Computational Electromagnetics (CEM) Prediction of a Windmill

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Dr. Kueichien Hill and Capt. Gregory Zelinski
Air Force Research Laboratory

Dr. Tri Van*, Mr. Christopher Vogel
ATK Space Systems Inc.

* Formerly with ATK

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Acknowledgements

- **Dr. Nicole Evers (General Electric)**
  - GE windmill geometry CAD files
- **DoD High Performance Computing Modernization Program**
  - High performance computers (SGI Origin)

Outline

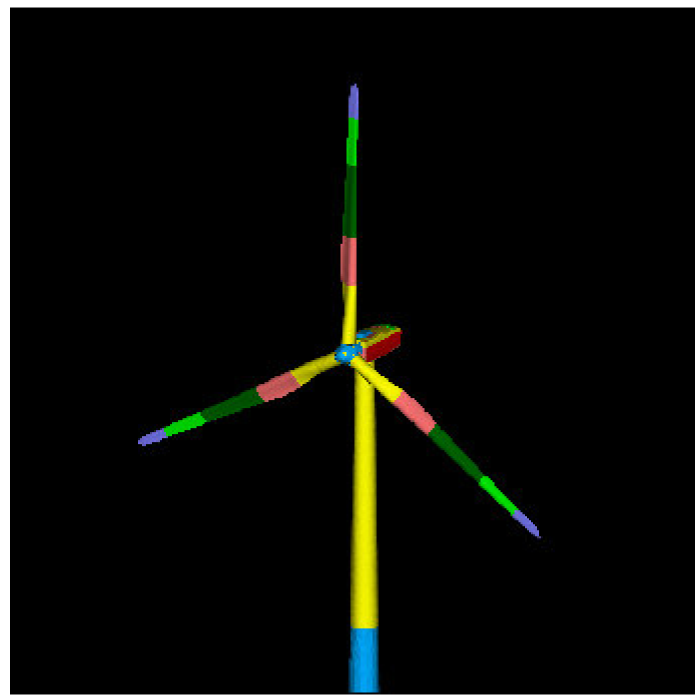
- **Objective of modeling effort**
- **Develop modeling procedure**
  - Generate geometry
  - Run CEM code
  - Generate RCS plots and Spectrograms
- **Validate modeling procedure**
  - L, S, C, X-band
  - Representative azimuth angles
  - Multiple elevation angles
    - L,S: -10º, - 5º, 0º, 5º, 10º
    - C,X: 0º only
- **Examine tradeoffs**
  - Multiple mesh densities
  - Entire geometry vs. only rotational parts
  - Sampling rate of rotational angles
  - Max Doppler estimation
- **Summary**

Objective of Windmill Modeling Effort

Determine if CEM tools can be used for new windmill designs with sufficient confidence to

- Assess RF environment impacts
- Avoid future need for field testing

General Electric Windmill

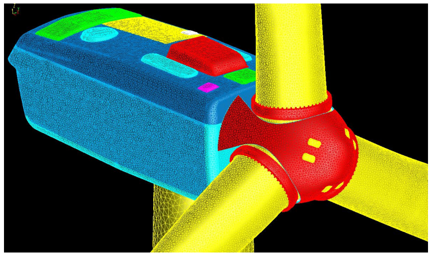


Windmill Model

Windmill Modeling

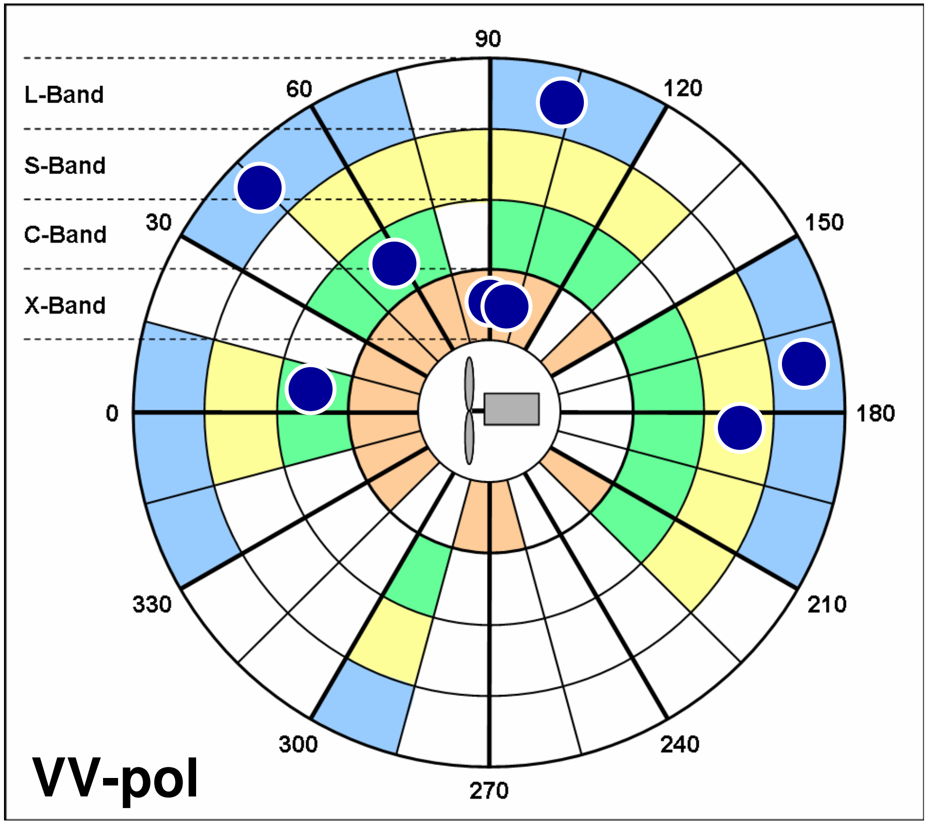
CEM predictions need to be accurate and timely.

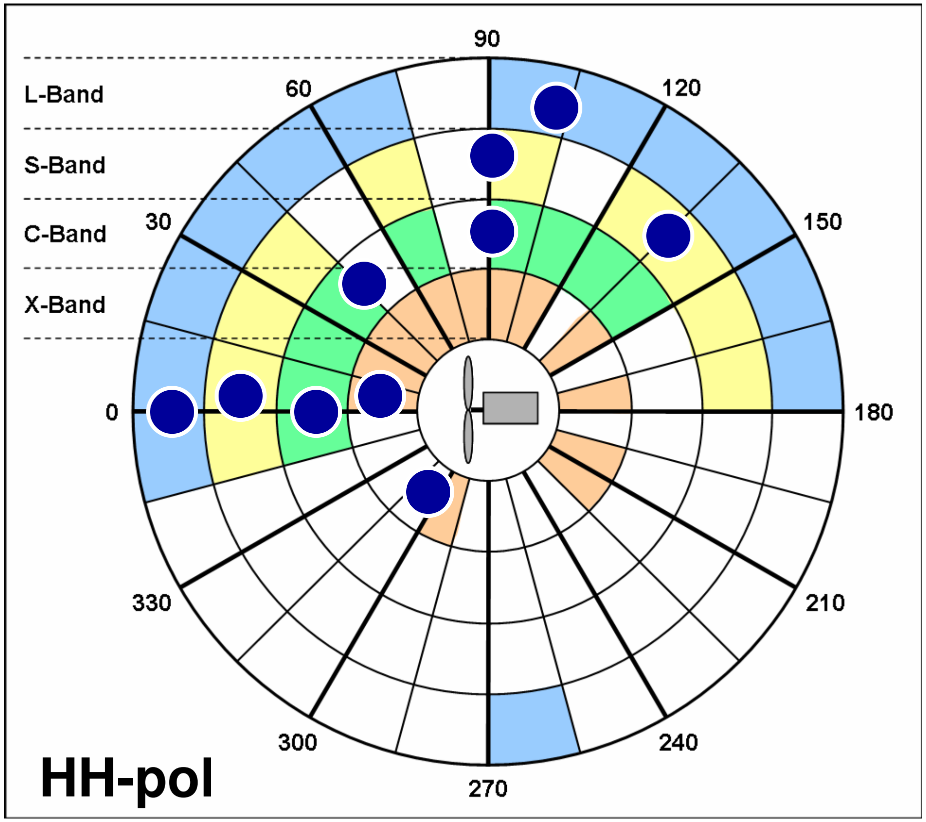
- **Accurate --- Can prediction reproduce measured data?**
  - Validate prediction with available measured data
    - Multiple bands: L, S, C, and X band
    - Multiple angles: azimuth and elevation
- **Timely --- Can we trade accuracy for speed?**
  - Do we need all the geometry fidelity?
    - True geometry with fine, medium, and coarse meshes
    - True geometry vs. simplified hub/nacelle/tower
  - Can we neglect blades and tower interaction?
    - Full geometry vs. rotational parts only
  - Can we reduce the blade rotational sampling rate?
    - 3 times Nyquist rate vs. 2 times Nyquist rate
  - Can we estimate the maximum Doppler frequencies?
    - Use a simple formulation



