Atmospheric Turbulence Measurements Using Small Unmanned Aircraft Systems

Dale Lawrence
Abhiram Doddi
John Farnsworth
Lakshmi Kantha

Aerospace Engineering Sciences
University of Colorado

Small UAS in Rugged Terrain

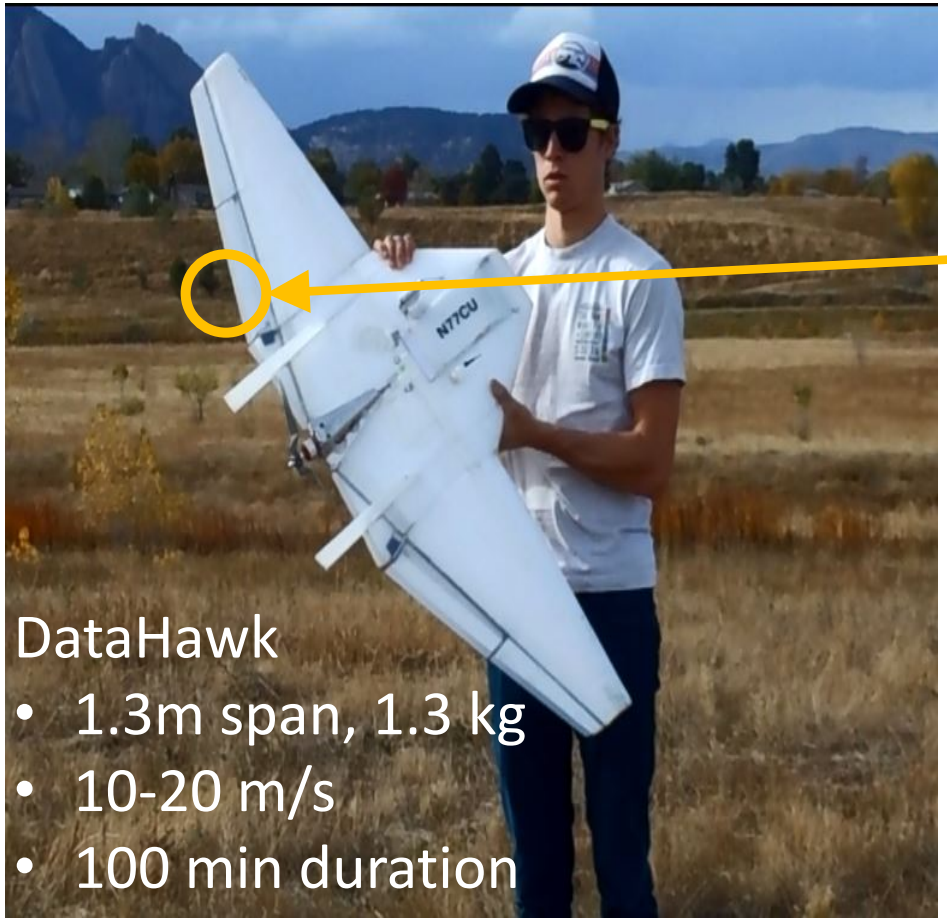
Turbulence Measurement on Small UAS

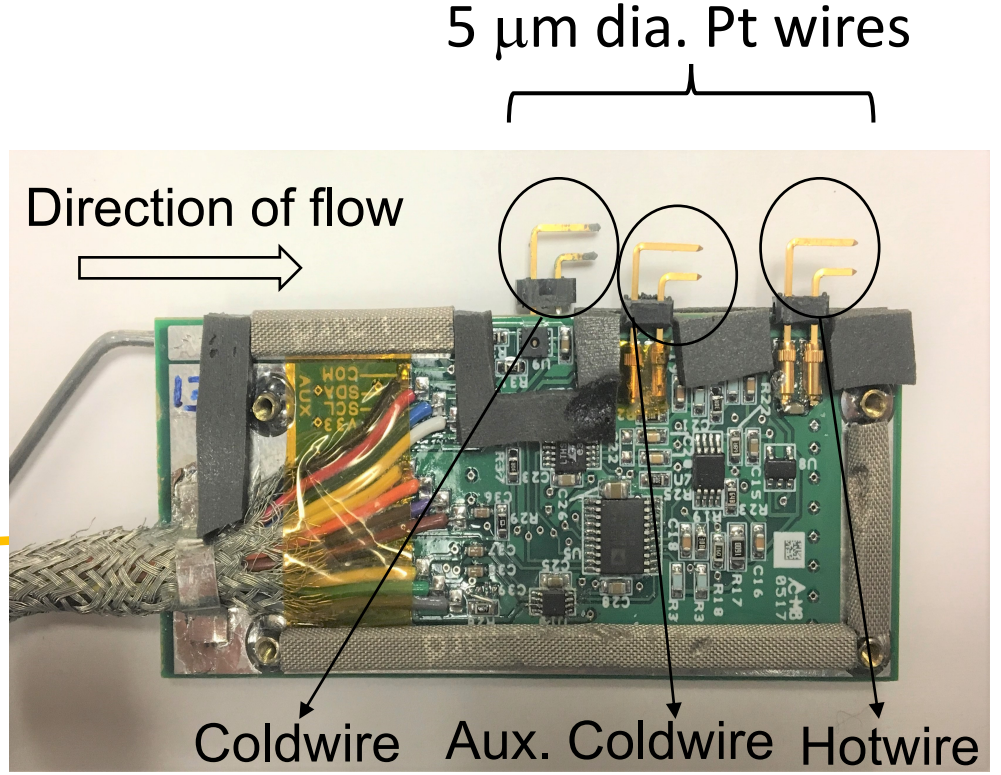
Requires high-bandwidth measurements to obtain confident spectral estimates (wide frequency range for spectral fits)

Requires small sensor elements for a small thermal time constant (e.g. micron-diameter wires for temperature, velocity)

Sensor elements must be protected from harsh operational conditions, without corrupting the turbulence measurements

DataHawk Fine Wire Turbulence Sensor

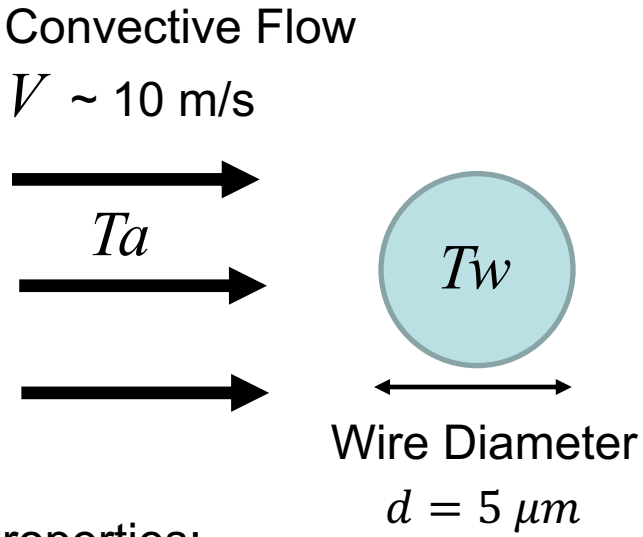




Custom electronics

- 400 Hz wire bandwidth (CVA)
- 800 Hz sampling
- Auto zero
- Ambient temperature compensation
- 20g, 0.5W, $500

Fine-Wire Convective Heat Transfer Model



Air Properties:

- Thermal Conductivity k
- Kinematic Viscosity ν

Surface Area

$A = \pi\ d\ L$

Radiative heat transfer ignored (< 1%)

