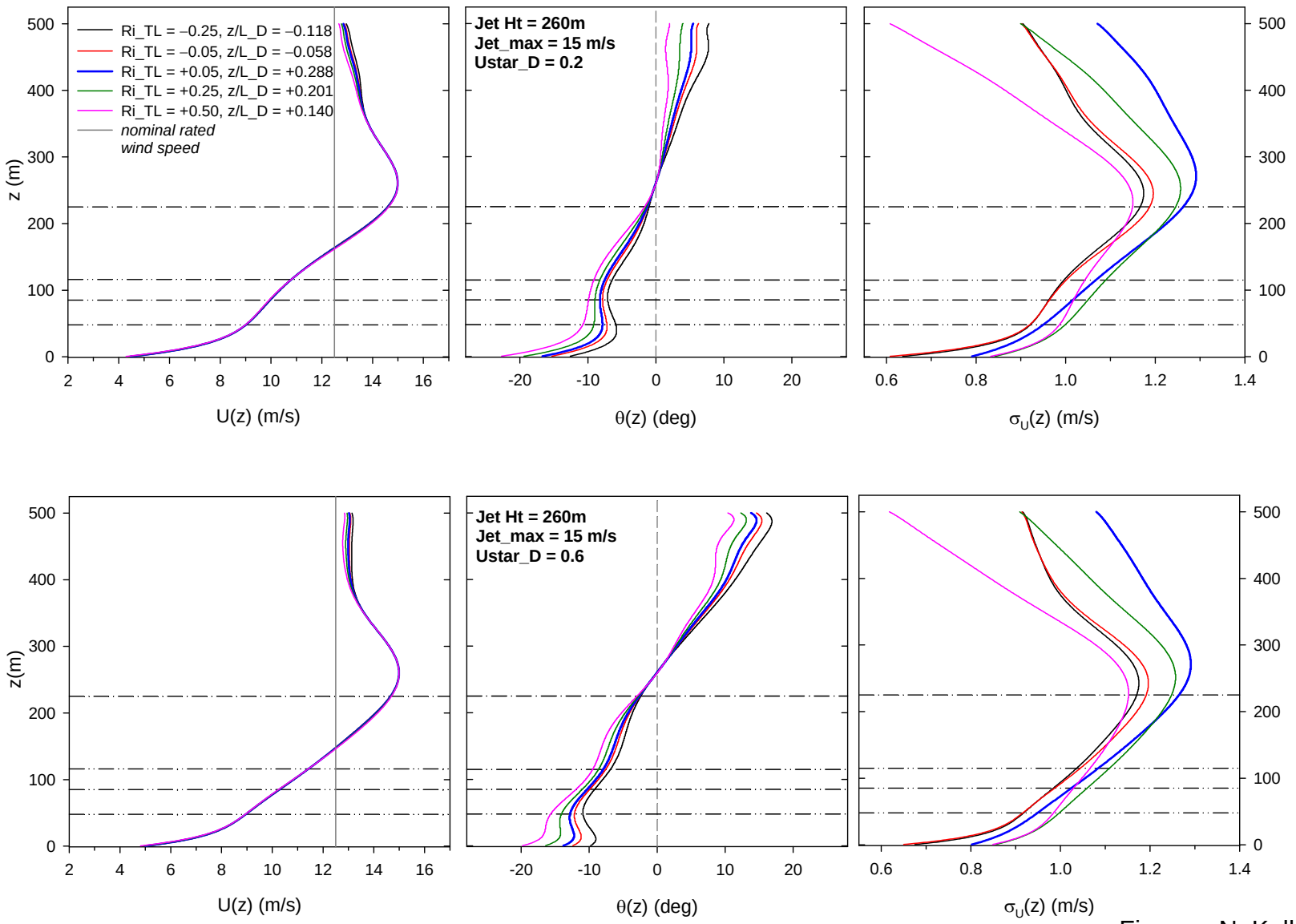
Modeling Wind Profiles: Jet Results





Figures: N. Kelley, NREL

Modeling Wind Profiles: Jet Results

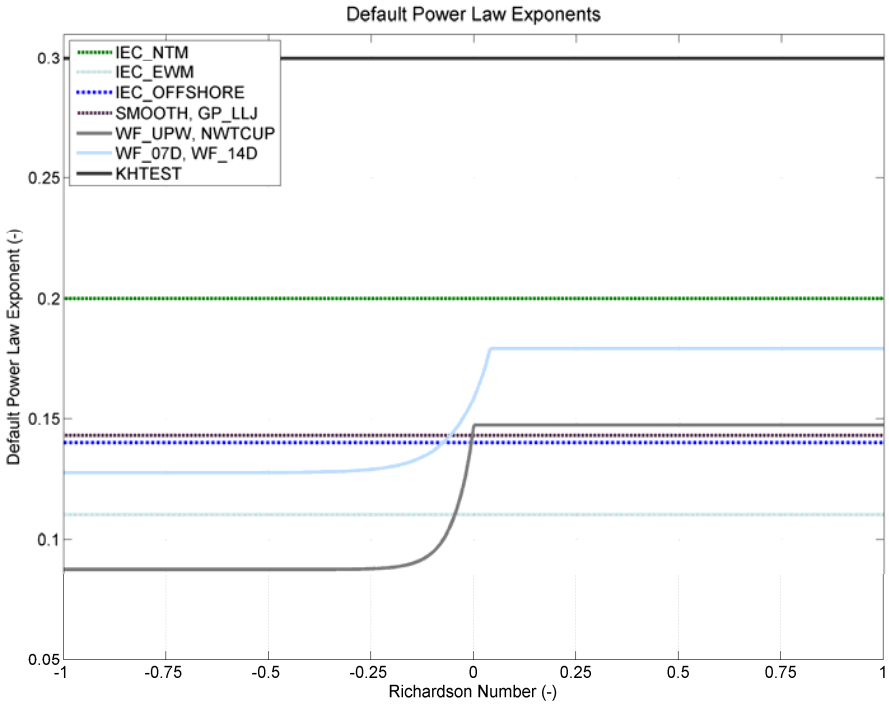


Figures: N. Kelley, NREL

Modeling Wind Profiles: Power Law

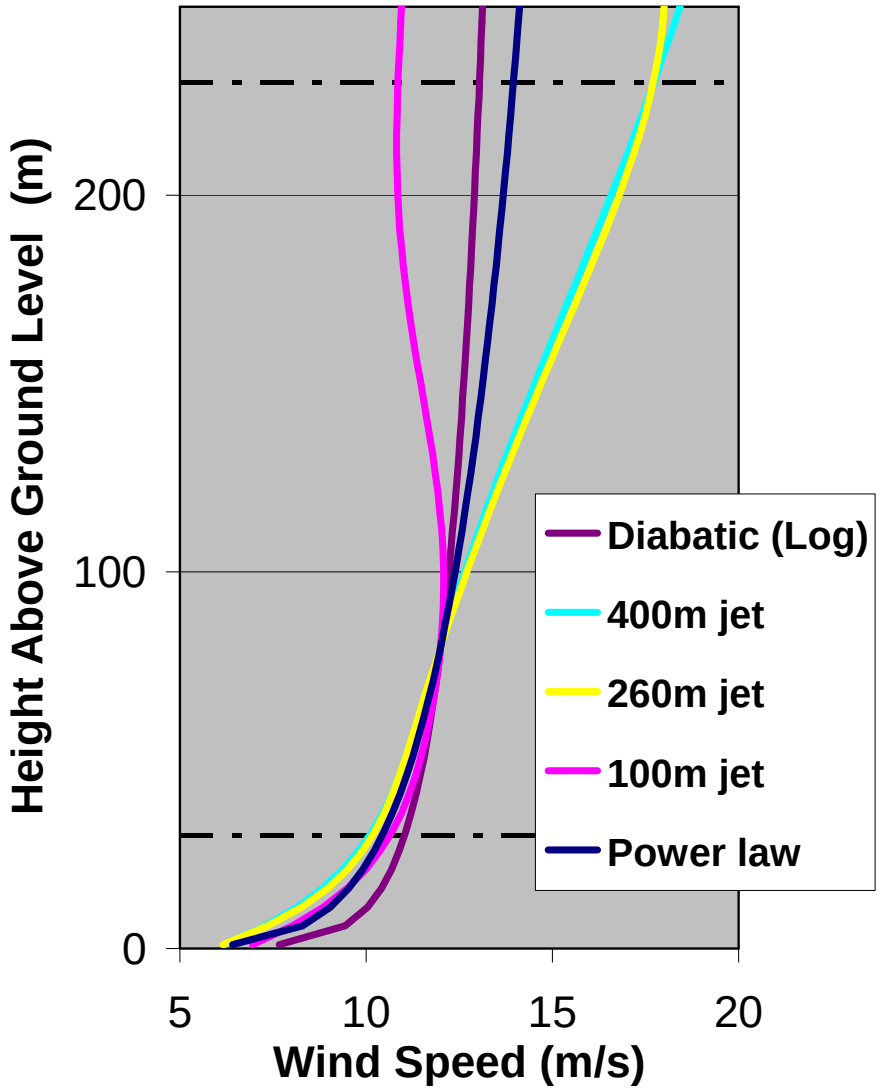