Windmill Modeling Matrix

Use available measured data to validate predictions



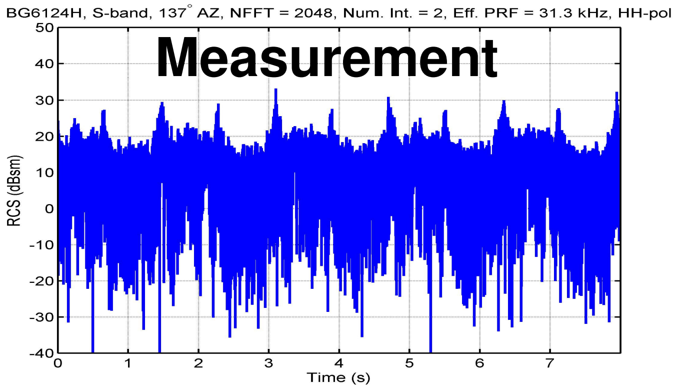


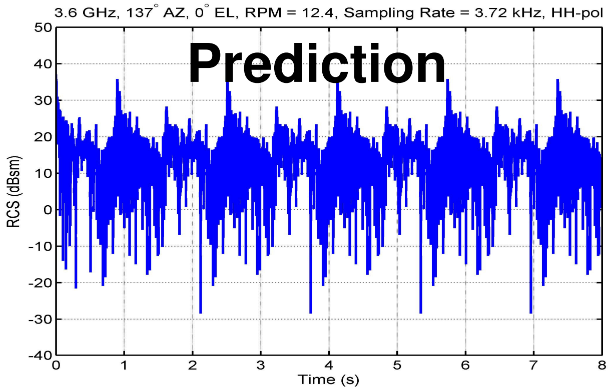
● Selected Prediction Angles and Frequencies

Windmill Modeling Validation

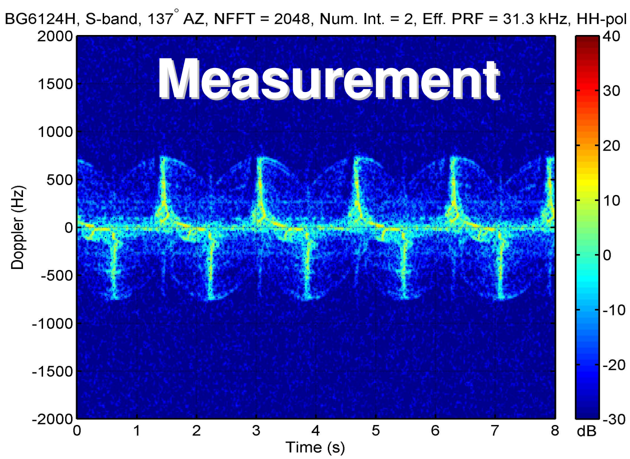
Compare measurement and prediction

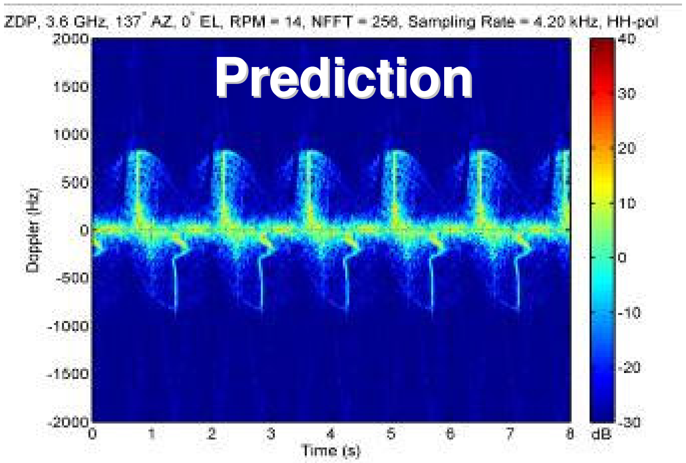
– Radar cross section (RCS) versus time





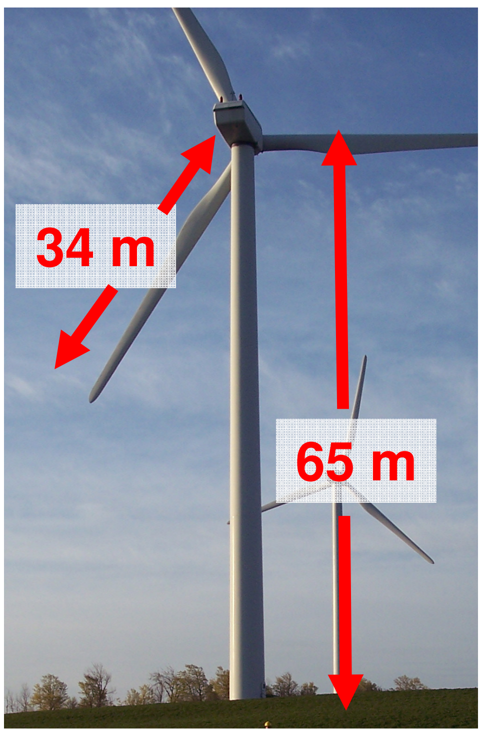
– Spectrograms (Doppler spectra versus Time)





CEM Prediction Tools

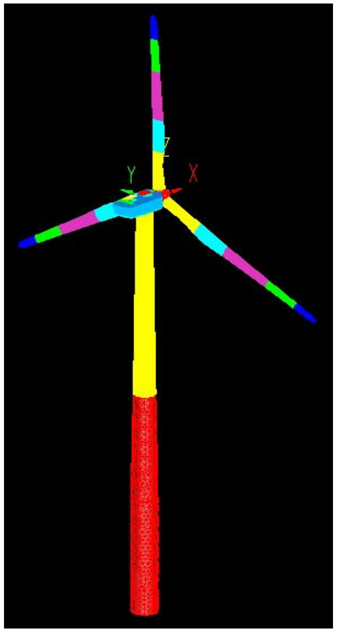
- **ACAD (CAD/mesh generation tool) is capable of producing**
  - High precision geometrical entities
  - High quality meshes suitable for CEM simulations



- **Xpatch (RCS prediction tool) is suitable for electrically large targets**
  - Windmill is electrically large even at the lowest frequency of interest
    - GE 34a blade is 170 λ long at 1.5 GHz
    - Tower is 325 λ long at 1.5 GHz