- 2D heat transfer:
  - Wire Length *L* = 2 mm
  - End effects ignored (*L*/*d* = 400)
- Electric current through wire cross section produces Joule heating power *P* and resultant wire temperature *Tw* according to

$$I\ V = \ P = H(V)(Tw\ - Ta)$$

$$Nu = \frac{h\ d}{k} \qquad Re = \frac{V\ d}{\nu}$$

$$P = Nu(Re)\ \pi k L\ (Tw\ - Ta)$$

Environmental Turbulence Power Spectra

Turbulence Parameter:
Kinetic Energy
Dissipation Rate ε

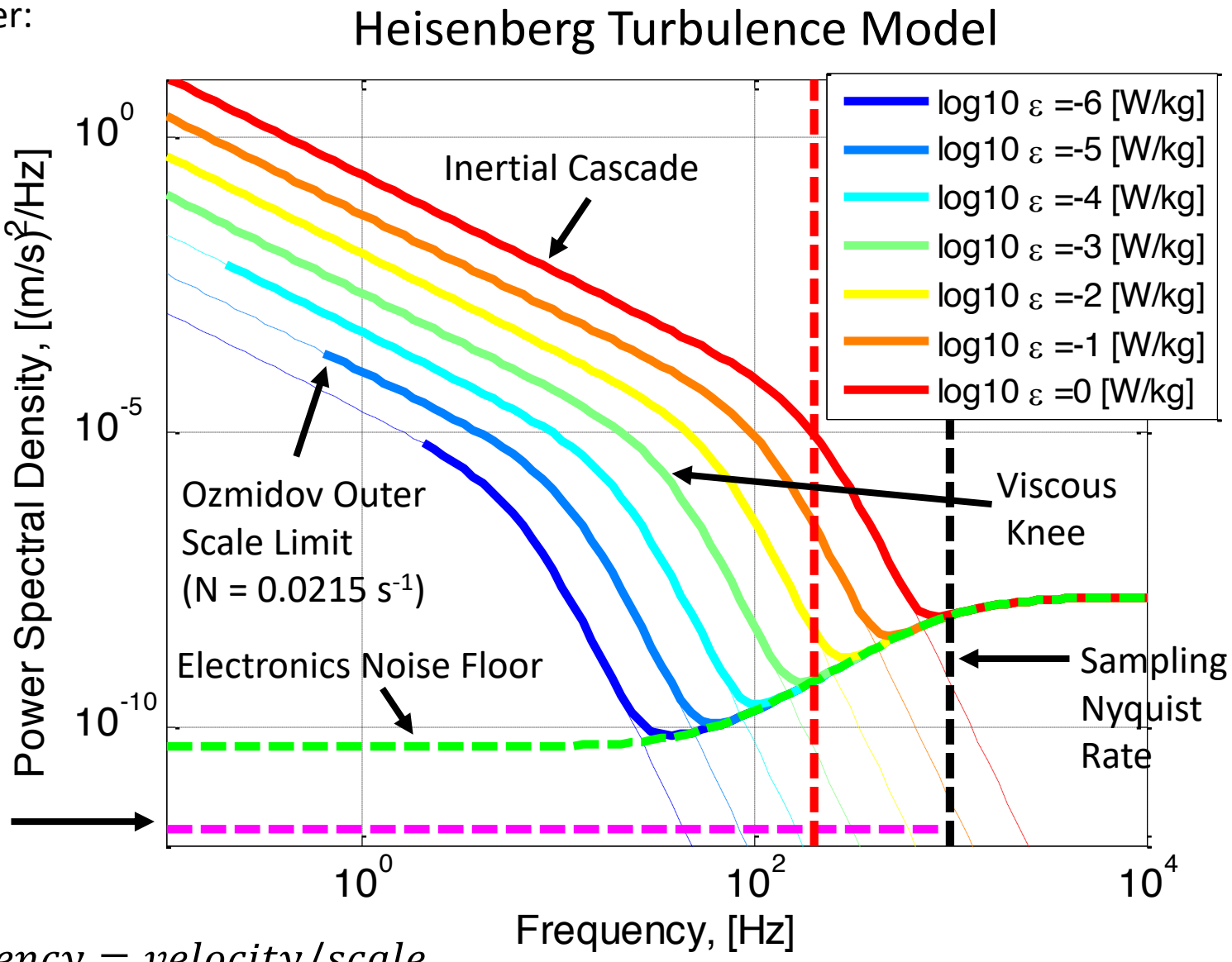
Ozmidov Scale

$$L_O = \left(\frac{\varepsilon}{N^3}\right)^{1/2}$$

Kolmogorov Scale

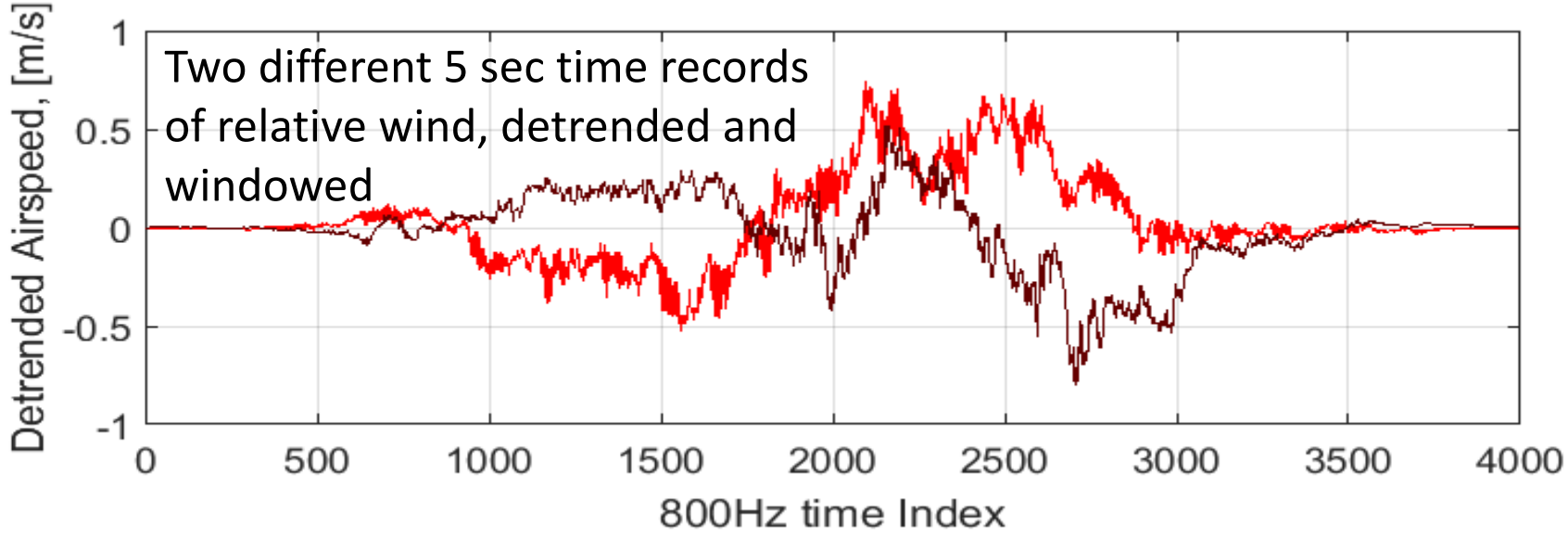
$$L_K = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