- Power law exponent, α
  - NWTCUP and WF_UPW models based on SeaWest Inflow dataset
  - WF_07D and WF_14D models based on SeaWest Outflow dataset
  - Exponent is a function of Richardson Number

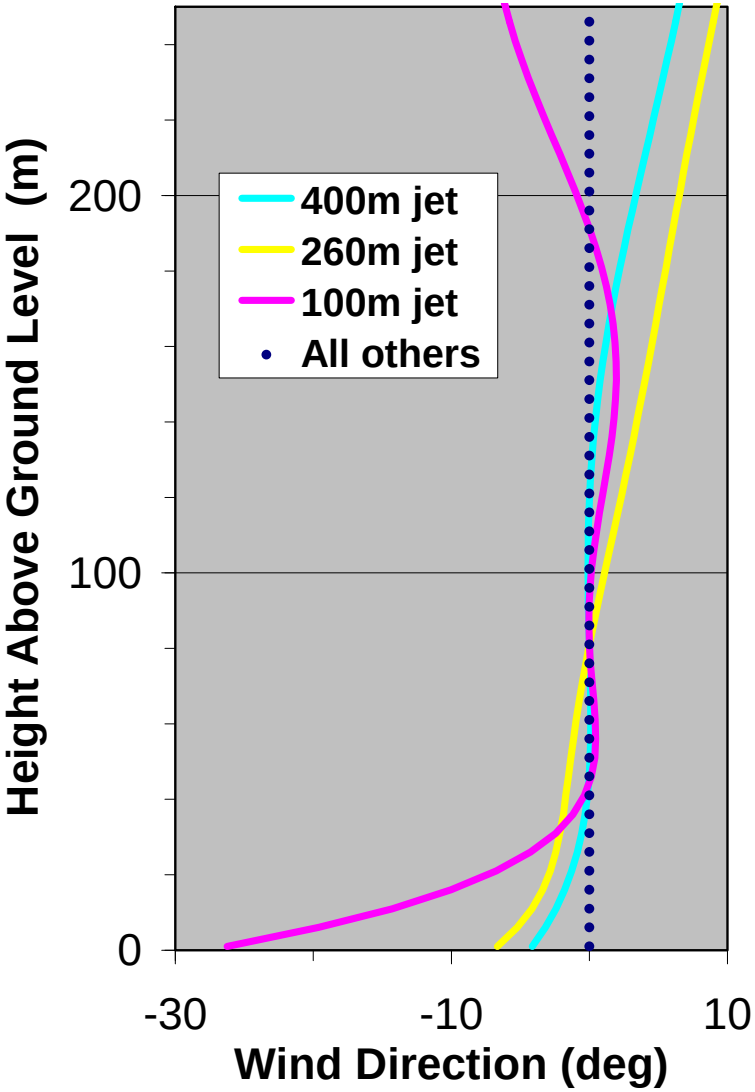
$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$$