Windmill Modeling Procedure

- **Generate geometry input**
  - Obtain CAD model in “standard” file formats (STEP and IGES) from General Electric
  - Rebuild CAD model and generate mesh in **ACAD**
- **Material input assumption**
  - Physical blades made of composite materials
  - Assume metal blades for computation
- **Run CEM codes**
  - Predict RCS using the **Xpatch** code on SGI Origin 3900 computer systems
  - Include the effect of blades and tower interaction
  - Assume no traveling wave, surface wave, etc.
- **Generate output products**
  - RCS vs. time plots
  - Spectrogram



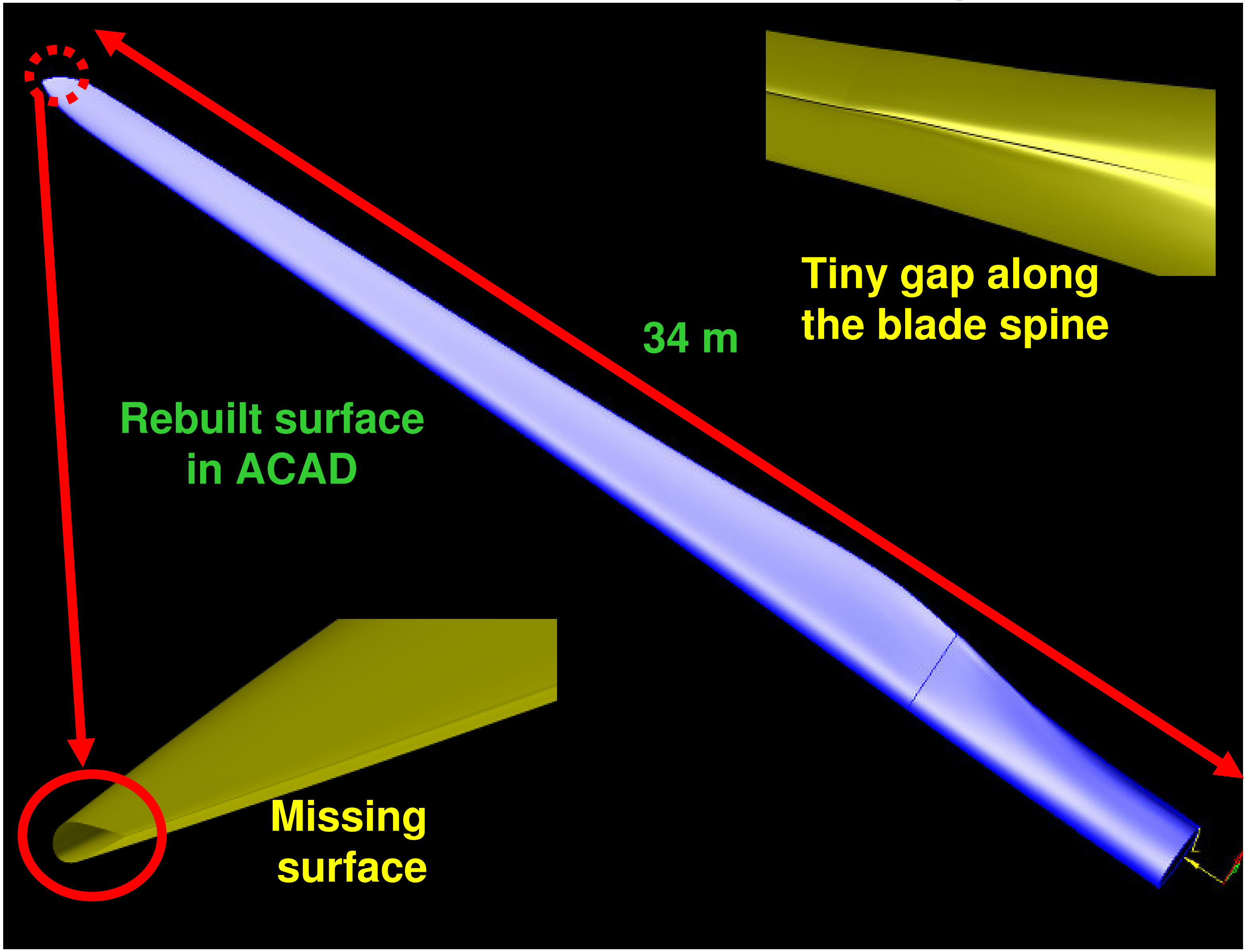
Windmill Model

SGI Origin 3900

Generate Geometry Input

Generate Geometry Input

Problem with CAD Geometry



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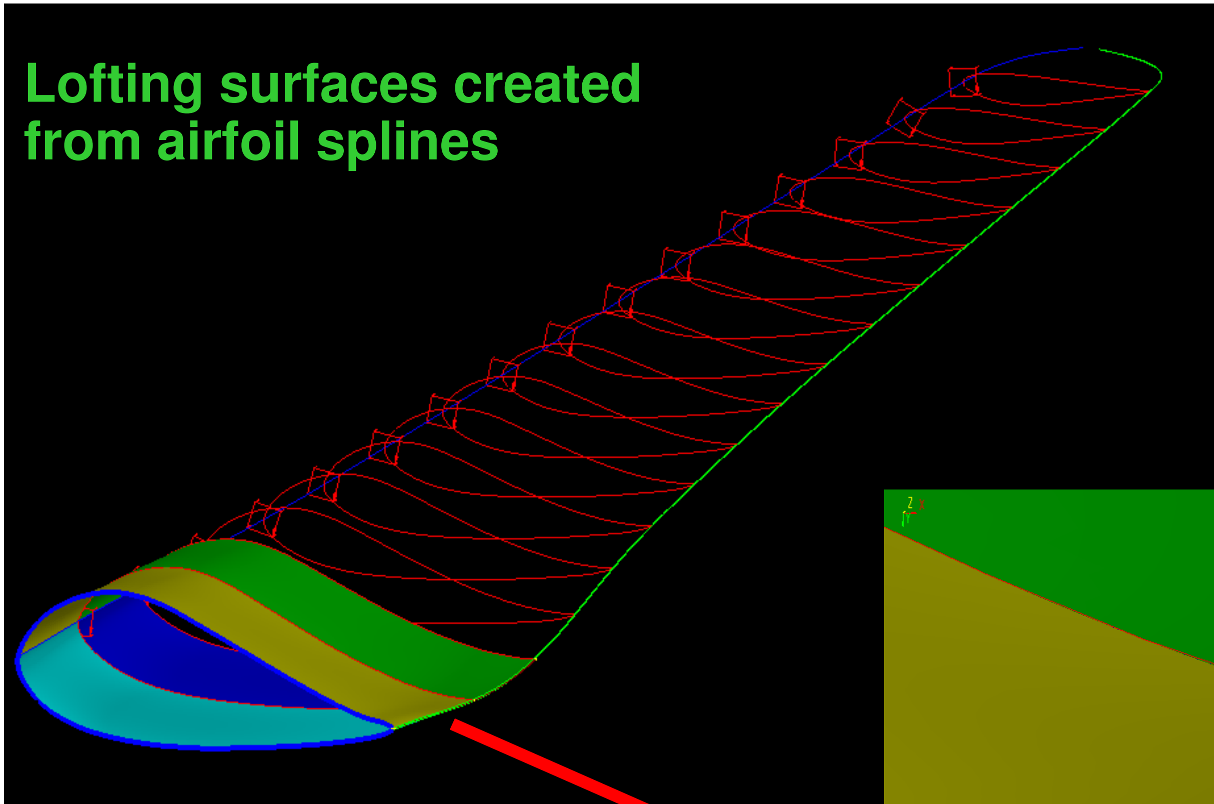
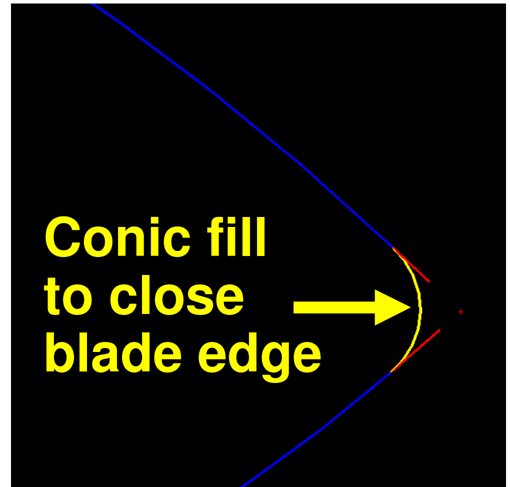
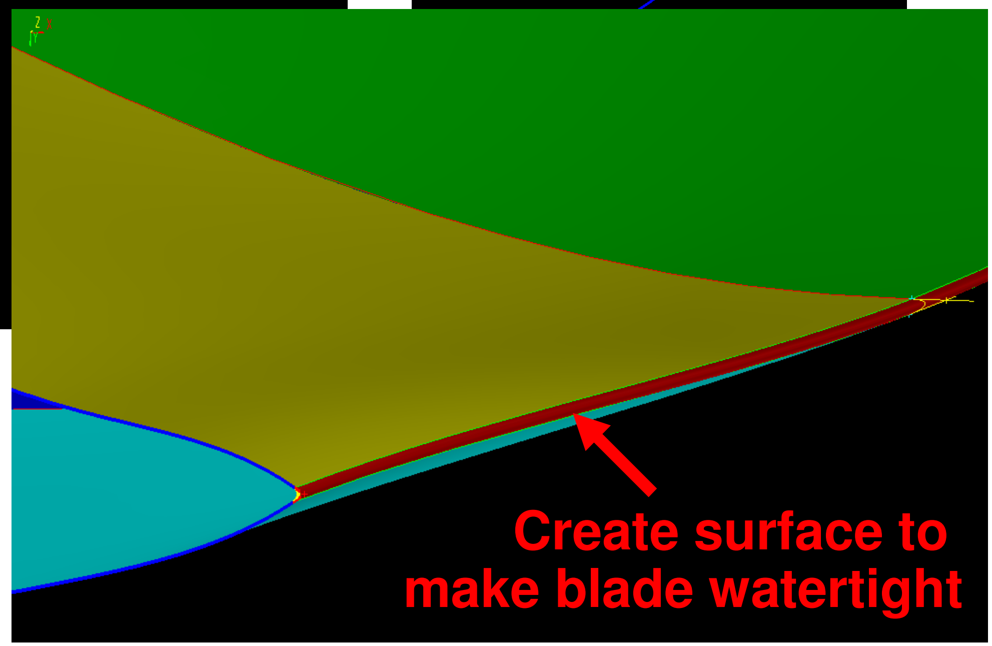
Generate Geometry Input