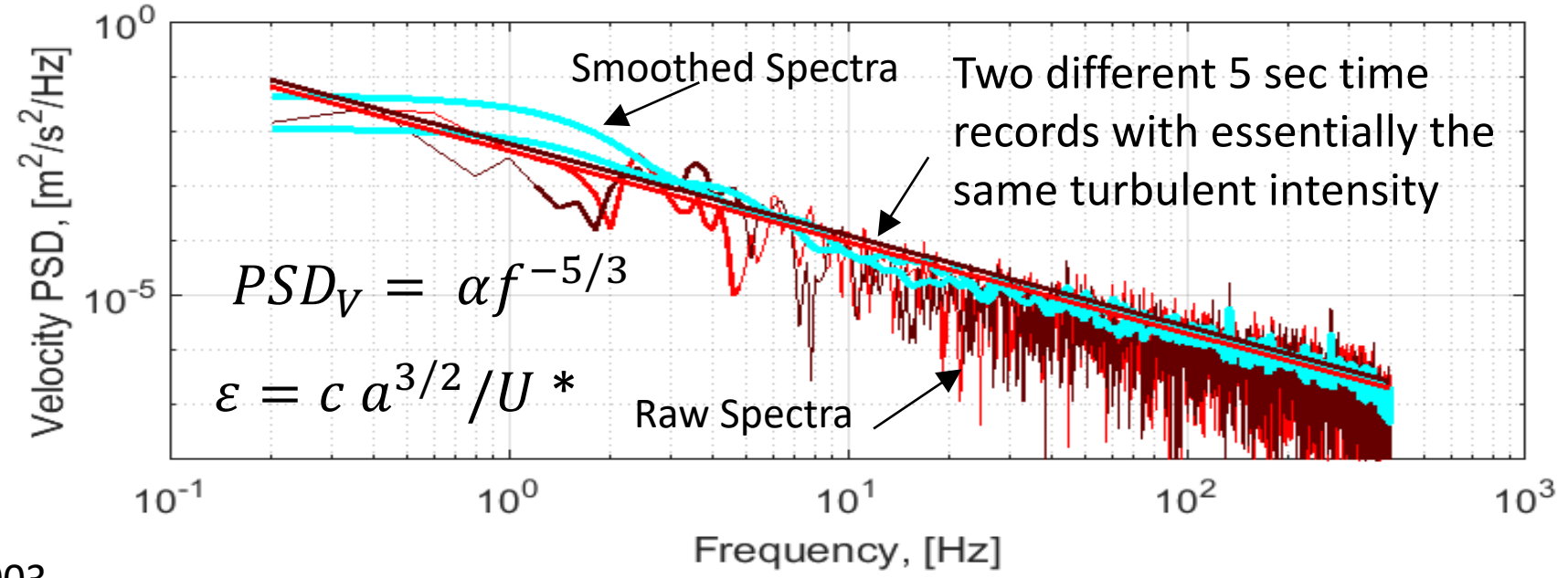
quantization noise floor



$$frequency = velocity/scale$$

Turbulence Spectral Estimation

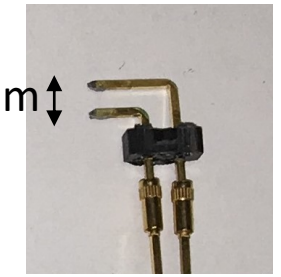


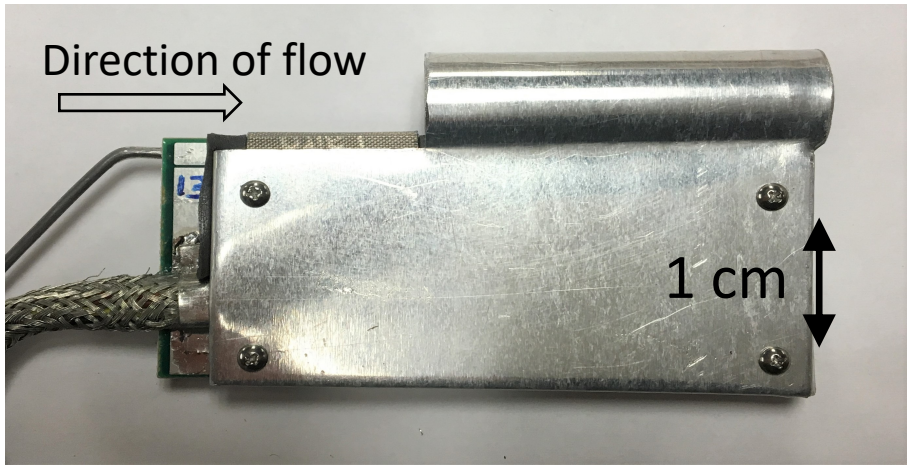


*Frehlich et al 2003

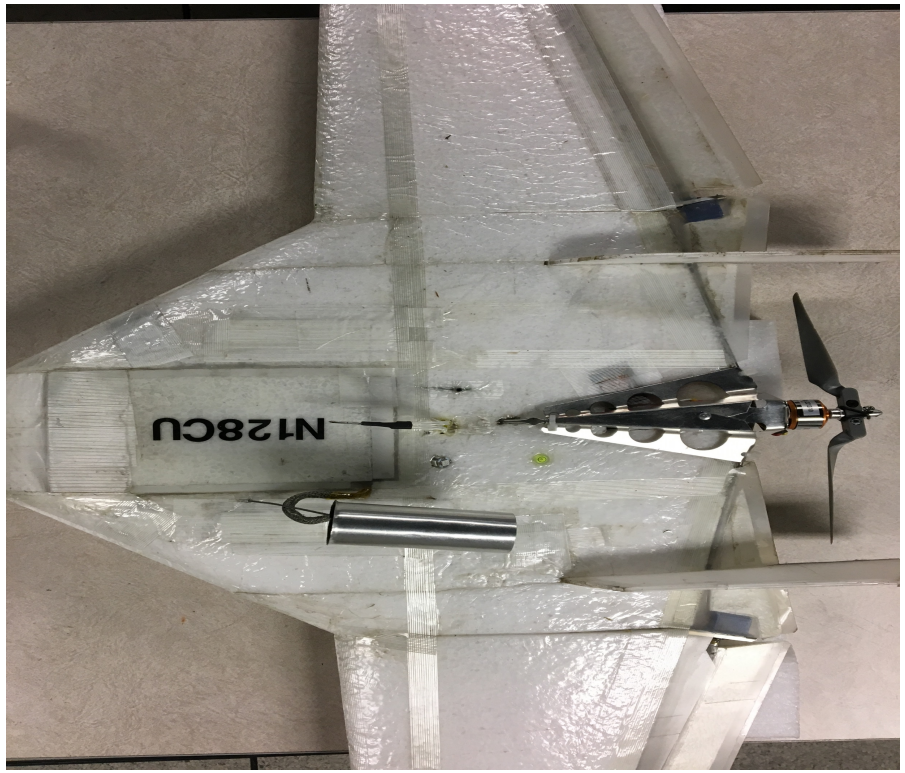
Sensor Protection Schemes

- Mounting behind the airframe leading edge
- Protective cylindrical shroud with ball deflector: protects against
  - Handling, flight ops
  - Solar radiation
  - Debris, raindrops and snowflakes
- Cylindrical shroud only
  - Avoids variable ball wake
  - Highly robust, except for particles entering the throat
- Wires mounted “backwards” (shielded by their own prongs)