Modeling Wind Profiles: Comparisons

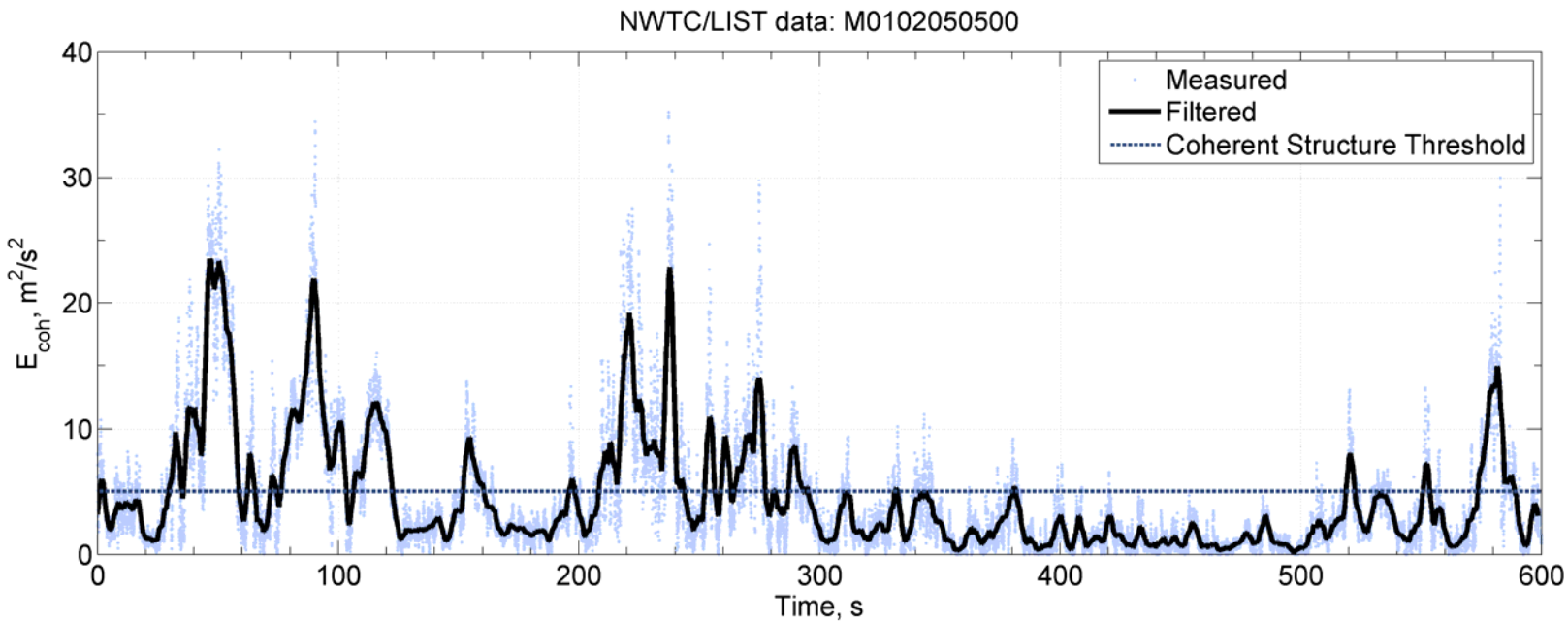
Wind profile models using 12 m/s wind speed at 80 m





Coherent Structures

Modeling Coherent Structures in TurbSim



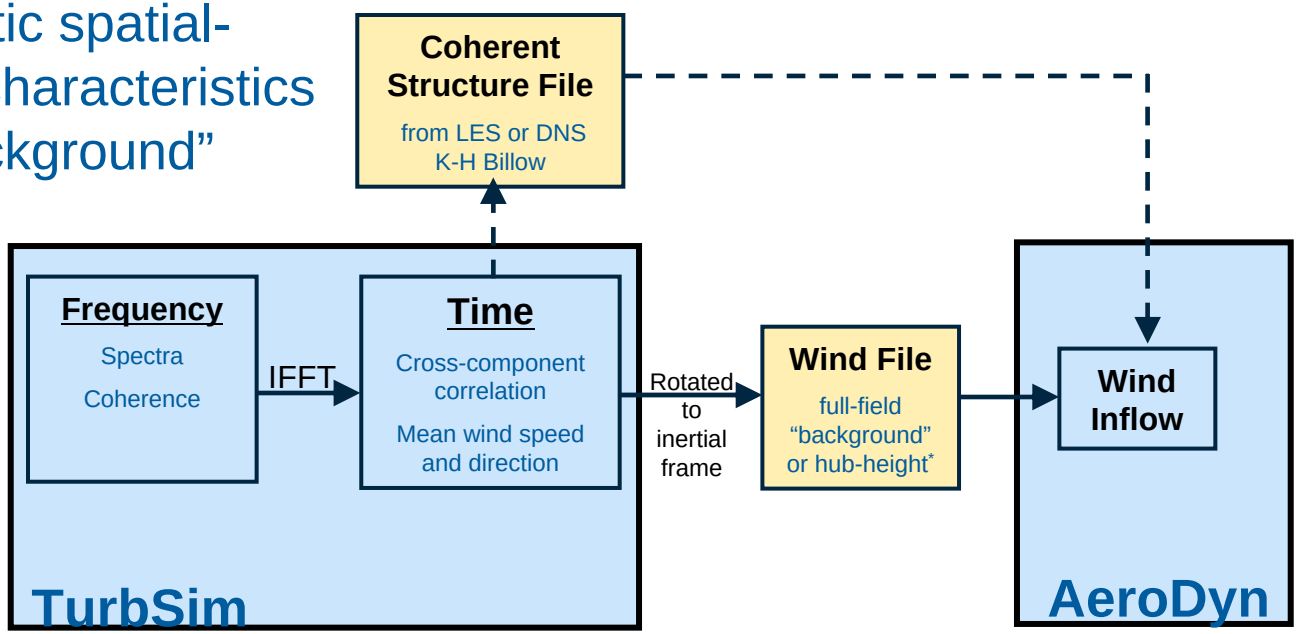
Modeling Coherent Structures

- What is a coherent structure?
  - For our analysis, a coherent structure was defined as **an event where the 3-s mean coherent turbulent kinetic energy (CTKE) meets a specified threshold value**
    - Threshold for Lamar LLJ dataset was 2 m^2/s^2
    - Threshold for NWTC/LIST, SeaWest Inflow, Outflow, and Thin Airfoil Row 37 datasets was 5 m^2/s^2

$$
\begin{aligned}
CTKE &= E_{coh} \\
&= \tfrac{1}{2}\sqrt{\left(u'w'\right)^2 + \left(u'v'\right)^2 + \left(v'w'\right)^2}
\end{aligned}
$$