Lofting Surfaces in ACAD



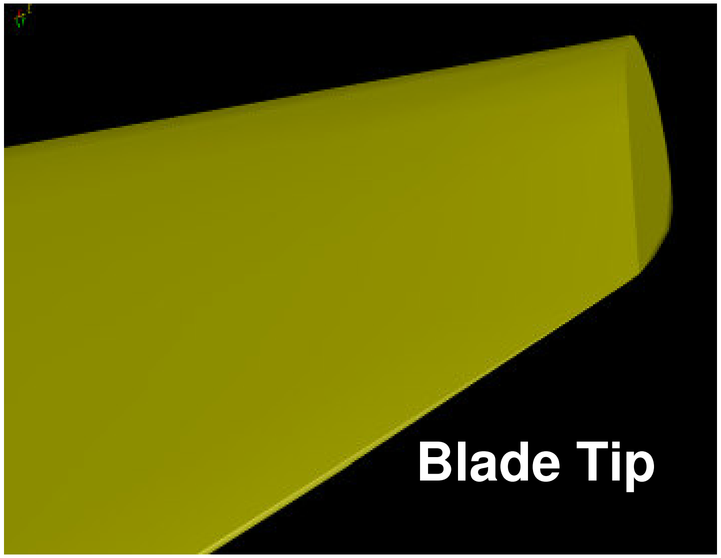


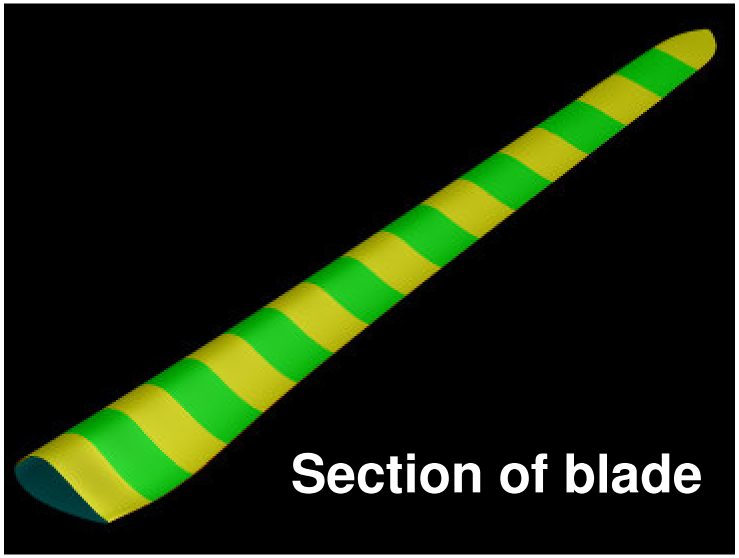
Surface needs to be watertight!