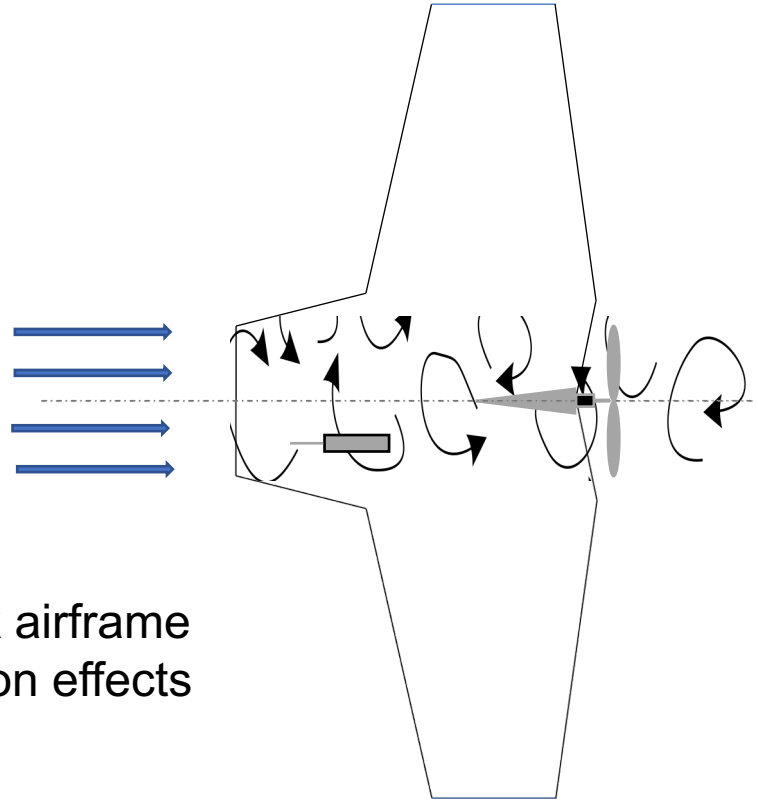


DH Turbulence sensors

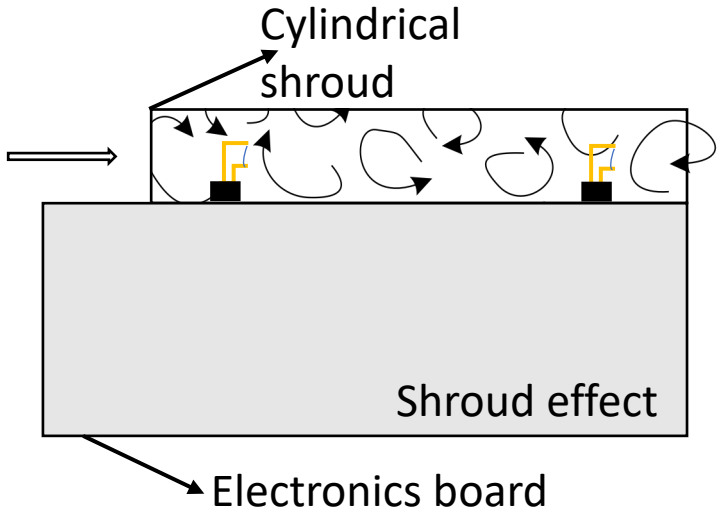


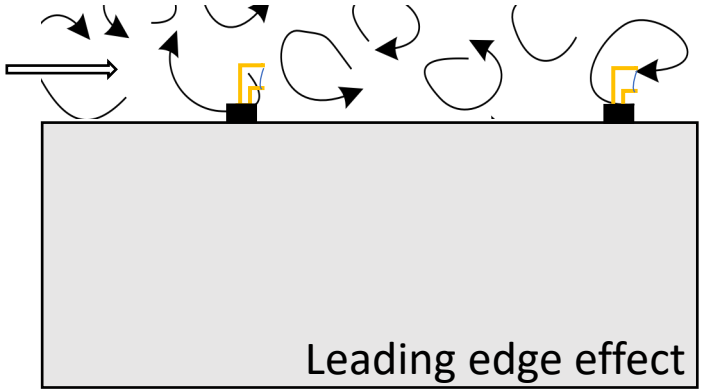
Obstructive Effects

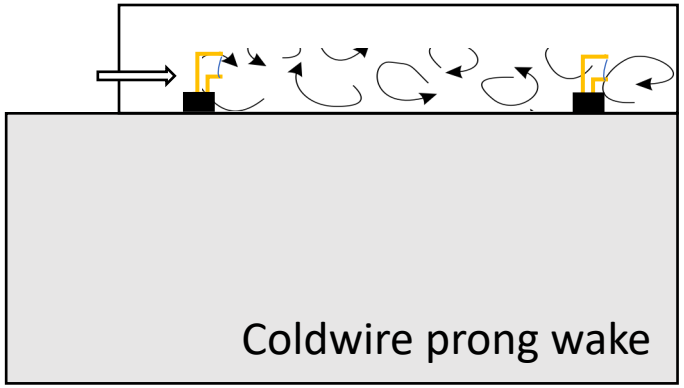
- DataHawk airframe
- Protective shroud
- Upstream wire and its prongs
- Leading edge of the sensor board



DataHawk airframe acceleration effects

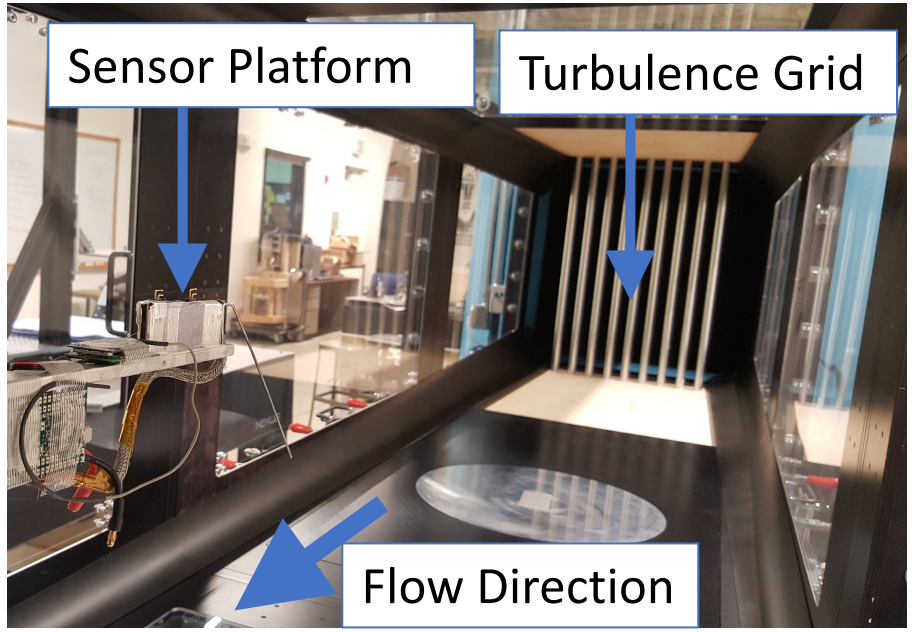


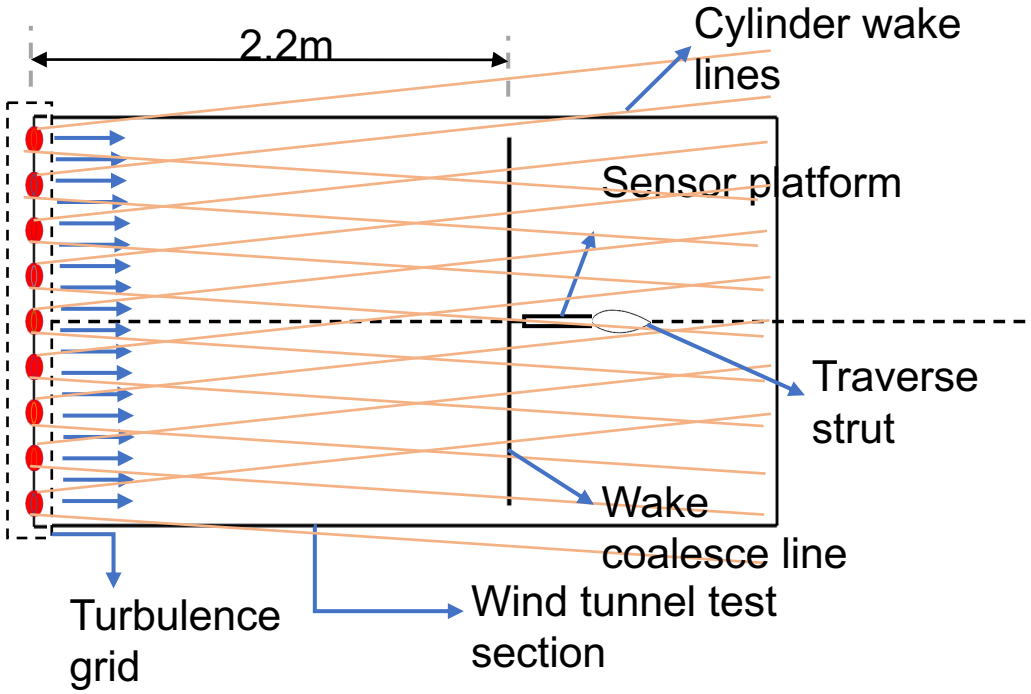




Wind Tunnel Sensor Characterization

- Test section 3m long, 0.8m square
- Nominal free stream velocity: 15m/s
- Traverse strut equipped with sensor mounting platform
- Coldwire, Hotwire and Pitot differential pressure sensors
- Upstream turbulence-generating grid