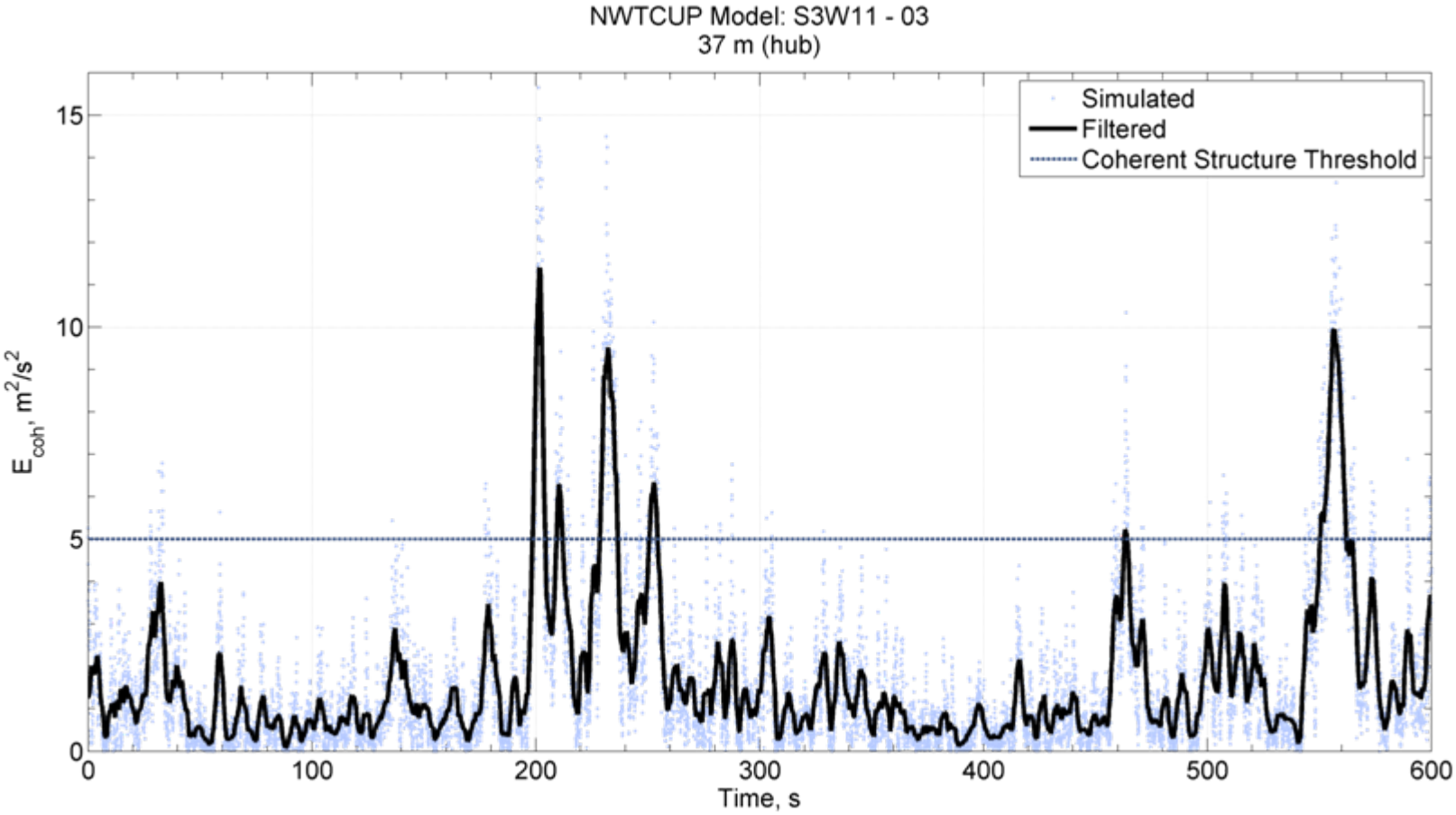
Modeling Coherent Structures

- Do the "background" wind fields generated by TurbSim contain coherent structures?
  - Yes, some of them do.
  - The "background" statistical wind files don't always generate *enough* structures when compared with measured data.
  - The coherent structure file is designed to add more events with realistic spatial-temporal characteristics to the "background" wind