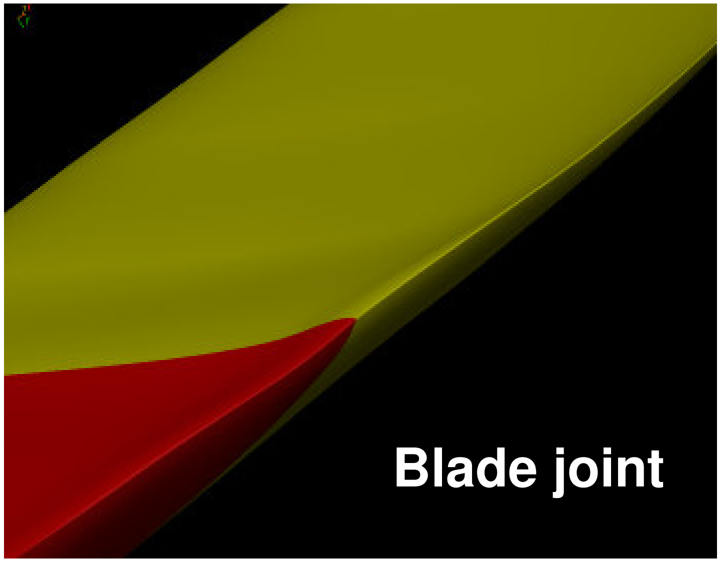


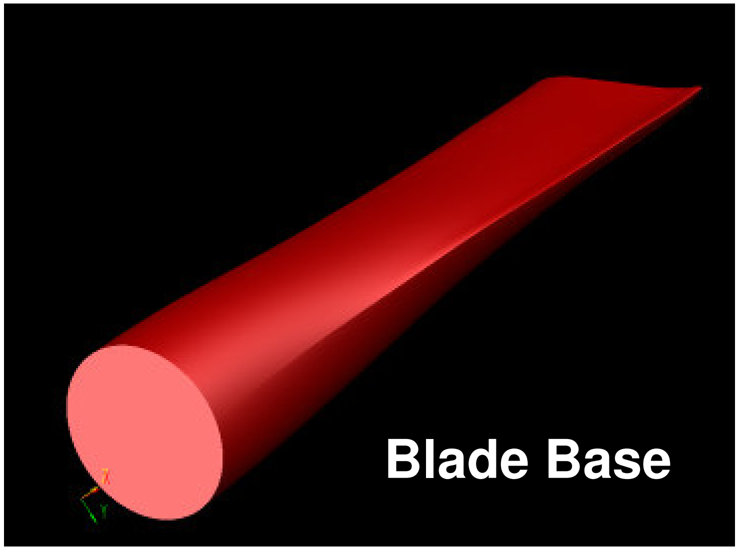
Generate Geometry Input

Rebuilt Blade in ACAD – Surface Needs to be Watertight



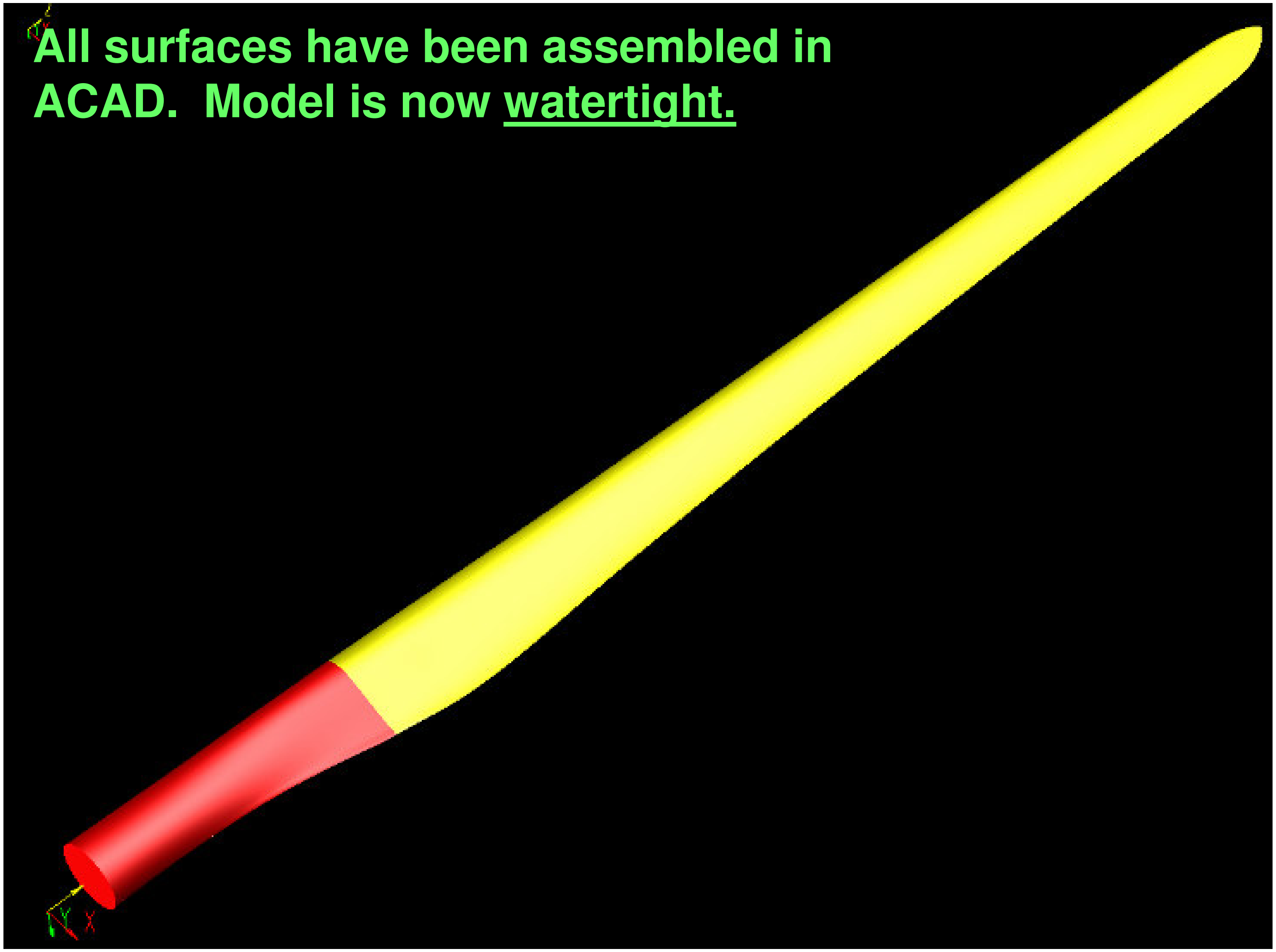






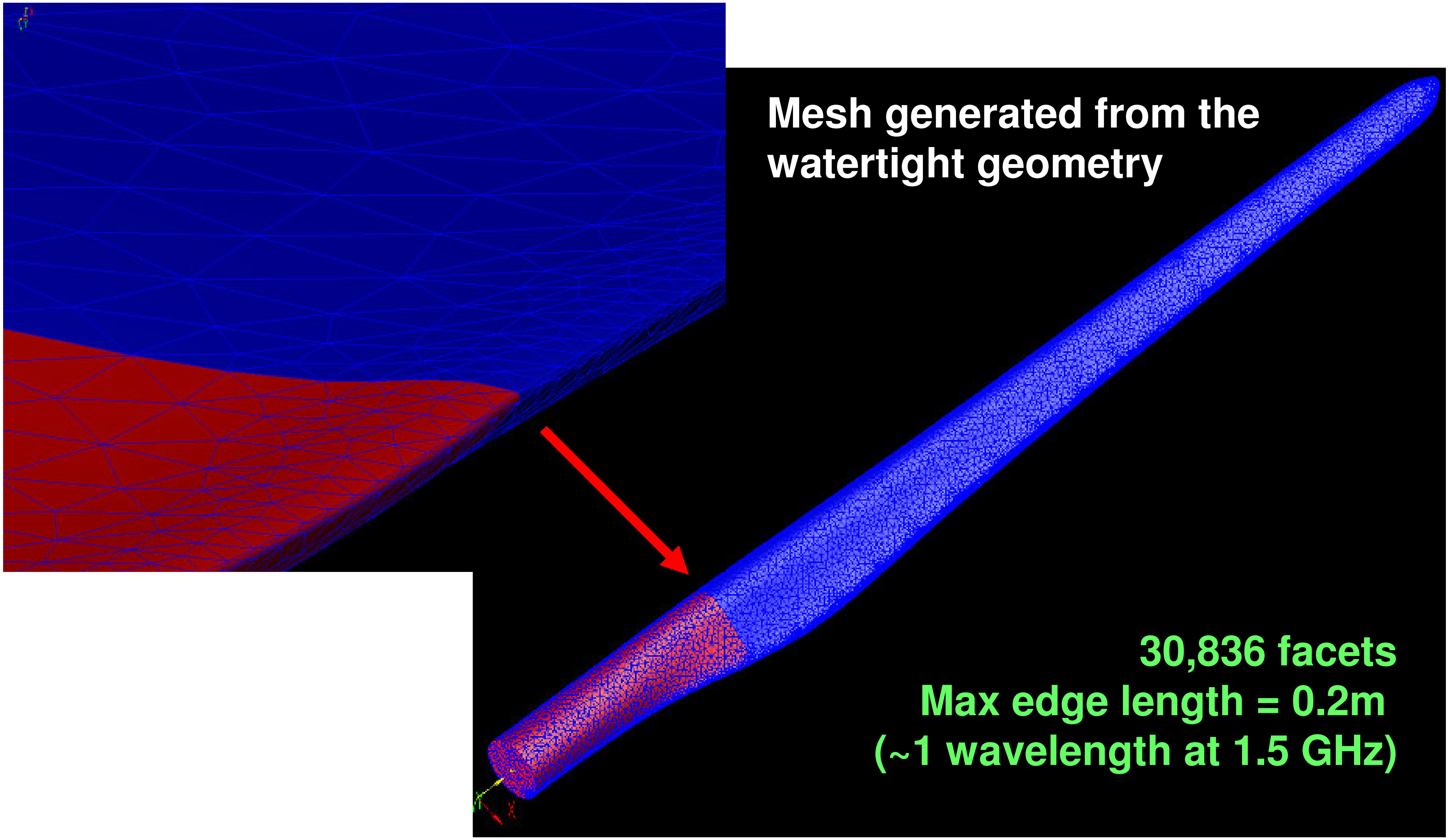
Generate Geometry Input

Rebuilt Blade in ACAD