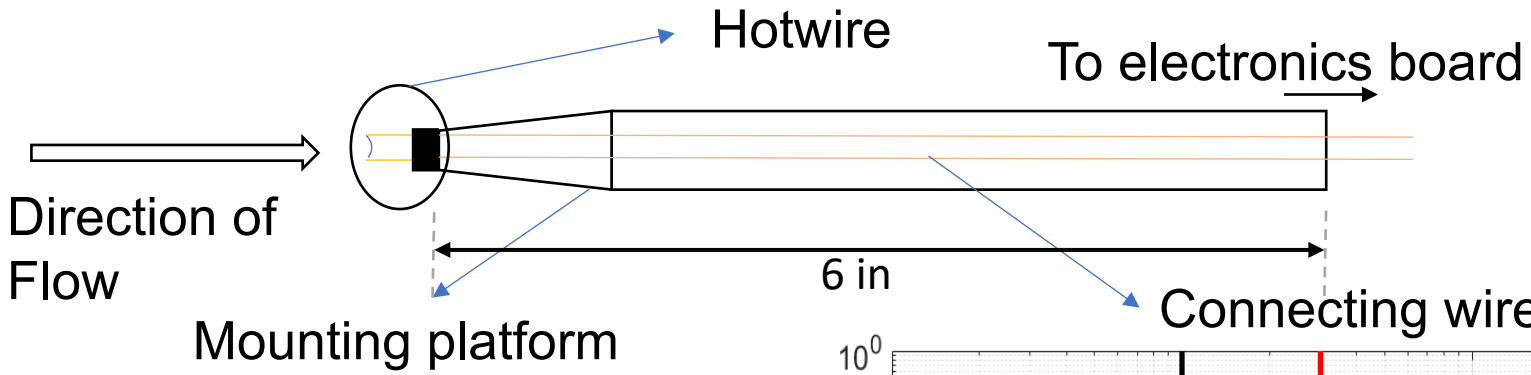


Turbulent Flow Field

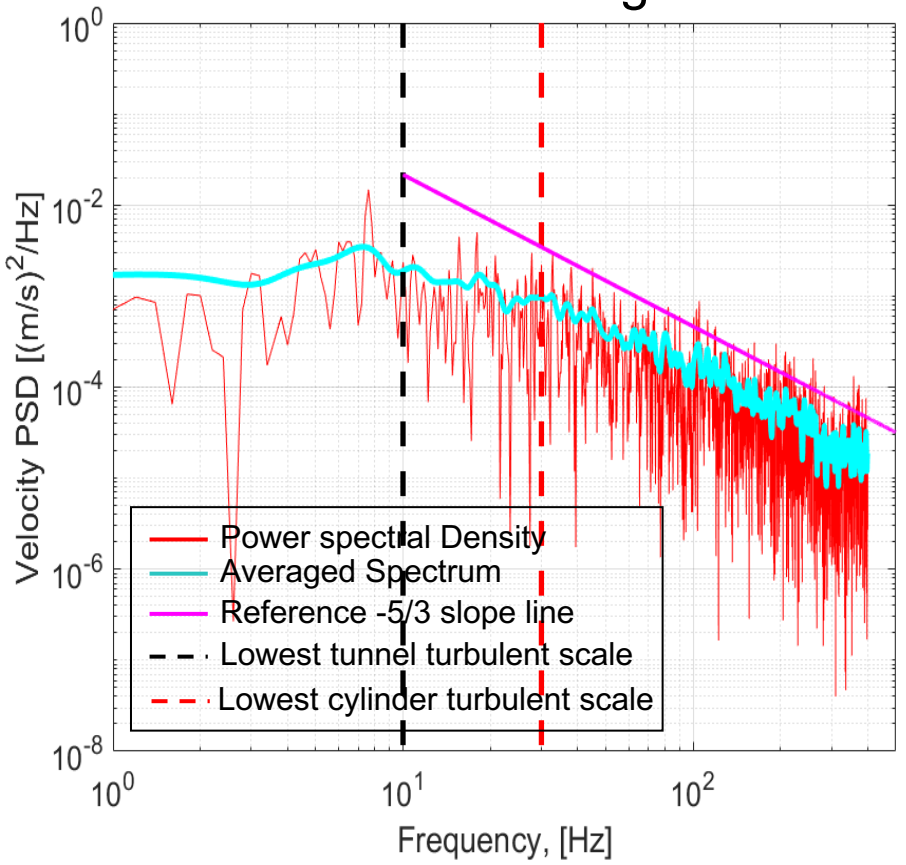
- 9 bars produce Re = 25400 *
- ~15 degree wake spread angle *
- Local velocity fluctuations less than 10% of the mean free stream velocity *
- Outer scale of turbulence at about 30 Hz (0.5m) *

*Schlichting – BLT
*Gutkin et al 2016
*Parnaudeau et al 2008

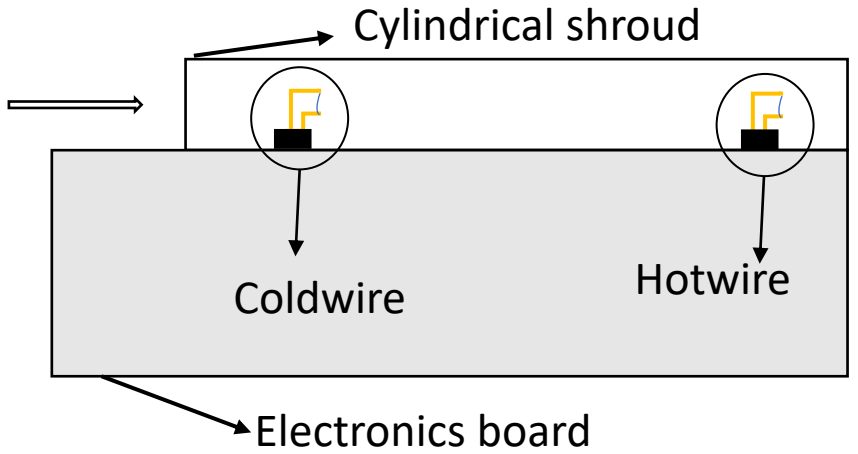
Hotwire in Free stream



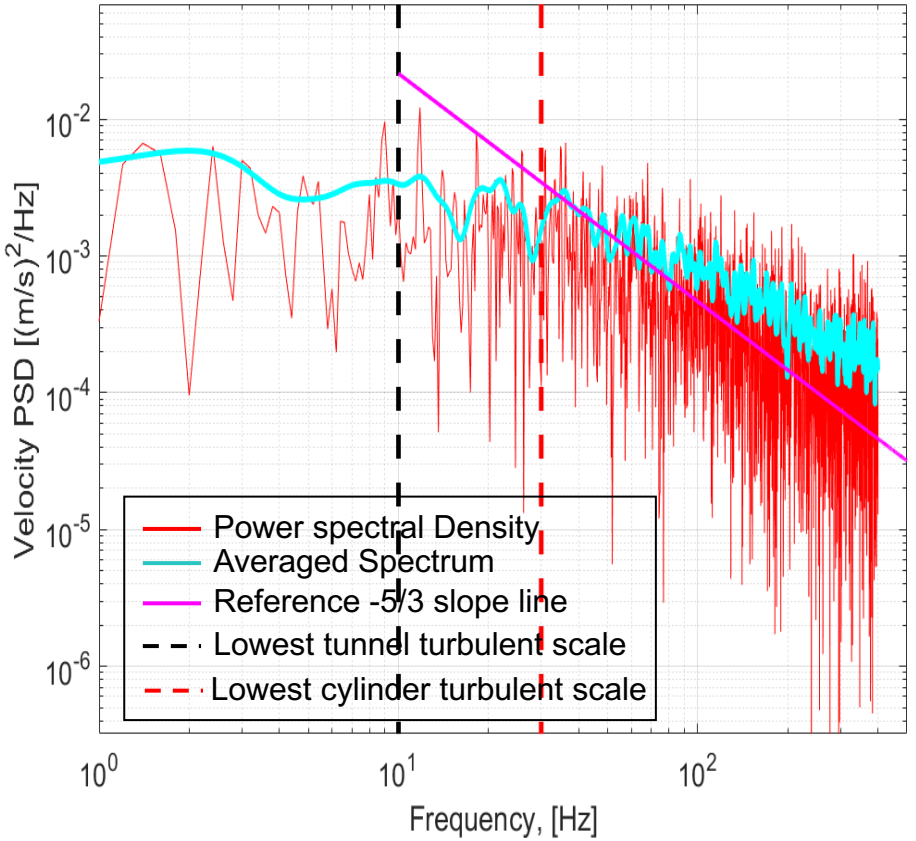
- Free stream measurement avoids wake effects
- Characteristic f^(-5/3) spectral slope from 30 Hz to 400 Hz