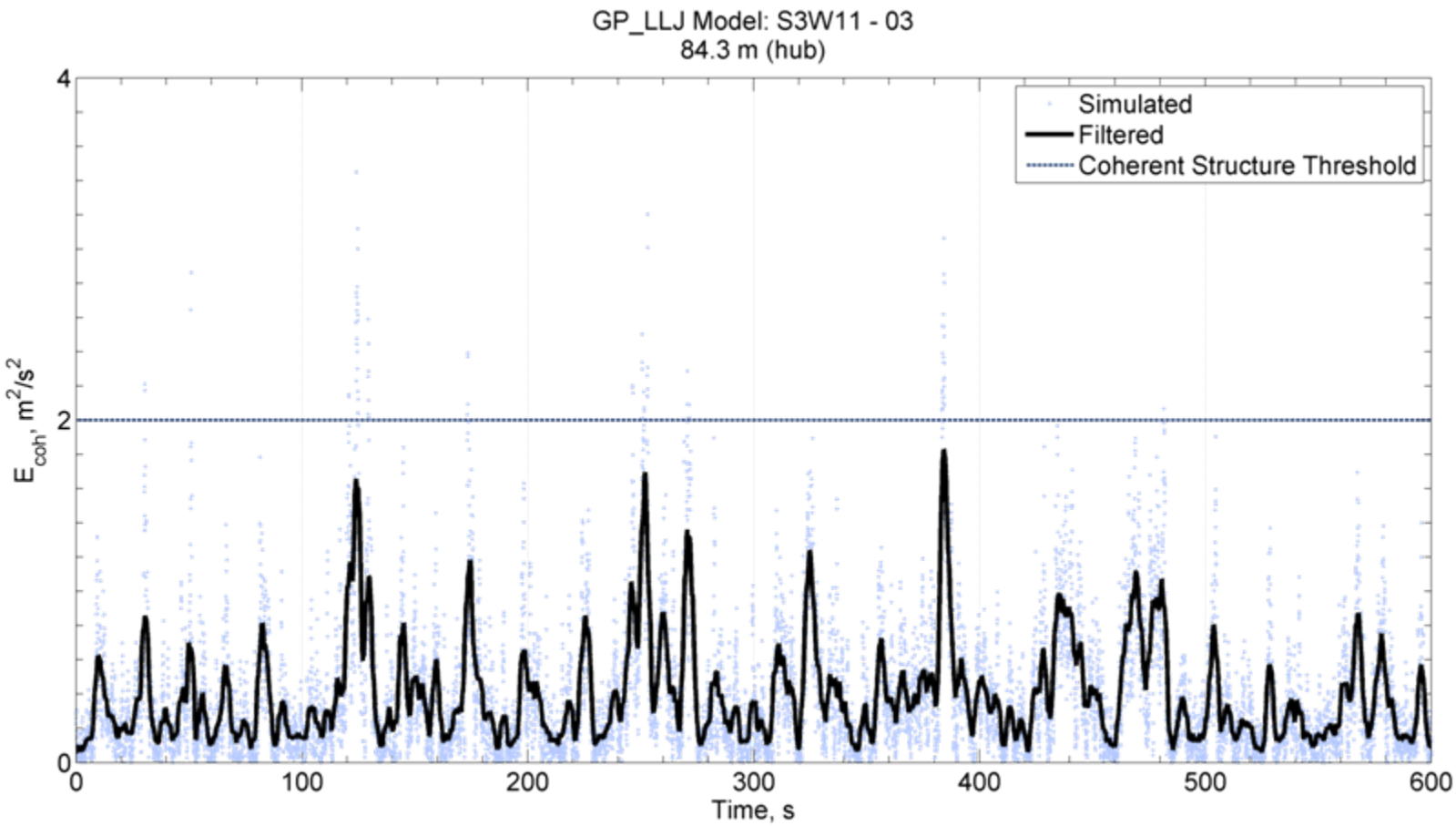
Modeling Coherent Structures

CTKE in a “background” wind file generated by TurbSim

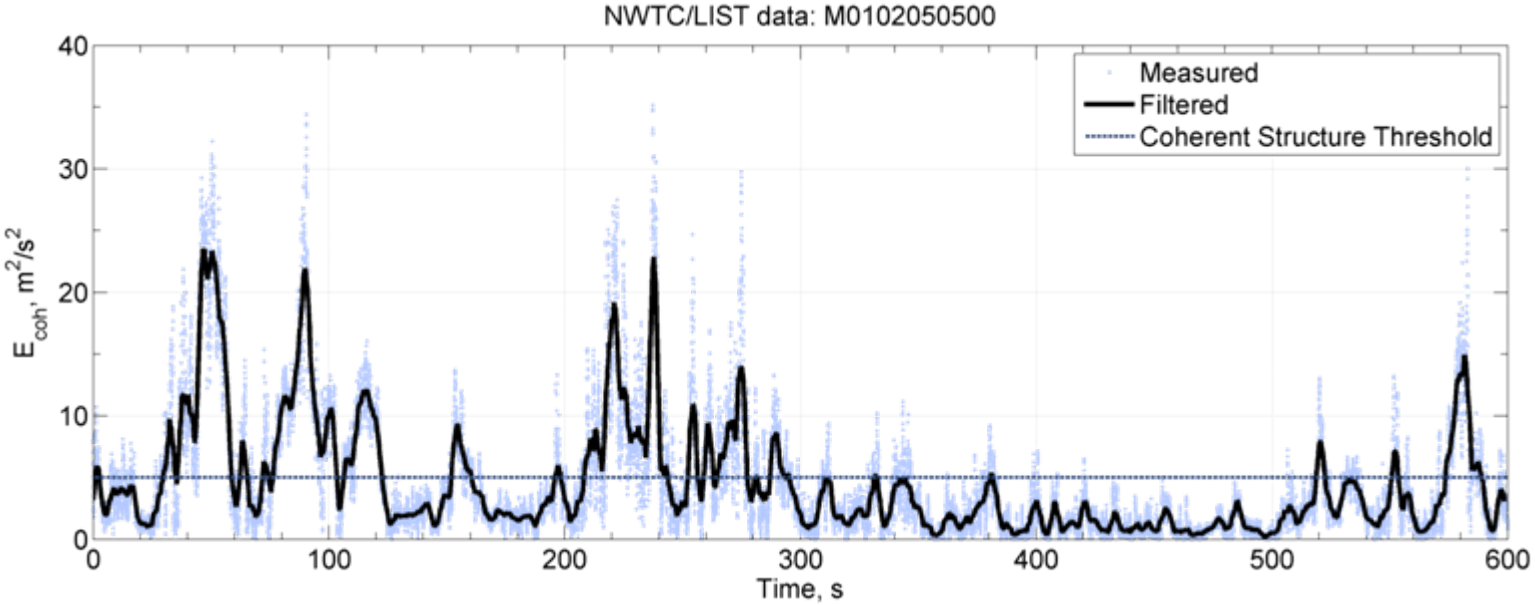


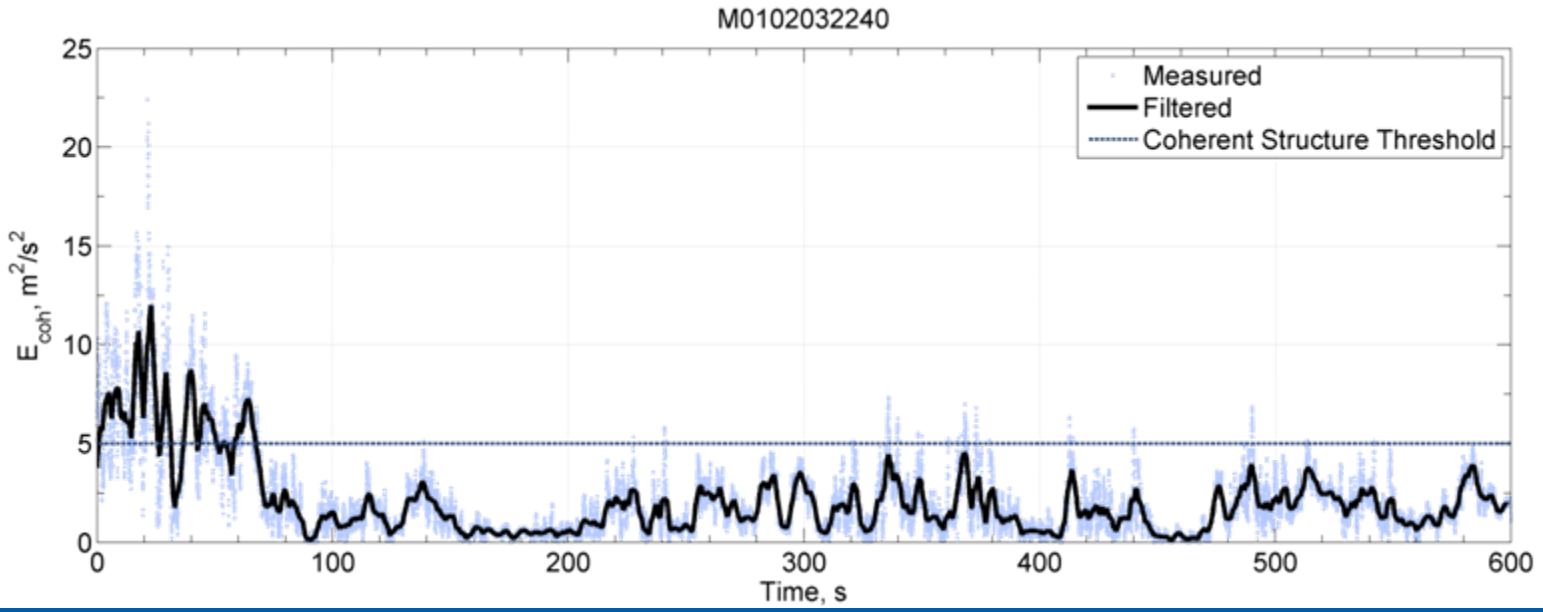
Modeling Coherent Structures

CTKE in a “background” wind file generated by TurbSim



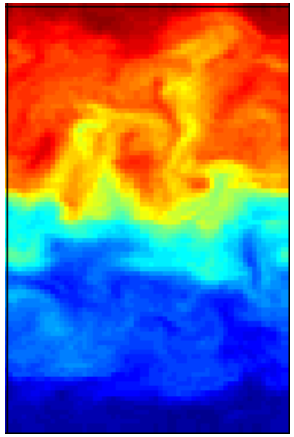
Coherent Structures: NWTC/LIST