Generate Geometry Input

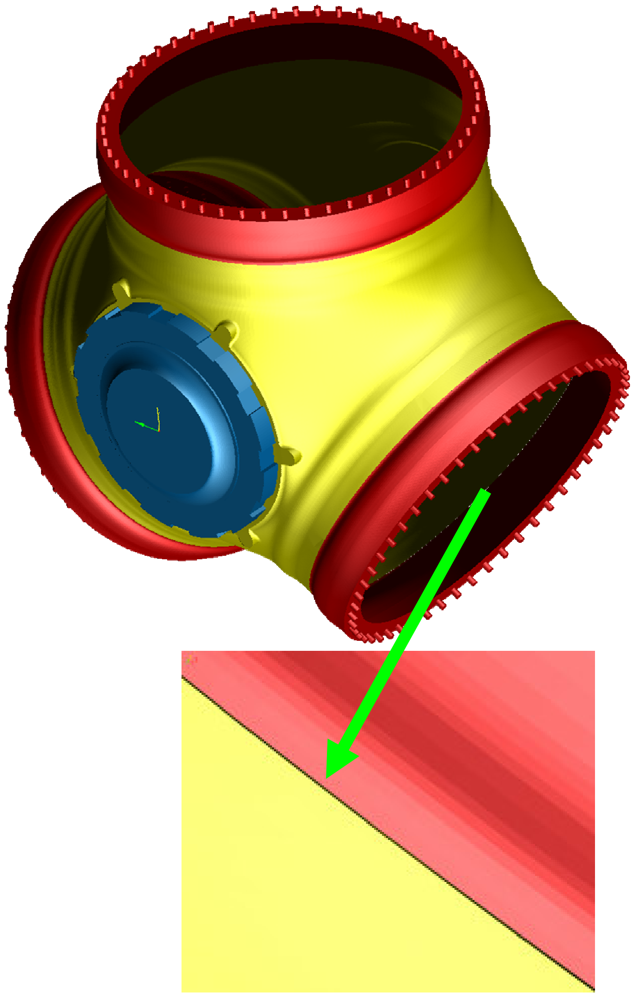
Mesh of a Blade

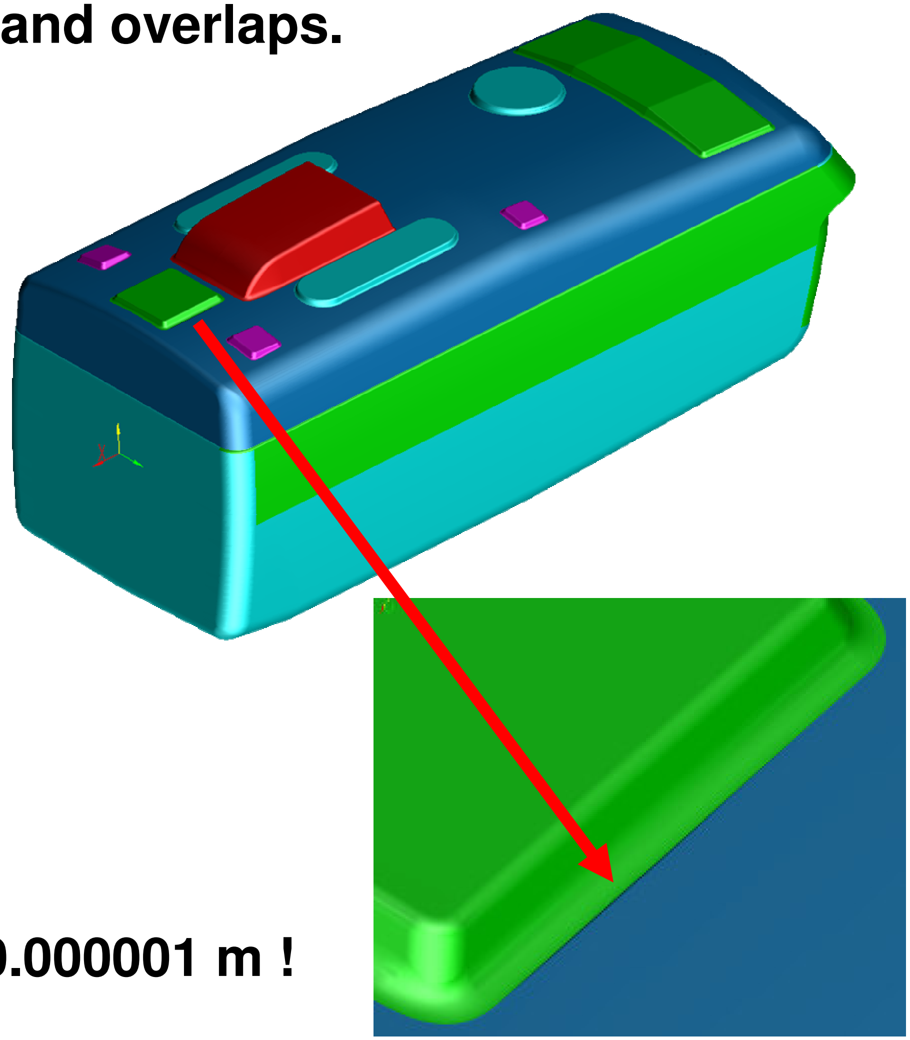


Generate Geometry Input

Problem with Nacelle and Hub

Even with extreme care, a mesh was not obtainable due to many "bad" surfaces with tiny slivers and overlaps.

