Experimental Wind Turbine Aerodynamics Research @LANL

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Acknowledgment: Suhas Pol (Post-doc), John Hoffman, Mario Servin, Eduardo Granados (Summer students), Ramiro Alarcon (Graduate student, NMSU), Chris Tomkins, Curtt Ammerman (LANL), Dale Berg, Matt Barone (Sandia)

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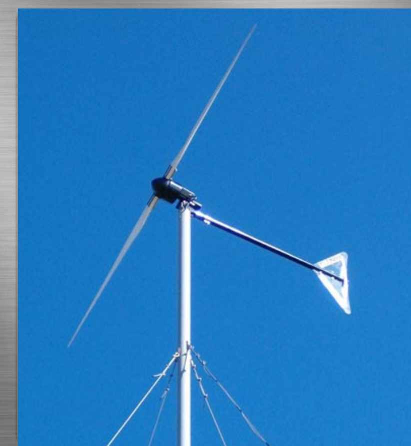
[1] Supported by LDRD-DR, "Intelligent Wind Turbines", Curtt Ammerman (PI)
[2] Supported by DoE-EERE, ''Rotating PIV Diagnostic Development", B J Balakumar (PI)

Experimental measurement of wind turbine flows:

Integrated design for inflow, blade and wake characterization



Laboratory-scale Experiments

Laminar, turbulent inflow under yaw

0.2m diameter;
2-20 m/s

PIV, hot-wire, LDV

Diagnostic Development

In-blade PIV, LF-PIV

2m x 2m PIV (scalable to 20m x 2m)

Fiber-optic routing through blades: PIV around blade BL through entire revolution

Field Experiments

4.5m and 20m diameter turbines

PIV, CSAT3, RM Youngs, Met-tower, power meter, strain gauge

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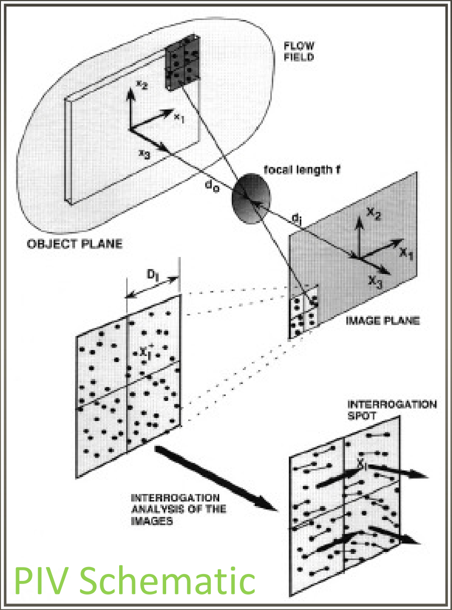
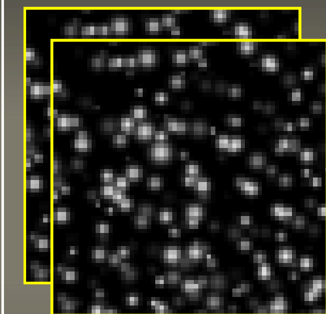
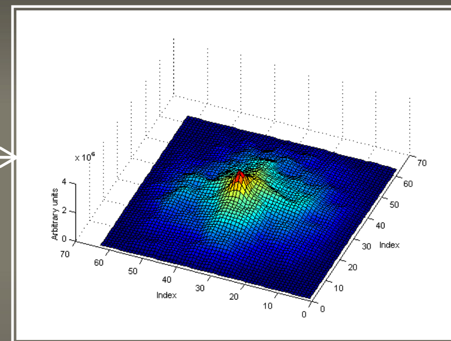
Breaking the Barriers in Particle-Image Velocimetry:

Application to Field Experiments

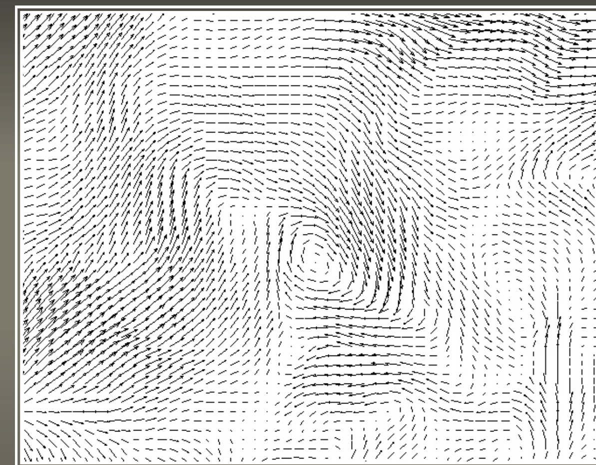


PIV Schematic


Acquire two images separated in time



Determine peak location in the correlation map


PIV measures 2-D velocity FIELDs : High spatial and temporal resolution

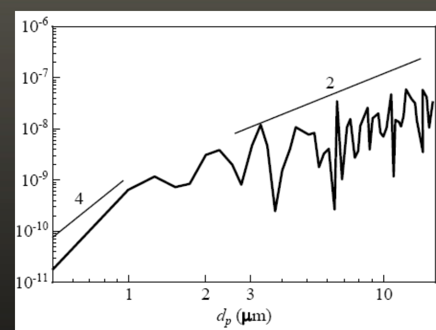
$$\bar{\mathcal{E}}_p \sim \frac{J_0 D_a^4 d_p^n}{z_0^2 Z_0^2 \lambda^n \Delta y_0 \Delta z_0}$$

If length scale in expt. scales up by m, mean exposure reduces by m^5! e.g.” m = 6 => exposure reduced 7000 times: more than 3 orders of magnitude!