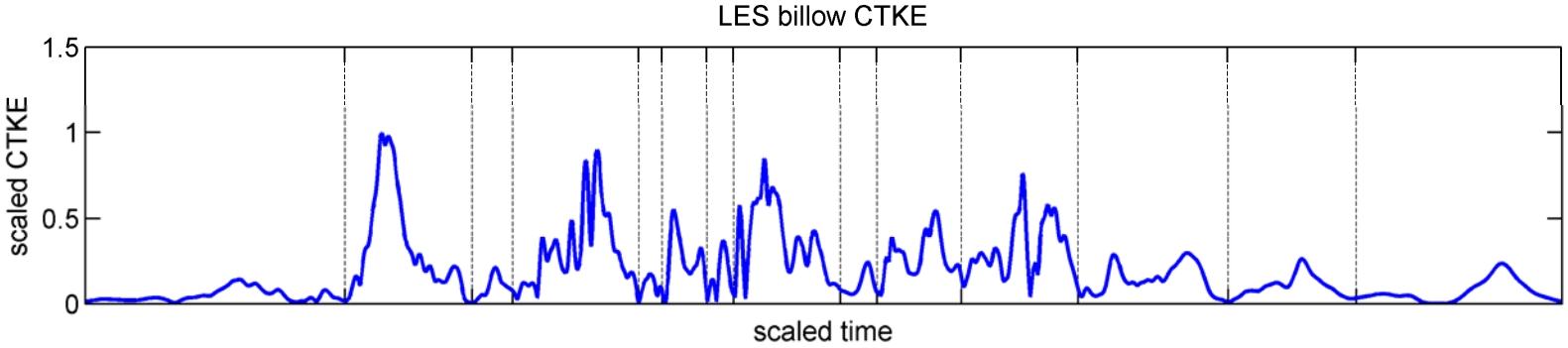


Modeling Coherent Structures: Method

- Two simulations of an evolution of a Kelvin-Helmholtz billow were broken into pieces
  - Large Eddy Simulation (LES) computed by the National Center for Atmospheric Research (NCAR)
  - Direct Numerical Simulation (DNS) computed by Colorado Research Associates (CoRA)