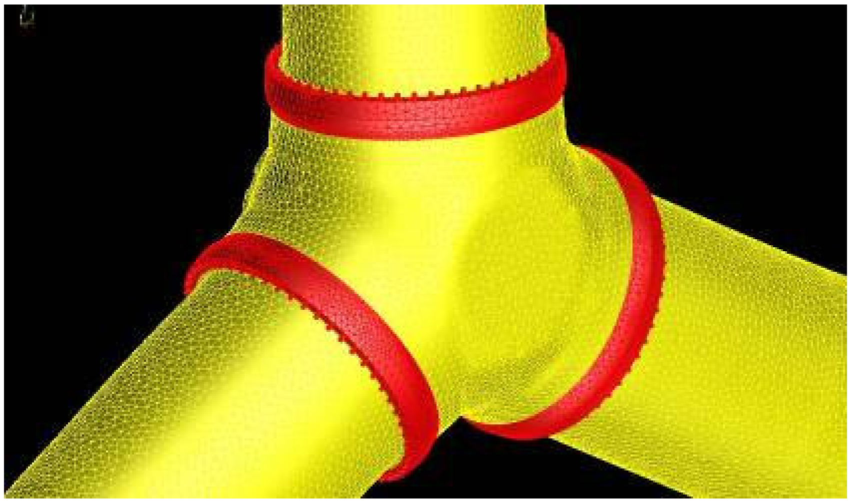


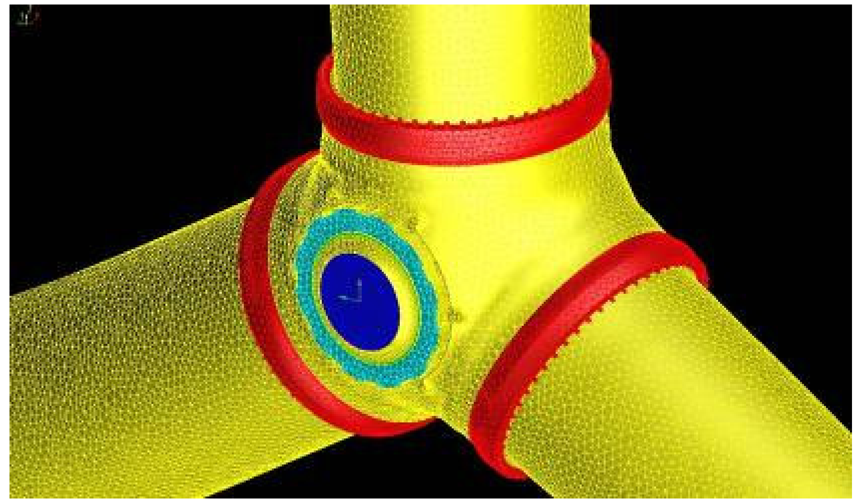


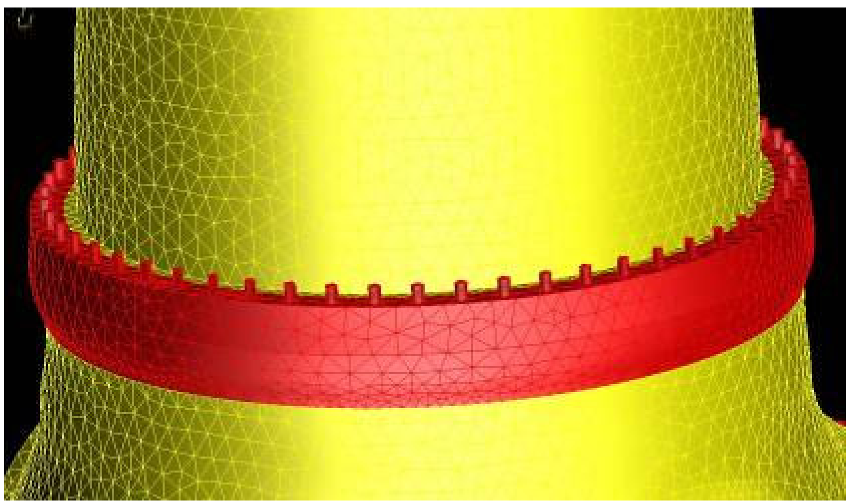
Gaps < 0.000001 m !