LANL LF-PIV

2m x 2m + scalable!

Field PIV
(Katz et al., Johns Hopkins)

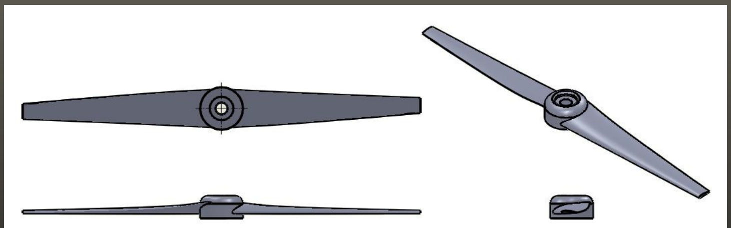


Mie Scattering: intensity goes as d_p^2. Hence use larger particles; but now particles are heavy and lag the flow… and so on…

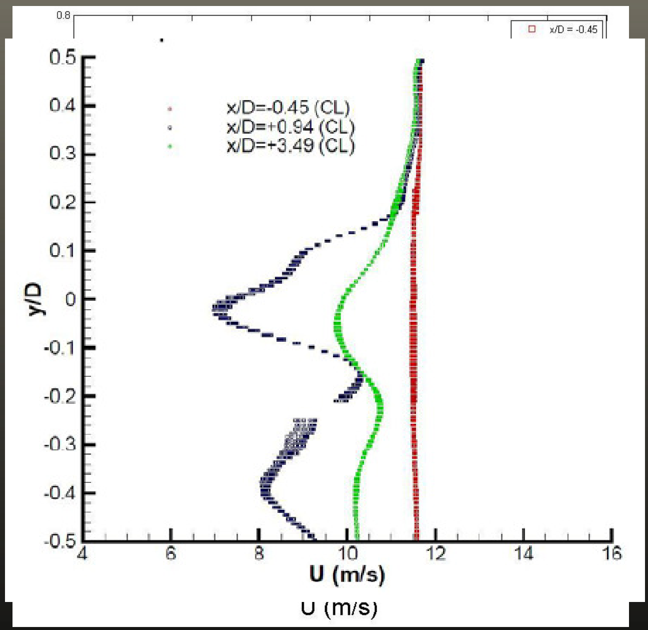
LANL is actively developing new generation PIV systems capable of large fields of view: Powerful diagnostic to provide new insights into turbulent flows around wind turbines

Wind tunnel experiment using model turbines:

Design wind turbine blades ab-initio using BEM theory



- Inflow, wake velocity profiles, output power, RPM are measured



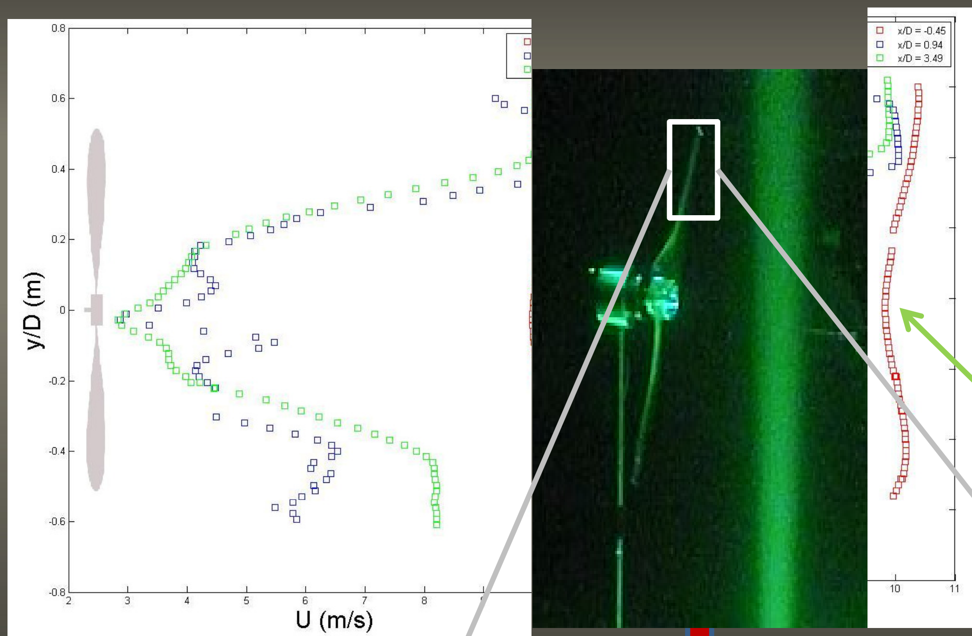
- Scaled model experiments provide validation data and understanding of fundamental physics
    - Wake structure in turbulent inflow under yaw with variable mean shear rates
    - Multiple turbine interactions and boundary layer separation

- Solidworks model of turbine and lift/drag coefficients of blade profiles allow easy simulation set up

Specifying a Wind Turbine, Inflow and Wake Completely:

Code Validation and Wake Physics

WAKE



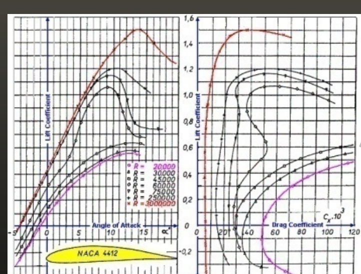
INFLOW

Measurement regions:
-1D to -3D (inflow)
1D to 8D (near and far wake)
Re_c= 25,000

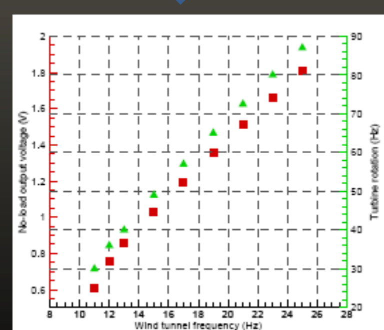
Inflow modification due to induction

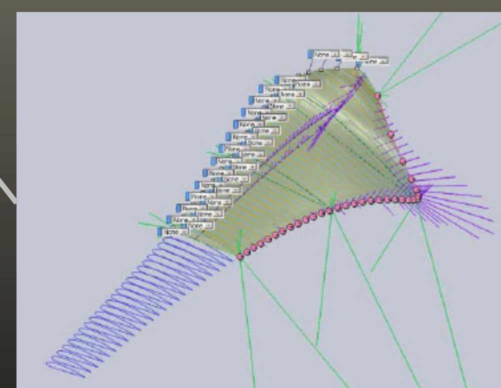
Phase locked wake measurements

EXTRACTED ENERGY



Lift, Drag and pitching moment plots + airfoil profile available

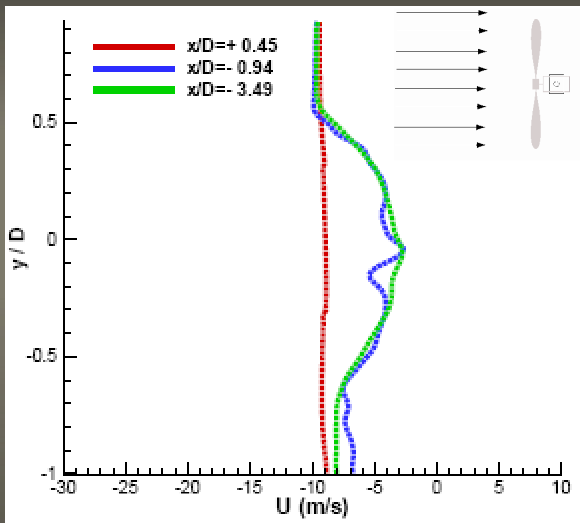




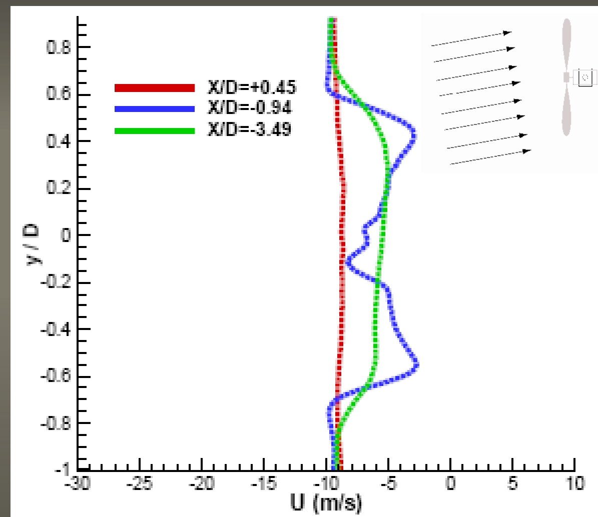
Blade geometry design:
Profile, twist and taper tables available for wind turbine blade

Detailed validation dataset for laminar inflow with and without yaw is available from LANL

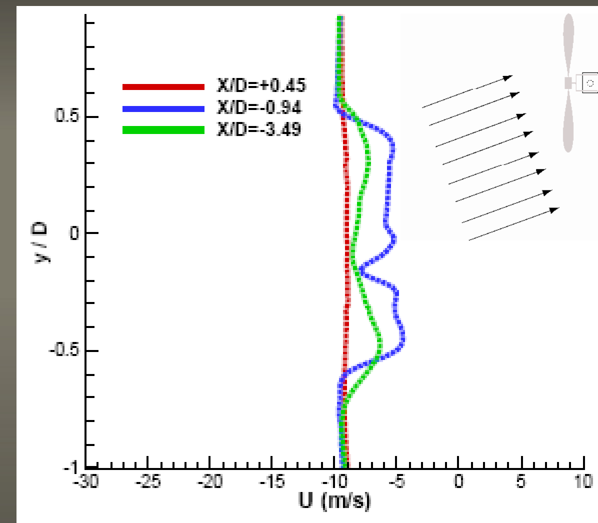
Wind Turbine Wakes under Yawed Inflow:
Validating numerical simulations under separation



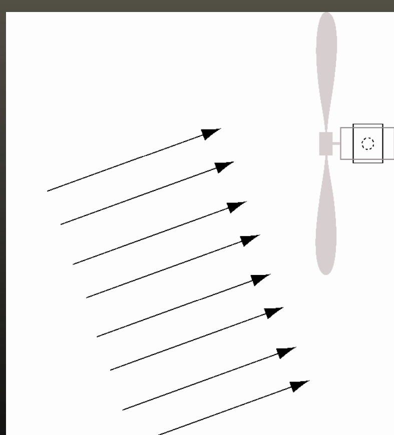
No Yaw; Normal inflow



Yaw angle = 10º



Yaw angle = 20º



Significant change in wake structure for yawed inflow: But can codes capture these complex phenomena?