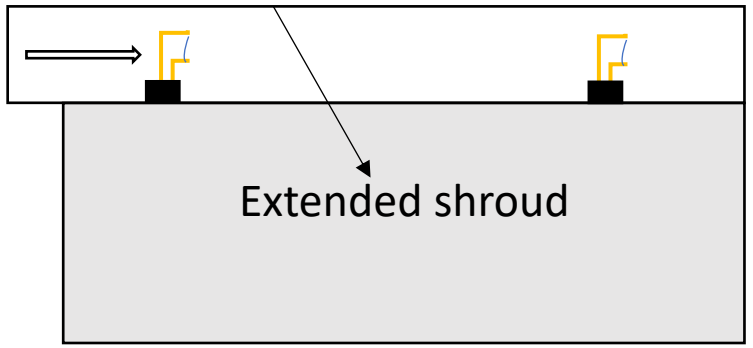
Sensor in normal configuration



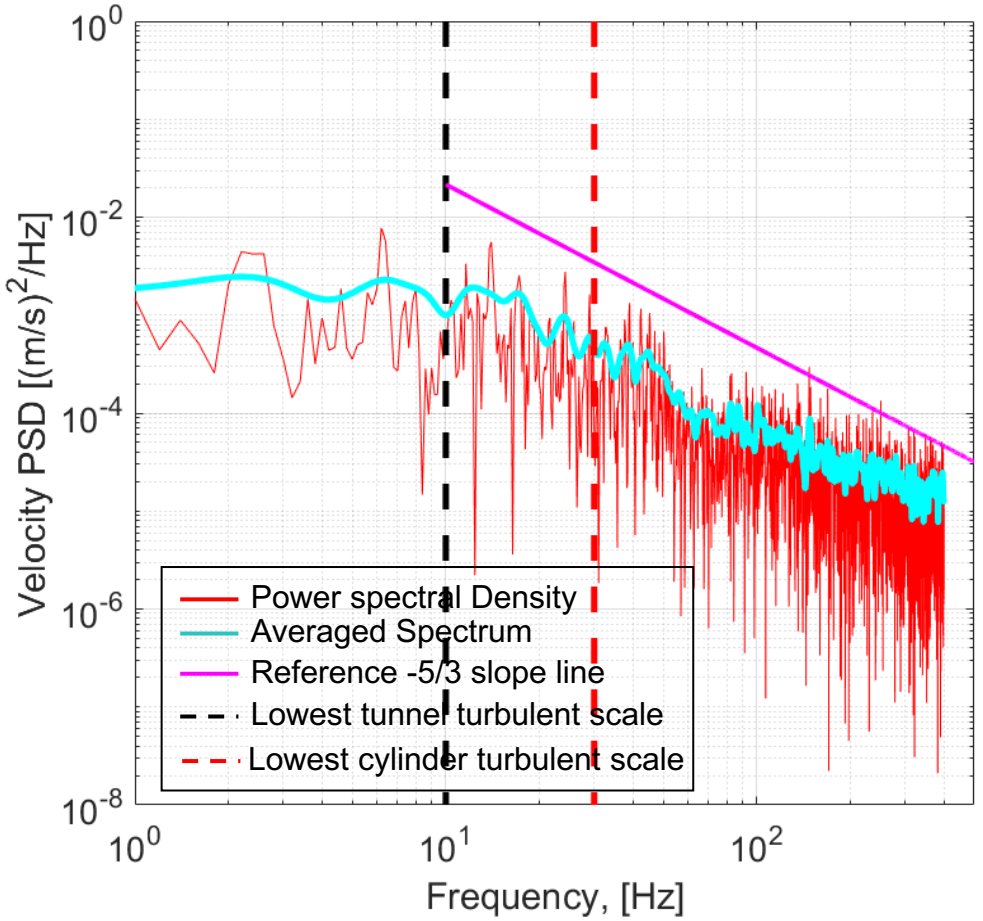
- Hotwire and coldwire prongs facing down stream
- Slope is reduced from the expected f^(-5/3) inertial cascade slope
- The obstruction increases turbulent intensity at small scales (but much larger than the expected millimeter scales)



Effect of 3-wire board leading edge

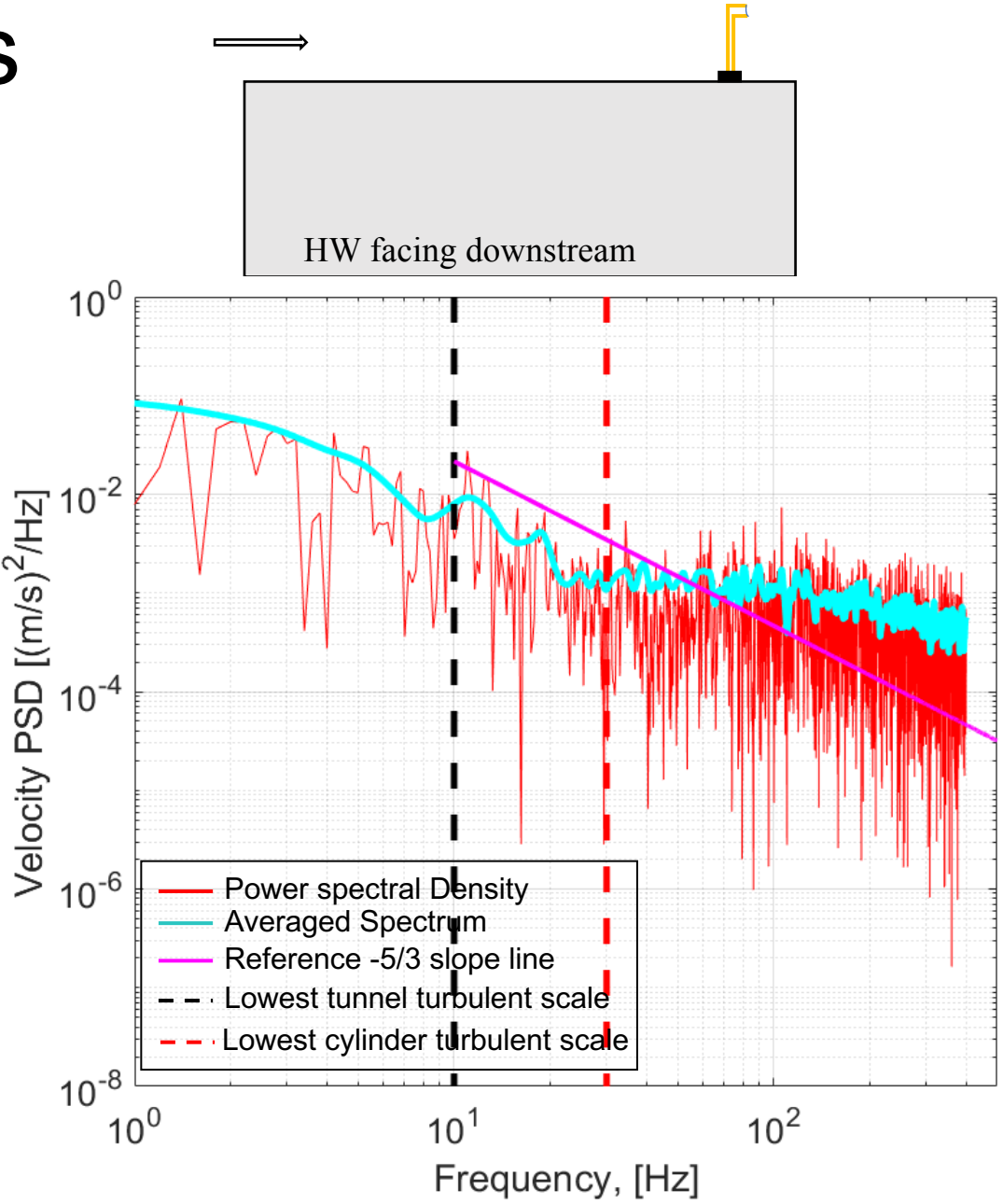


- Isolate the effect of wake due to leading edge
- Shroud extends beyond 3-wire board leading edge
- Extension length – 0.63 cm
- Suppressed power above 20Hz
- The current design uses the extended shroud



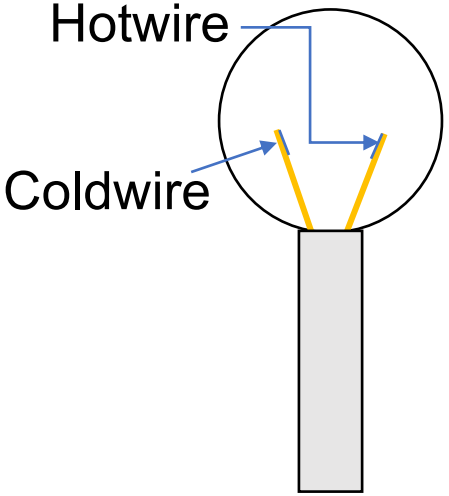
Effect of Prongs

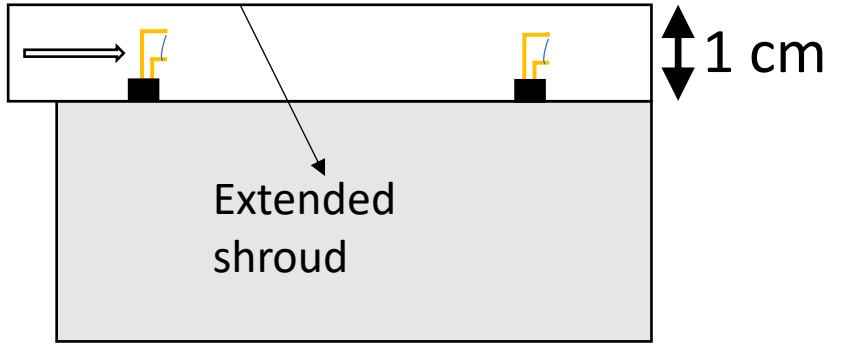
- Extended HW prongs
- Avoid leading edge effects
- Elevation in power expected at high frequencies only (small scale)
- The obstruction effect extends to lower scales also
- Prongs elevate the turbulence