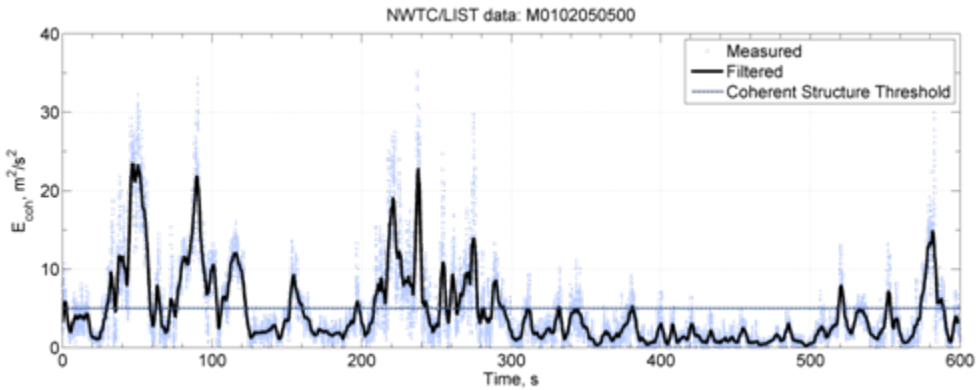


- Boundaries of pieces were determined by CTKE at the center of the billow



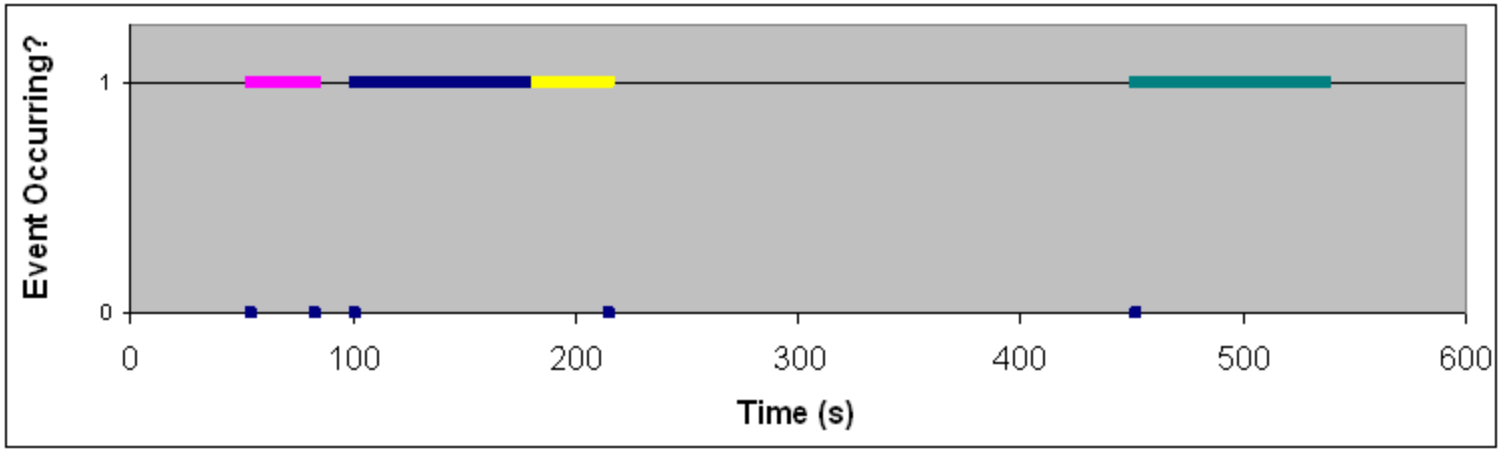
Modeling Coherent Structures: Method

- Data binned by wind speed and stability categories
  - 2-m/s wind-speed bins
  - 5 stability bins based on Richardson number (2 unstable, 3 stable)
- For each bin, we calculated
  - Rate parameter (inter-arrival time)
  - Total length of all coherent structures in 10-min records
  - Peak CTKE of the coherent structures in 10-min records



Modeling Coherent Structures: Method

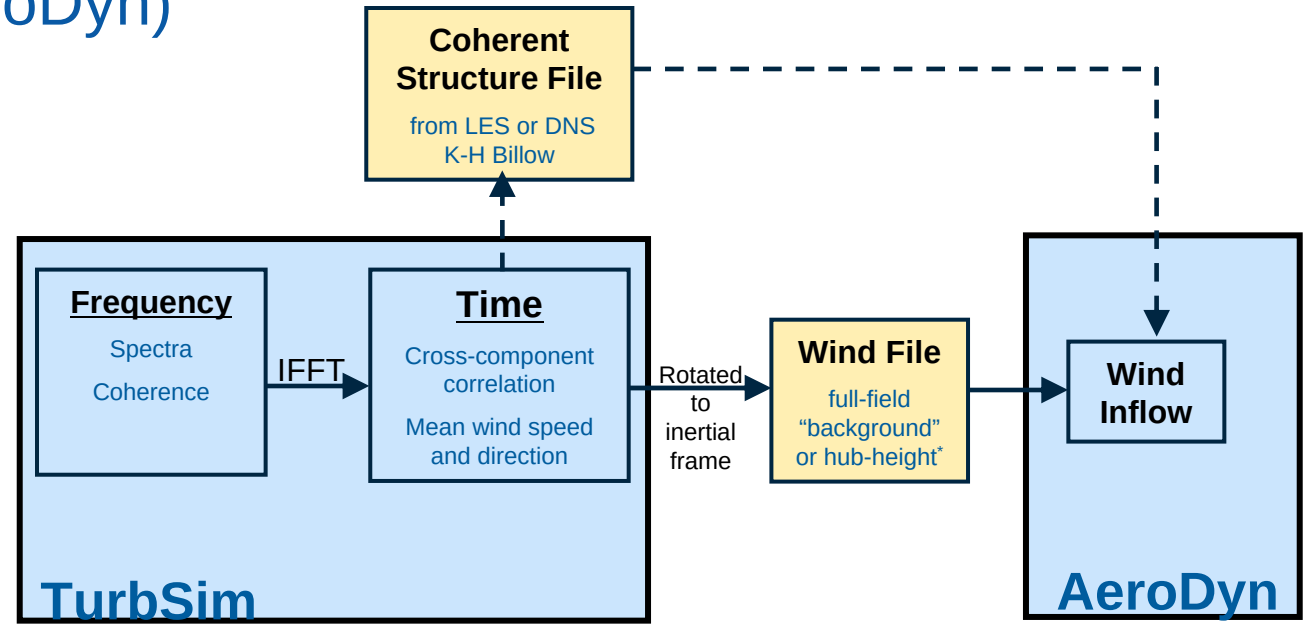
- Pieces of KH billow are added to the coherent structure file
  - KH billow pieces are chosen from a uniform distribution
  - Event start times are chosen from an exponential distribution using calculated rate parameter
  - Extra pieces are concatenated to ensure total length of events is at least the expected length of coherent structures



In this example 3 events occurred; Event 2 formed from 2 concatenated pieces (colors denote separate pieces of KH billow)

Modeling Coherent Structures: Method

- KH billow pieces are scaled in time and space
  - Stored as non-dimensional structures
  - Time and velocity are scaled to achieve the peak CTKE (given a particular space scale)
- Structures are superimposed on background wind field (in AeroDyn)



Modeling Coherent Structures: Results

- Event inter-arrival times (time from start of one event to the next) are functions of stability, background wind speed at the center of the billow, and height of the billow:

$$IAT = \begin{cases} f\left(u_{center}, z_{center}\right) & \text{GP_LLJ} \\ f\left(u_{center}, Ri\right) & \text{Other models} \end{cases}$$