- Local angle of attack changes (Dynamic stall)
- Separation around airfoil
- 3D boundary layer effects

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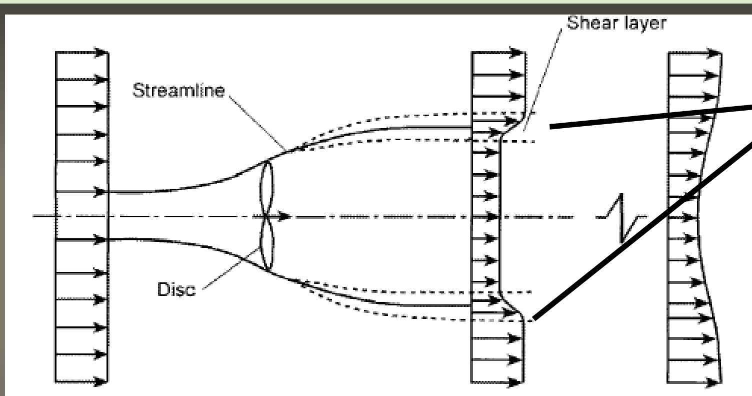
Wind tunnel experiment using model turbines:
Turbulent inflow conditions and turbine-turbine interactions



Wake development behind a wind turbine

Turbulent production is most important in the shear layer, which drives the turbulent momentum flux into the wake region and causes wake recovery.

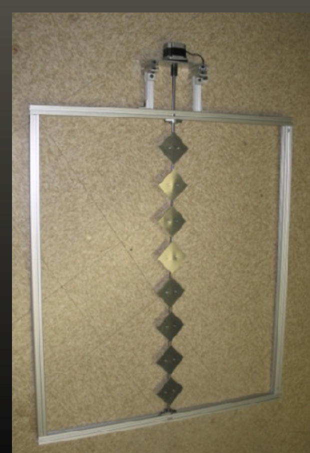
Turbulent Kinetic Energy Equation

$$\frac{D\left(\frac{1}{2}q^2\right)}{Dt} = \frac{\partial\left(\frac{1}{2}q^2\right)}{\partial t} + U_j\frac{\partial\left(\frac{1}{2}q^2\right)}{\partial x_j}$$

Production

$$= -\frac{\partial}{\partial x_j}\left(\overbrace{\frac{\overline{p'u_j}}{\rho}}^{2a} + \overbrace{\frac{1}{2}\overline{u_j q^2}}^{1b,2b}\right) \underbrace{-\overline{u_i u_j}\frac{\partial U_i}{\partial x_j}}_{3} + \underbrace{\nu\,\overline{u_i\frac{\partial^2 u_i}{\partial x_j^2}}}_{4,5}$$

Inflow shear and shear stress influence the production of TKE and determine the wake scales and structures.



At LANL, we are developing an active grid system to systematically study the effect of inflow shear and turbulence on wake structure (one axis shown in Fig).

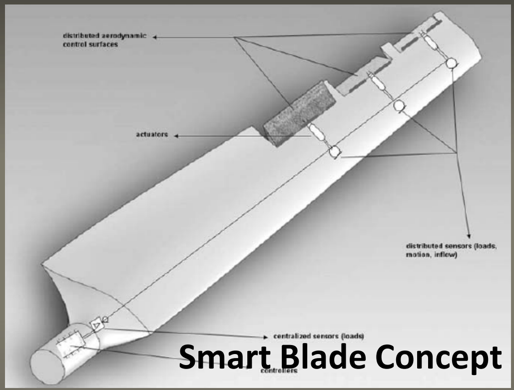
Active grid design parameters:

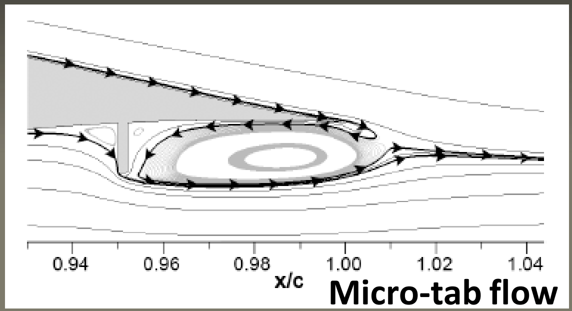
* Mean shear ~ 0 – 15 /s
* Re_t ~ 0 - 700
* Re_c ~ 25000 – 40000
* Well characterized turbine profile, inflow and wake measurements
* 1 turbine to array of 12 turbines (3x4 rows)
* Up to 15 degree yaw

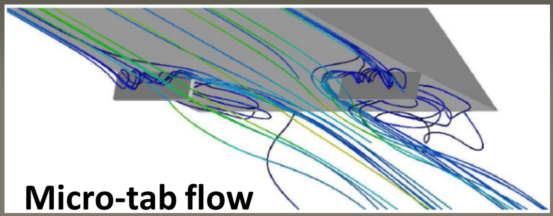
Top figure from Crespo et al., Wind Energy, 1999.

Rotating PIV Diagnostic Development:

Measure separated flow around blades, Flow around micro-tabs etc.