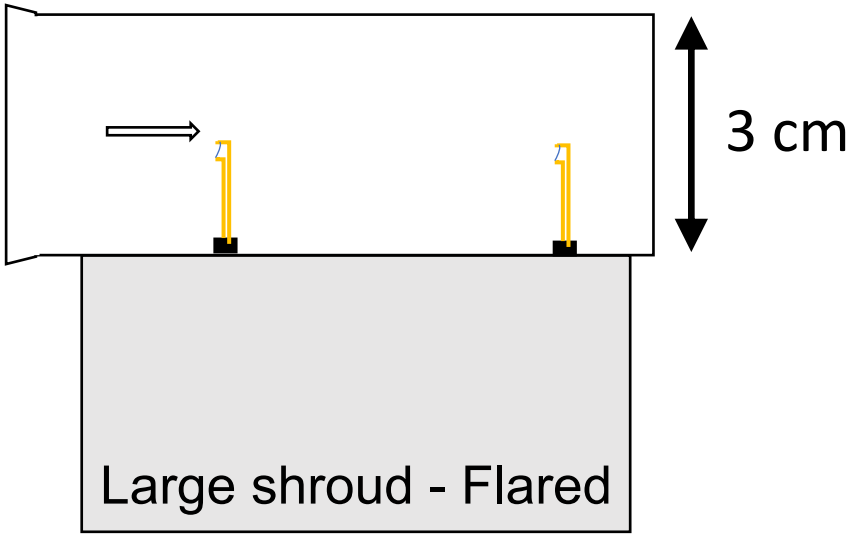


Effect of Shroud diameter

- Shroud Diameter increased to 3 cm
- Shroud extends leading edge by 0.63 cm
- HW and CW facing upstream
- Elevated HW and CW prongs separated by an angle (forming a ‘V’)

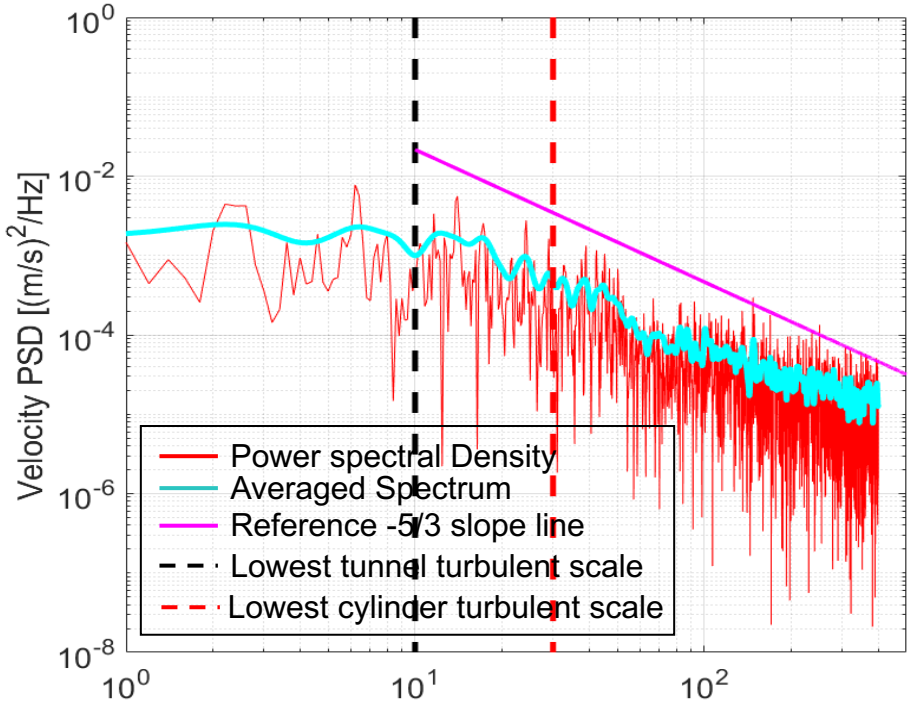


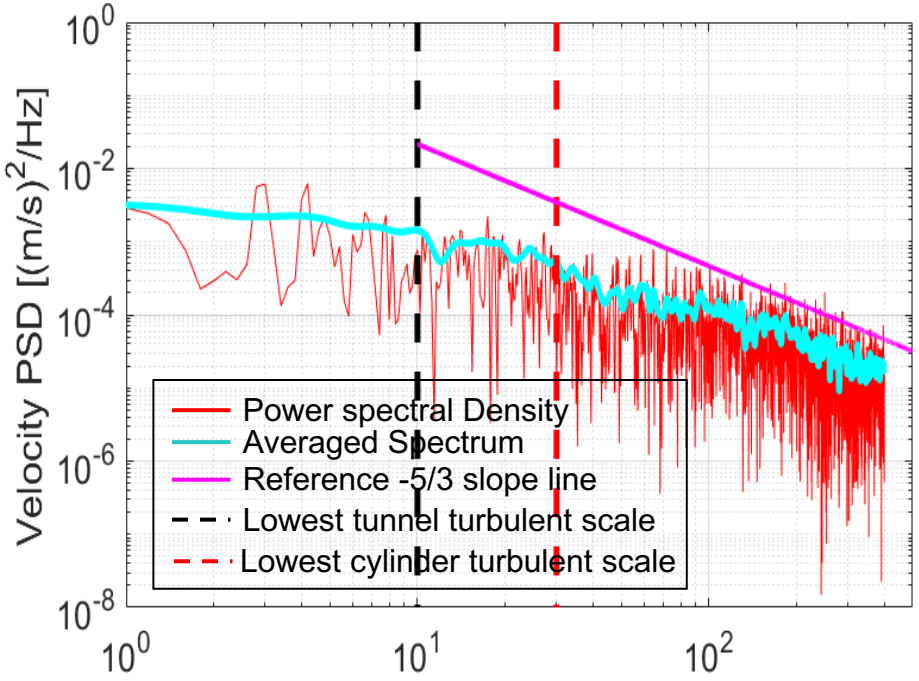




Effect of Shroud diameter

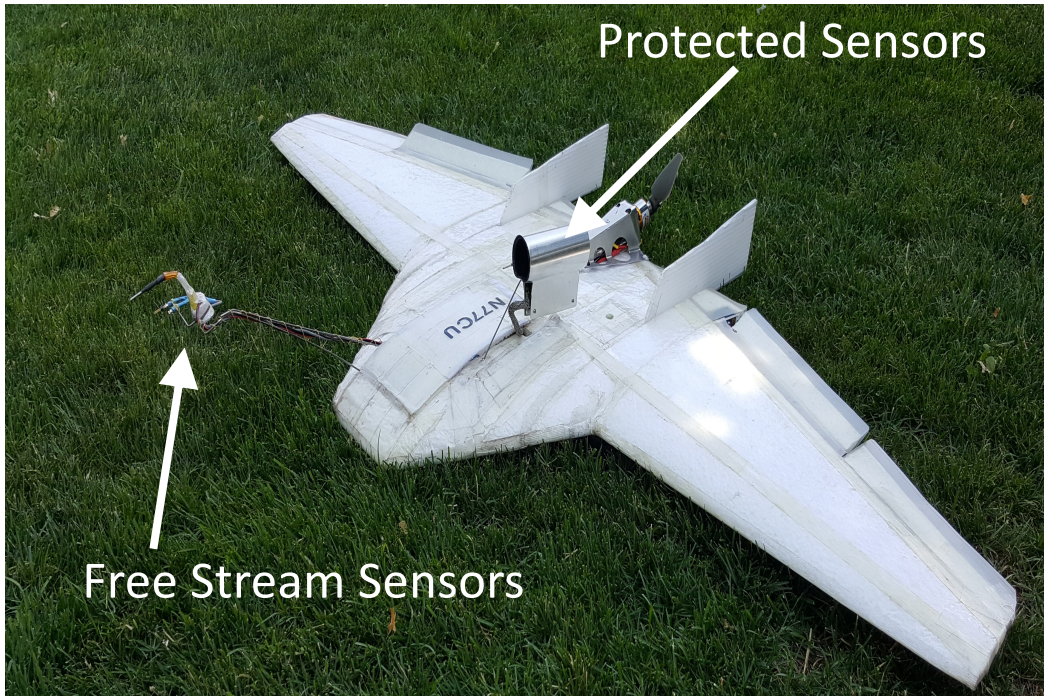
- Comparing extended shroud with small and large diameter
  - Average power in smaller shroud is slightly less
  - Easy to change the wires in case of breakage
- Flaring the shroud has no noticeable effect