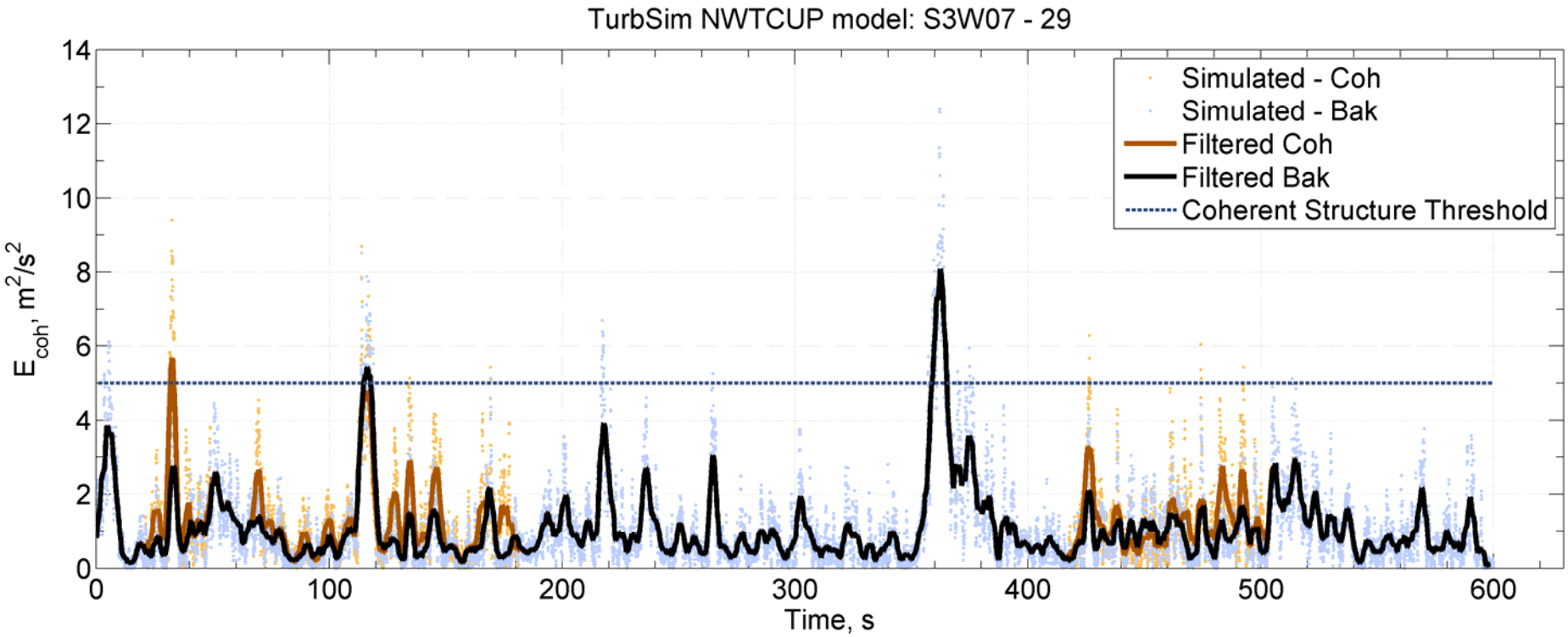
- The expected lengths of coherent structures are random distributions, based on PDFs of each dataset

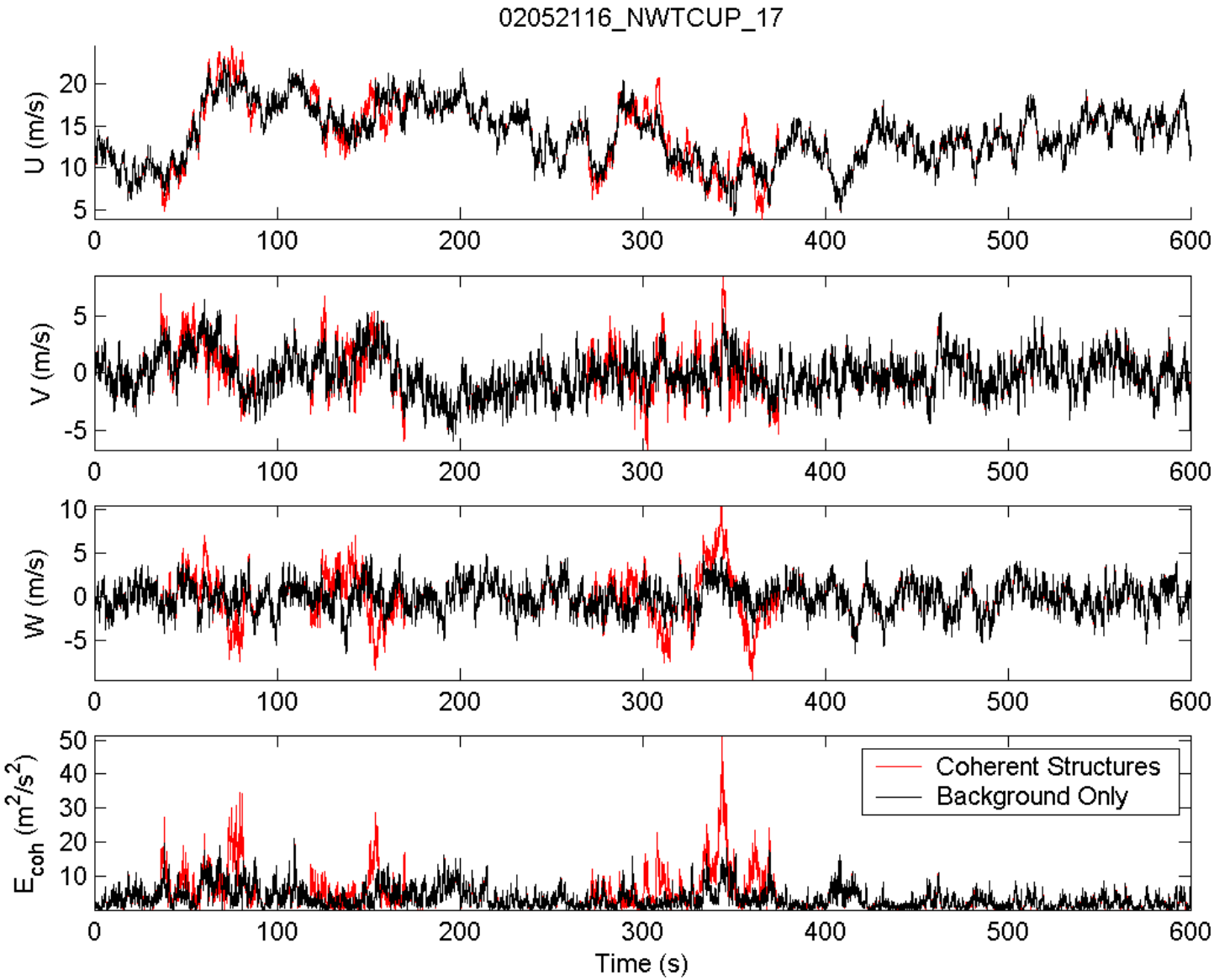
Modeling Coherent Structures: Results

- The peak CTKE values, used for scaling the intensity of the superimposed events, are functions of
  - stability (Richardson number), *Ri*
  - wind speed, *u*
  - standard deviation of vertical velocity, σ_w
  - friction velocity, u_*
  - random values, *X*

$$CTKE_{\max} = \begin{cases} X & \text{GP_LLJ} \\ f\left(Ri, \sigma_w, u_{center}\right) + X, & \text{NWTCUP} \\ f\left(Ri, \sigma_w, u_{center}\right), & \text{WF_UPW, WF_14D} \\ f\left(Ri, \sigma_w, u_*\right) + X, & \text{WF_07D} \end{cases}$$

Modeling Coherent Structures



Coherent structures superimposed on background wind

Modeling Coherent Structures