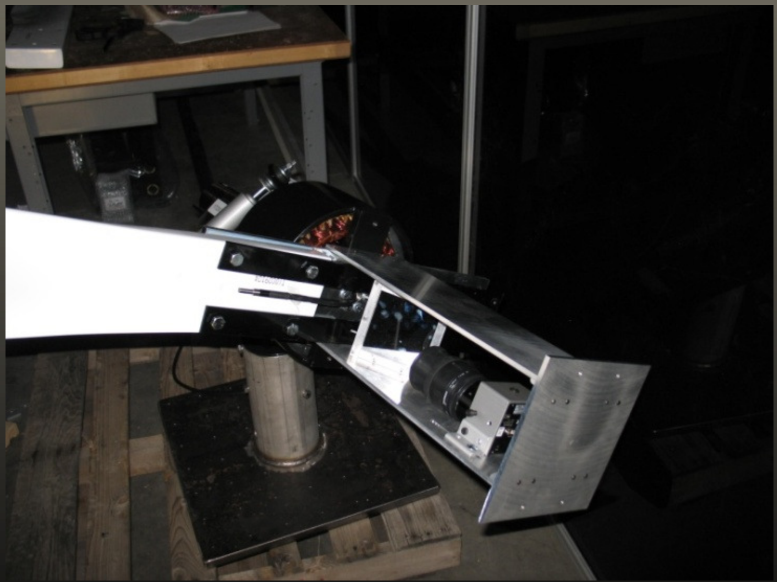






[1] Barlas & van Kuik, Progress in Aerospace Sciences (2010), [2] van Dam et al, Journal of Physics (2007), [3] Mayda et al, AIAA paper 2005-1185

Patent in preparation

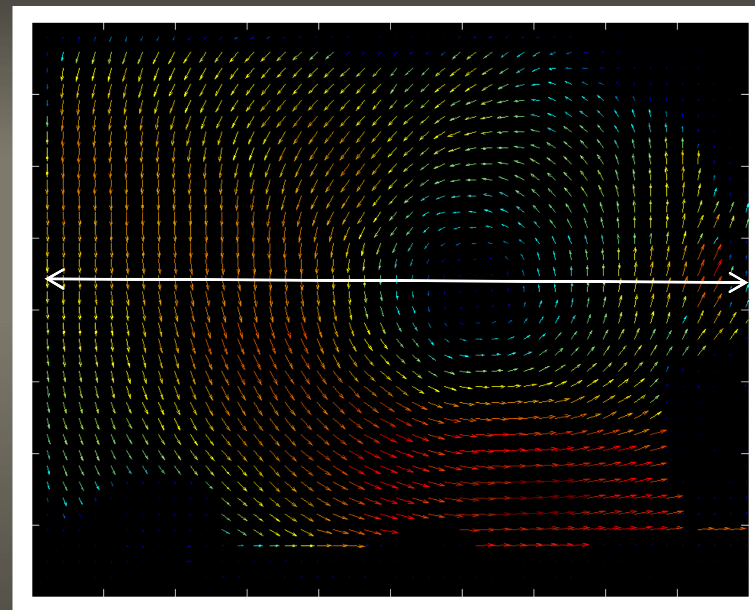


LANL's In-blade rotating PIV system: Measure blade boundary layer at all phases of blade revolution. Time series of dynamic stall, micro tab performance, separation and 3D effects

[1] Supported by DoE-EERE, In-blade PIV Diagnostic Development, BJ Balakumar (PI)

LANL Large-Format PIV Diagnostic Development:

High resolution inflow turbulence, Wake velocity structure



<u>LF-PIV</u>: 300 Hz, 0.03m spatial resolution

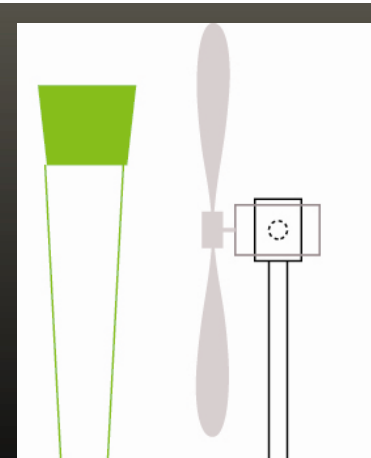
-- can measure flows not measured by LIDAR or sonic anemometers with high spatial and temporal resolution, ability to measure blade and near turbine flows

VS

LIDAR: O(1m) spatial resolution (cannot measure flows very close to turbines, blade flows or very near wake regions)

Sonic Anemometer: 20Hz (intrusive, single point, slow)