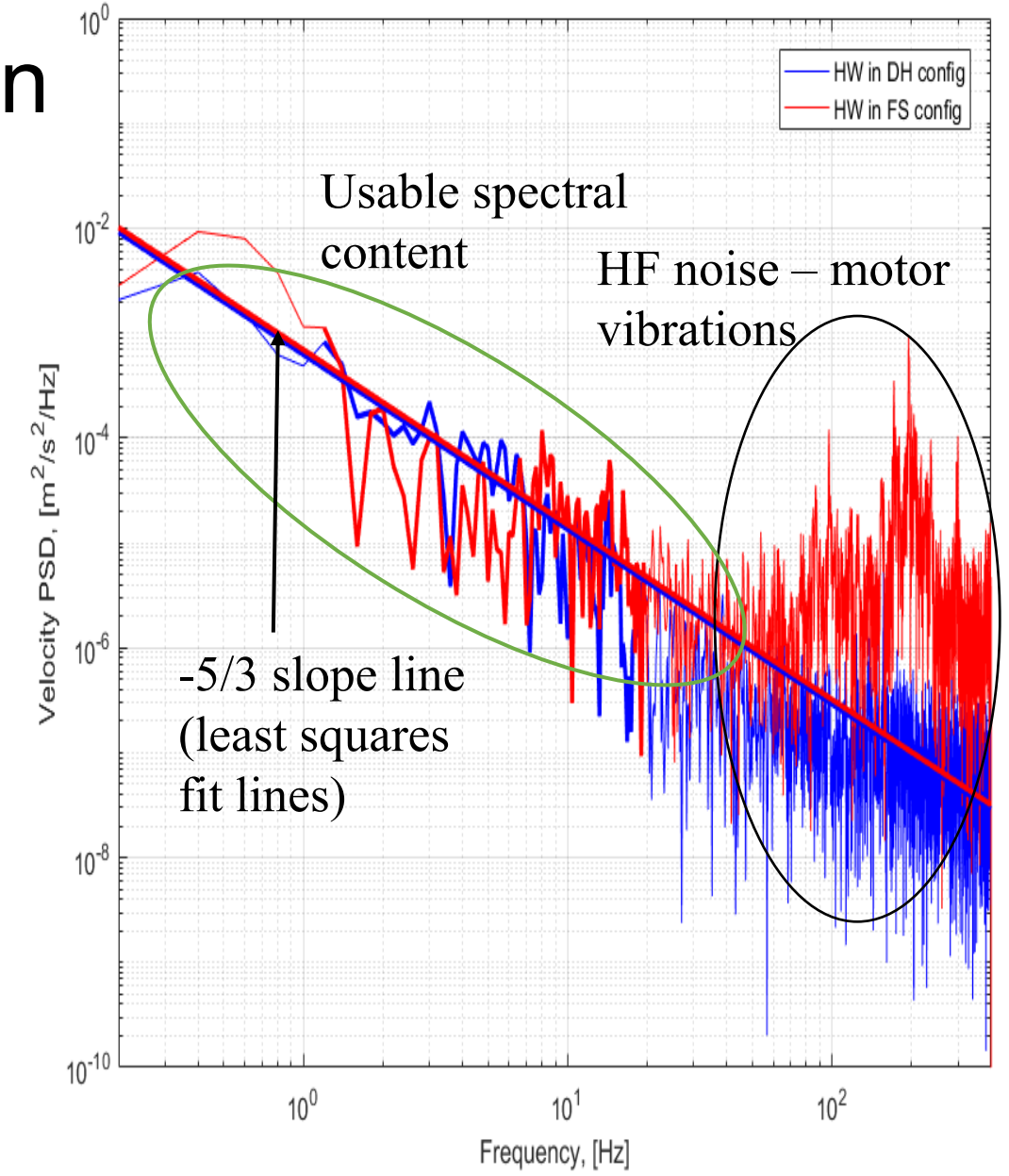
Effect of DH airframe

- Flight test with simultaneous measurements in the free atmosphere
- Sensors separation distance – 0.3m



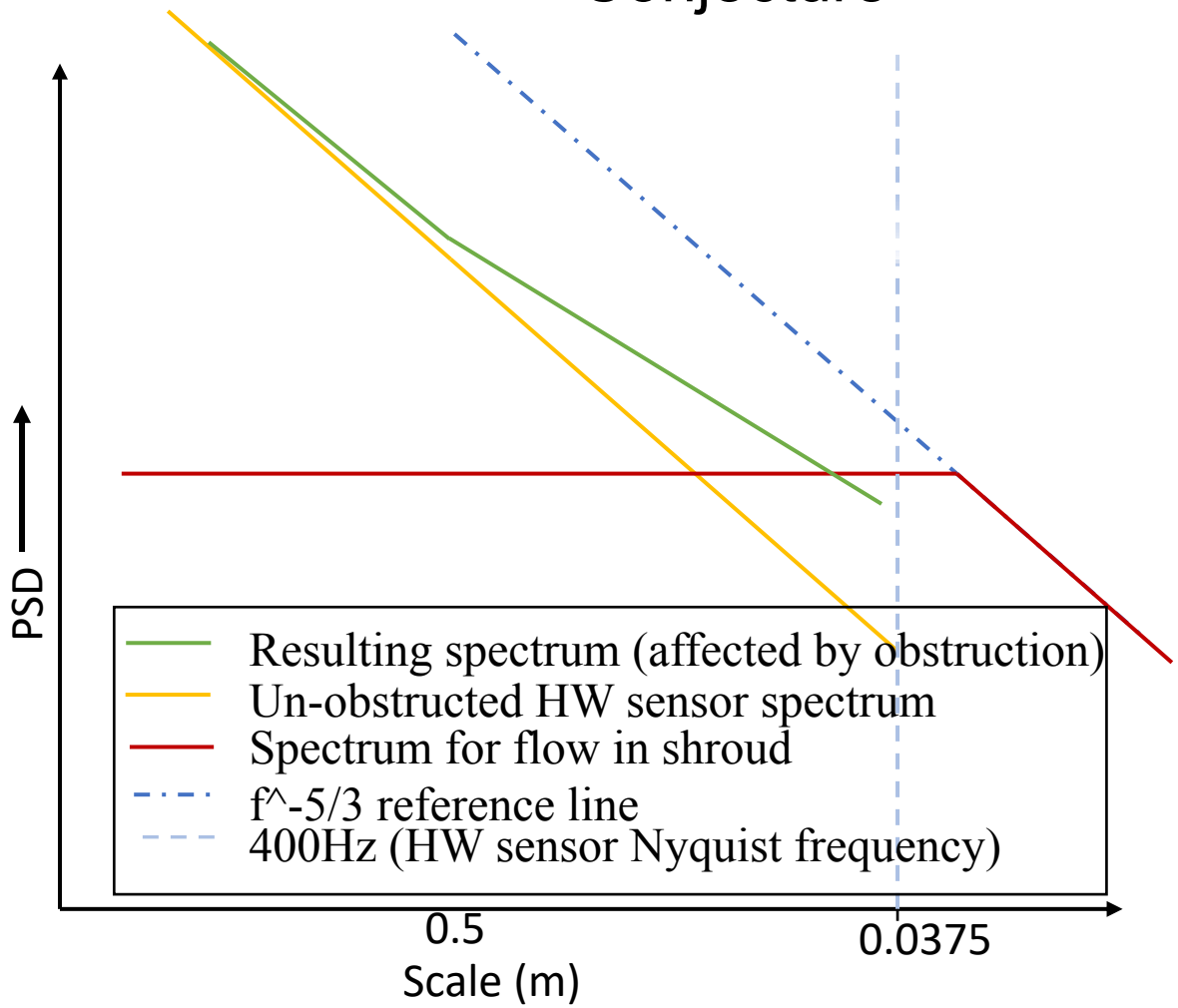
Free Atmosphere Characterization on DataHawk

- 80 spectral estimates (using 5 s time records)
- Both low and high turbulence conditions
- Mean PSD intensity reduction from FS to protected measurements = 8 %
- ε reduction factor 0.89 was obtained
- FS mount accentuates vibration artifacts (> 50 Hz)



Conclusion and Conjecture

Conclusion

- The protective schemes employed affect 0.5m scales and smaller
  - Shroud
  - Prongs
  - DataHawk body
- But these effects are predicted to affect millimeter scales only
- The study shows the effects extends to much larger scales than predicted

Conjecture