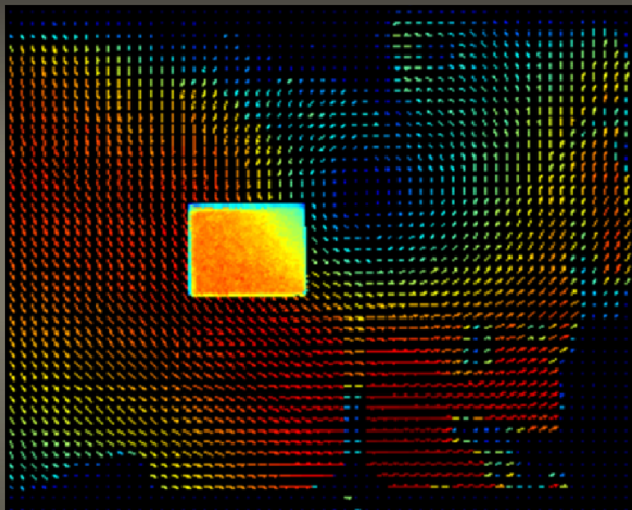
Non-intrusive inflow using LF-PIV

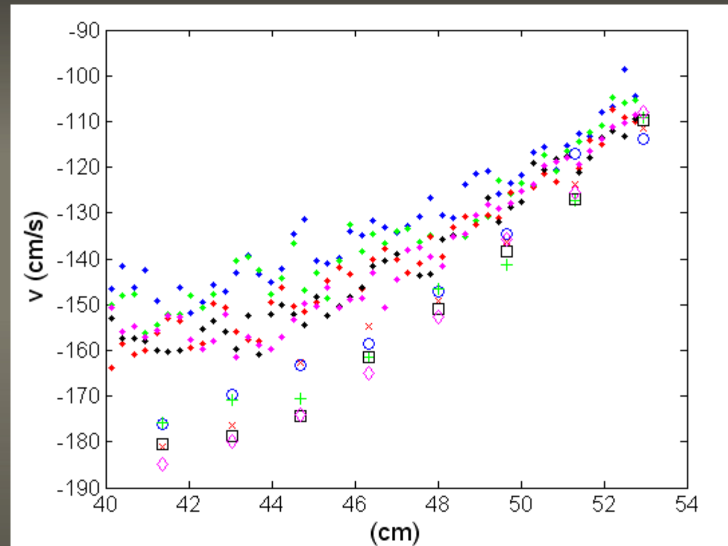


Large Format PIV: Multi-point, precise velocity measurement, measurement of time-series wake profiles, two-point spatial and temporal correlation contours in the wake . Scalable to 20m x 2m.

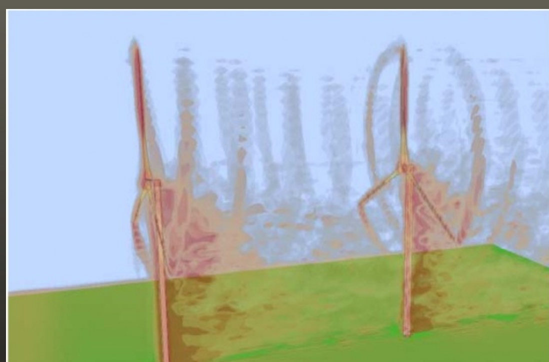
Large-Format Particle-Image Velocimetry:

Two-point correlation, Wake spatial structure, Sub-grid scale stresses





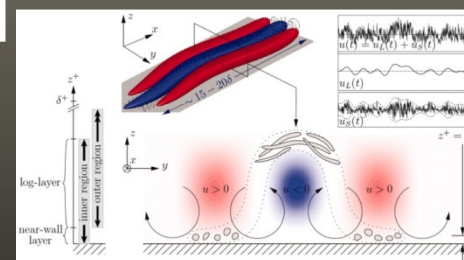
LF-PIV is within +-5% of conventional PIV (worst case). Allow investigation of flow structures and detailed velocity statistics.



High resolution LES ~ 2m; LF-PIV will provide experimental data for physics-based SGS models. Image: Eunmo Koo, Rod Linn (LANL)

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial U_i}{\partial x_j} - \epsilon + \frac{\partial}{\partial x_j}\left[(\nu+\nu_T/\sigma_k)\frac{\partial k}{\partial x_j}\right]$$

Dissipation determines evolution of kinetic energy and hence scales of turbulence present. LF-PIV can measure dissipation and dissipation fields directly.

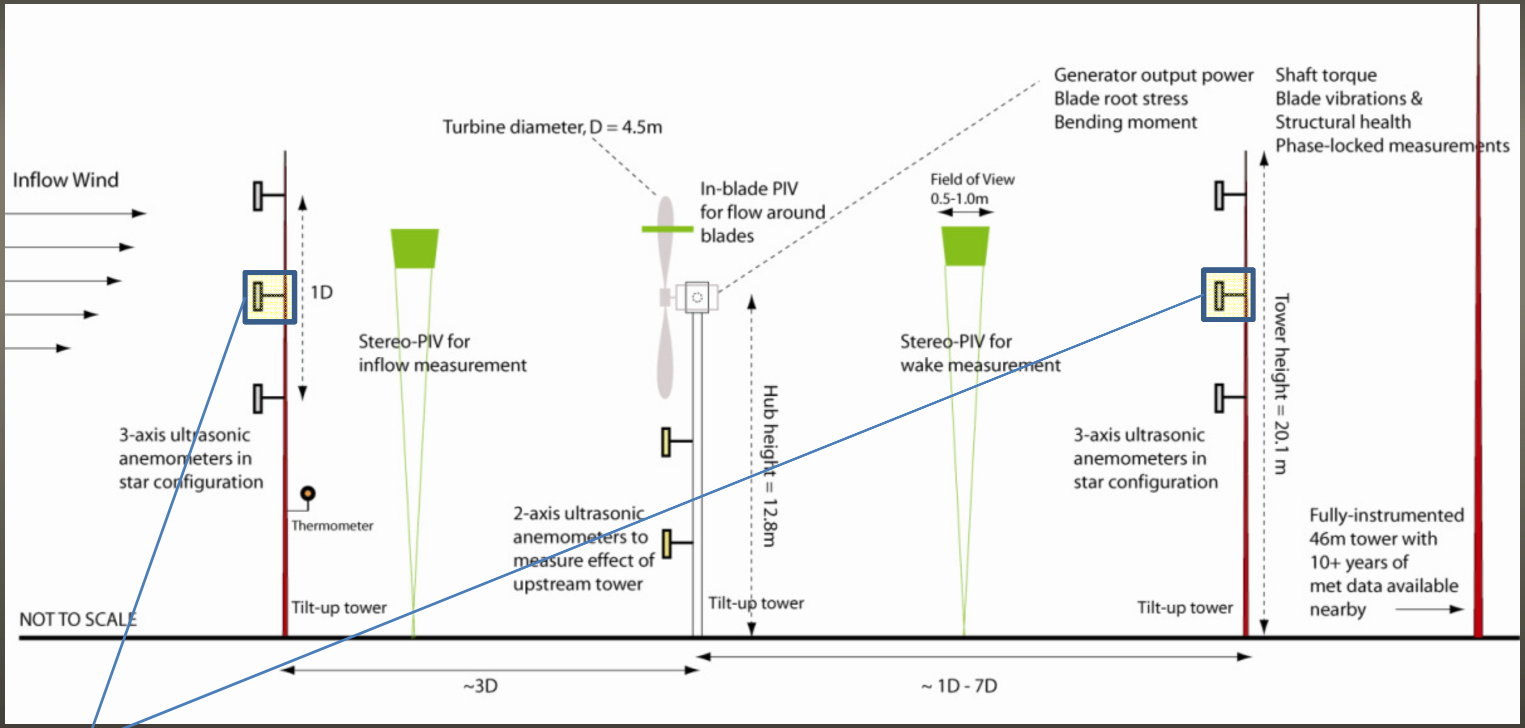


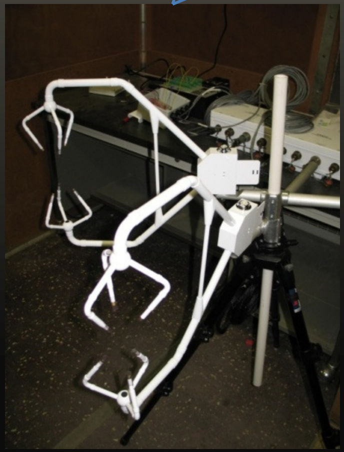
LF-PIV for coherent structure identification. Image: Marusic et al, Science (2010)

LF-PIV can measure numerous unknown physics such as dissipation field structure, SGS stresses, wake structures (including meandering), boundary layer structures.

Wind Turbine Field Experiment Campaigns:

Going beyond sonic anemometry using large-format PIV

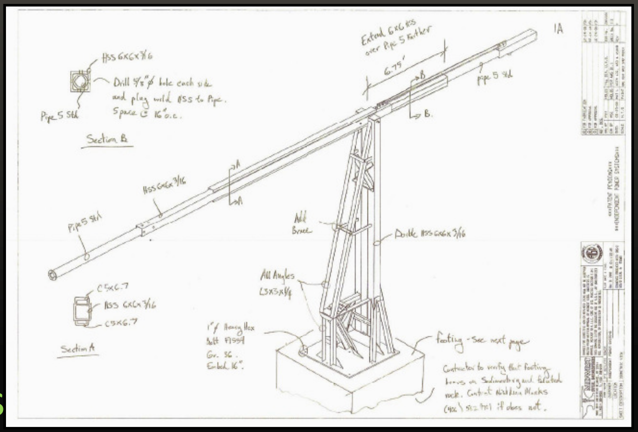




10x CSAT3 anemometers monitor inflow and wake; 2D RM Young; with LF-PIV

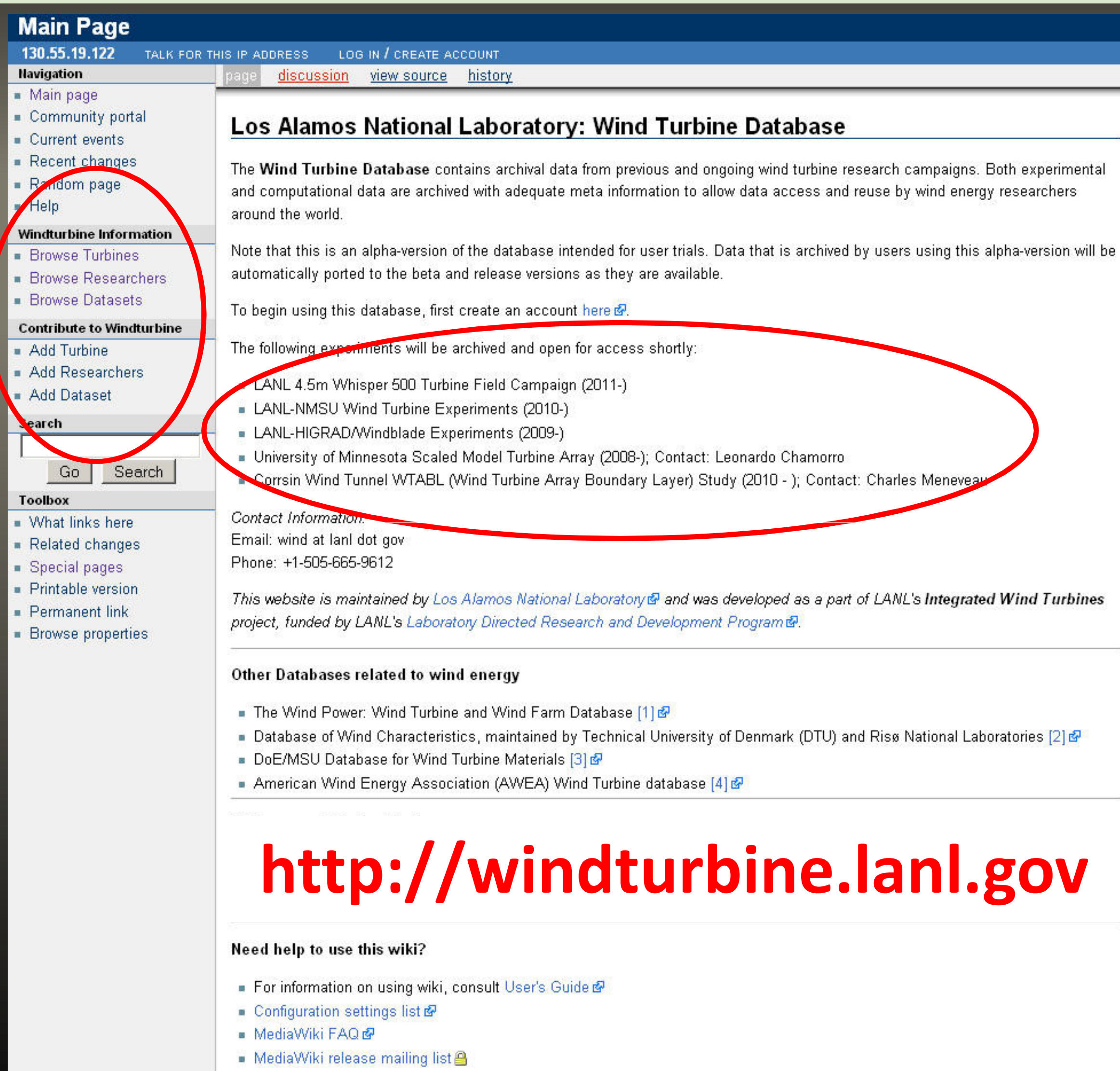
Aerodynamic, structural and power data: Highly detailed integrated experimental datasets for CFD

Tilt-down sensor and turbine towers



LANL Wind Turbine Database:

Assimilating & sharing data from wind turbine experiments



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Los Alamos National Laboratory: Wind Turbine Database

The **Wind Turbine Database** contains archival data from previous and ongoing wind turbine research campaigns. Both experimental and computational data are archived with adequate meta information to allow data access and reuse by wind energy researchers around the world.

Note that this is an alpha-version of the database intended for user trials. Data that is archived by users using this alpha-version will be automatically ported to the beta and release versions as they are available.

To begin using this database, first create an account here.

The following experiments will be archived and open for access shortly:

- LANL 4.5m Whisper 500 Turbine Field Campaign (2011-)
- LANL-NMSU Wind Turbine Experiments (2010-)
- LANL-HIGRAD/Windblade Experiments (2009-)
- University of Minnesota Scaled Model Turbine Array (2008-); Contact: Leonardo Chamorro
- Corrsin Wind Tunnel WTABL (Wind Turbine Array Boundary Layer) Study (2010 -); Contact: Charles Meneveau

Contact Information:
Email: wind at lanl dot gov
Phone: +1-505-665-9612

*This website is maintained by Los Alamos National Laboratory and was developed as a part of LANL's **Integrated Wind Turbines** project, funded by LANL's Laboratory Directed Research and Development Program.*

Other Databases related to wind energy

- The Wind Power: Wind Turbine and Wind Farm Database [1]
- Database of Wind Characteristics, maintained by Technical University of Denmark (DTU) and Risø National Laboratories [2]
- DoE/MSU Database for Wind Turbine Materials [3]
- American Wind Energy Association (AWEA) Wind Turbine database [4]

http://windturbine.lanl.gov

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Summary & Future work

- Detailed scaled model experiments are underway to investigate the wake structure as a function of the wind turbine inflow field to develop advanced wake models and validate simulations
  - Full characterization of turbine geometry including airfoil characteristics under stalled conditions along with power and torque measurements for normal and yawed operating conditions.

- Novel diagnostic leaps at LANL enable the investigation of new wind turbine flow physics in important aerodynamic flow regimes that are poorly understood thus far
  - Large-Format PIV (LF-PIV) measurements with a field of view of 2m x 2m (and scalable to 20m x 2m, amongst the largest in the world) have been demonstrated at LANL to measure directly local inflow, dissipation fields, sub-grid scale stresses around wind turbines
  - In-situ rotating PIV system allows the measurement of the blade boundary layer, 3D separation around blades and flow around active control elements for the first time

- Future work (FY11/12): Detailed field experiments on 4.5m & 20m turbines will provide data to validate simulations and help understand Reynolds number scaling of flow physics
  - The heavily instrumented 4.5m turbine experimental campaign is designed to discover aerodynamic mechanisms that cause load fluctuations and impact turbine reliability
  - The 20m test will test field PIV measurements around large turbines that approach commercial models while simultaneously providing valuable validation data.

LANL DATABASE **http://windturbine.lanl.gov**