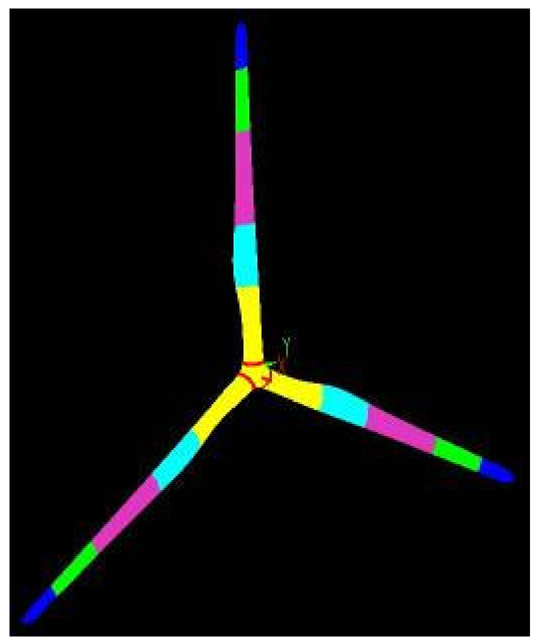
Generate Geometry Input

Hub and Blades Mesh



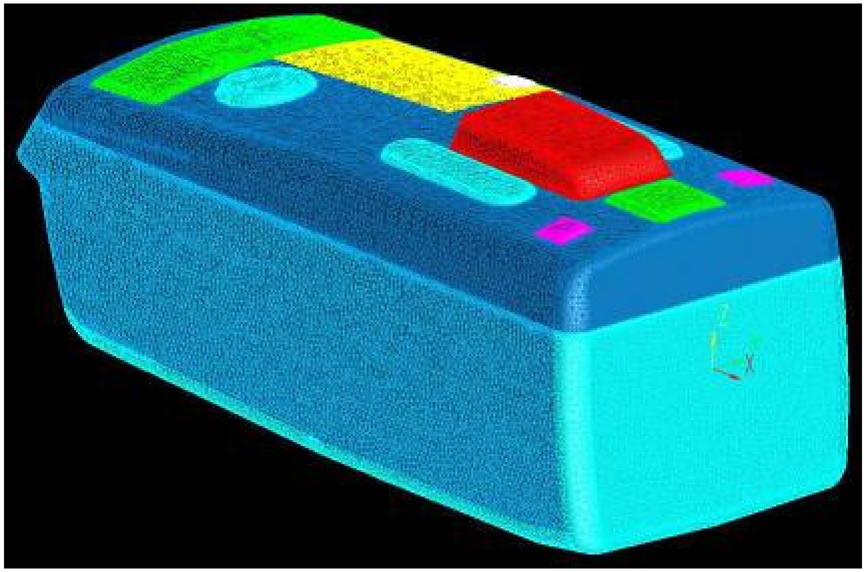


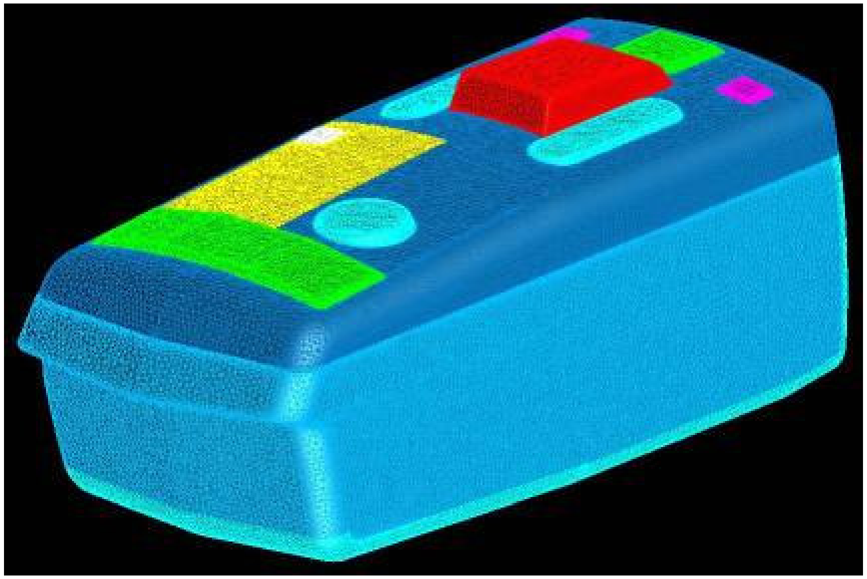


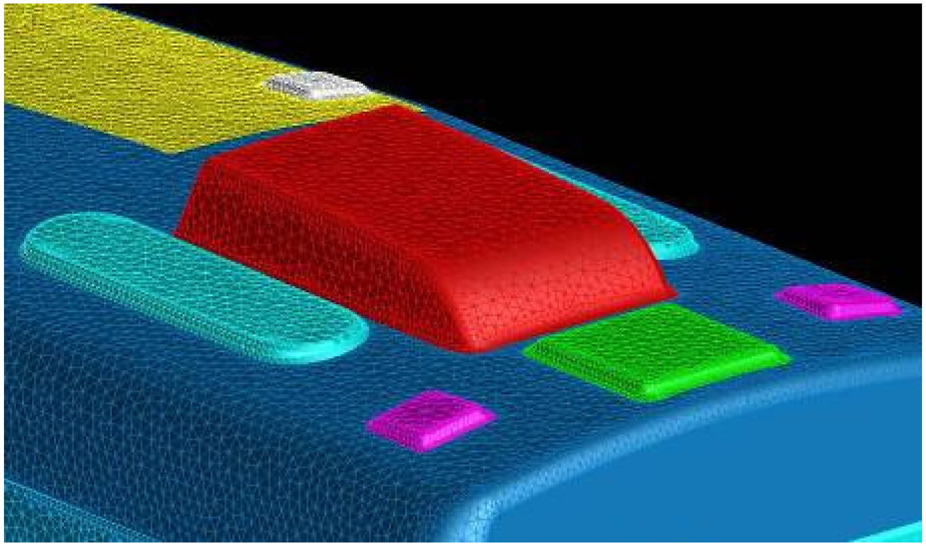


Generate Geometry Input

Nacelle Mesh

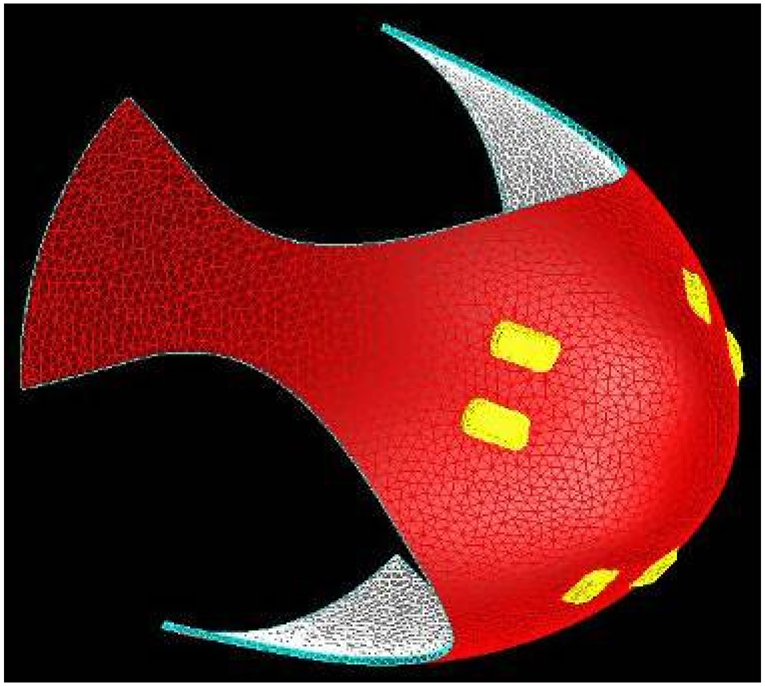


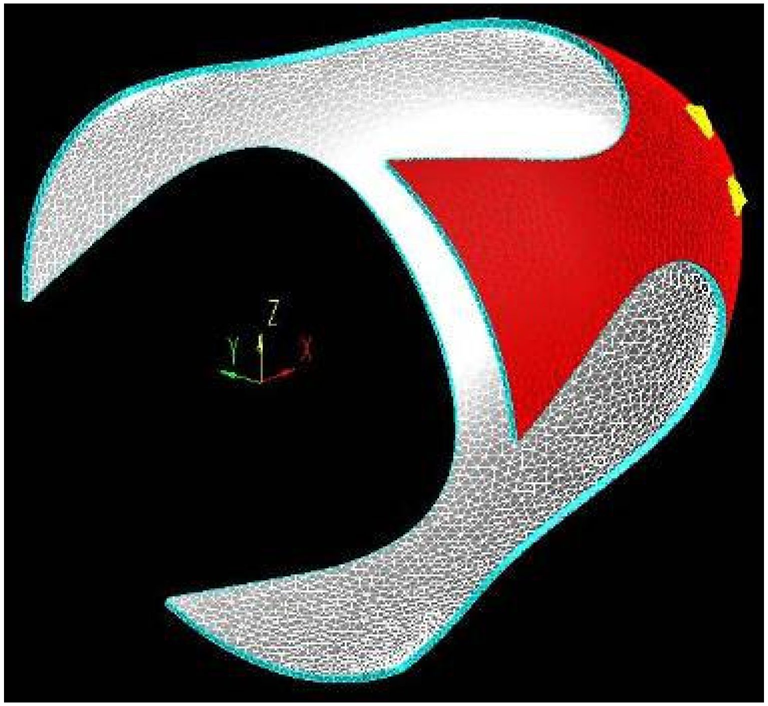




Generate Geometry Input

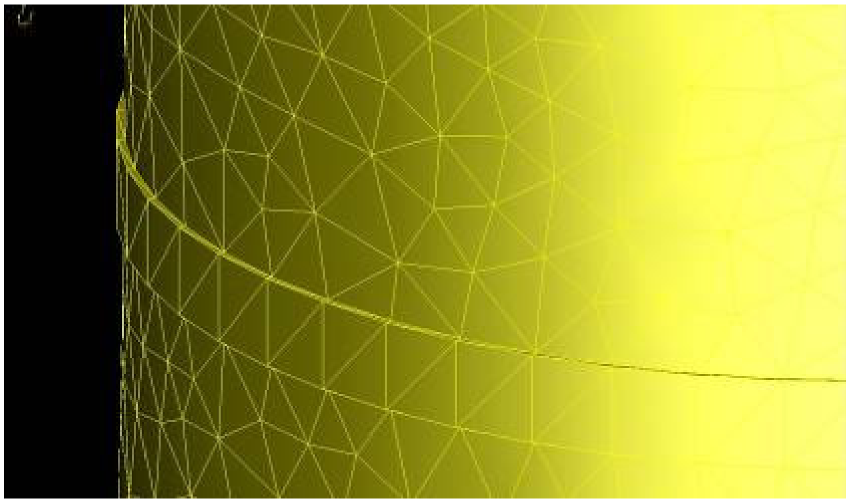
Nose Cone Mesh

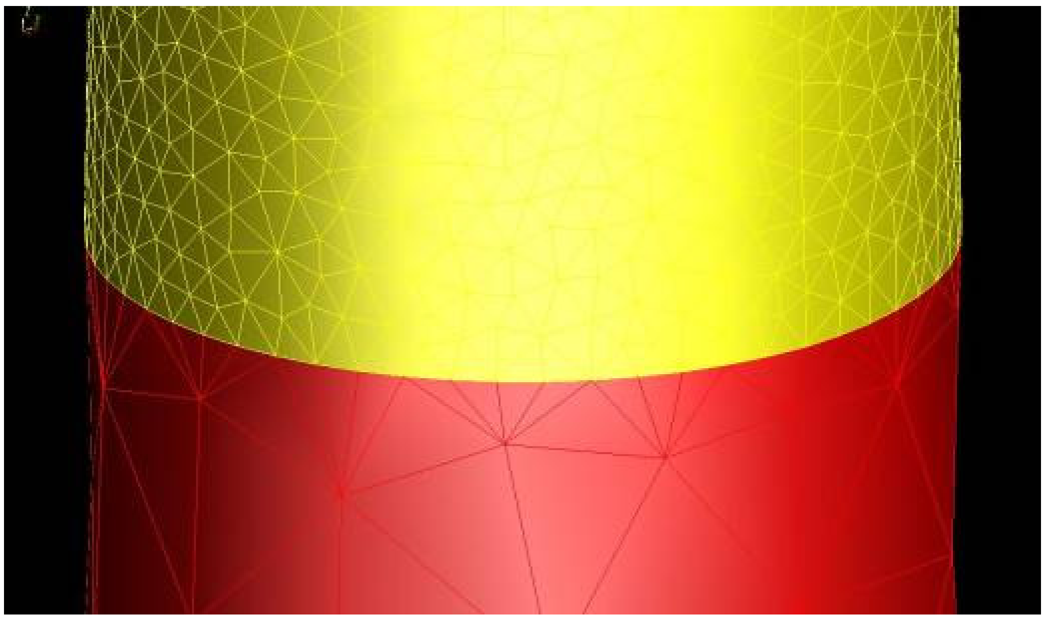




Generate Geometry Input

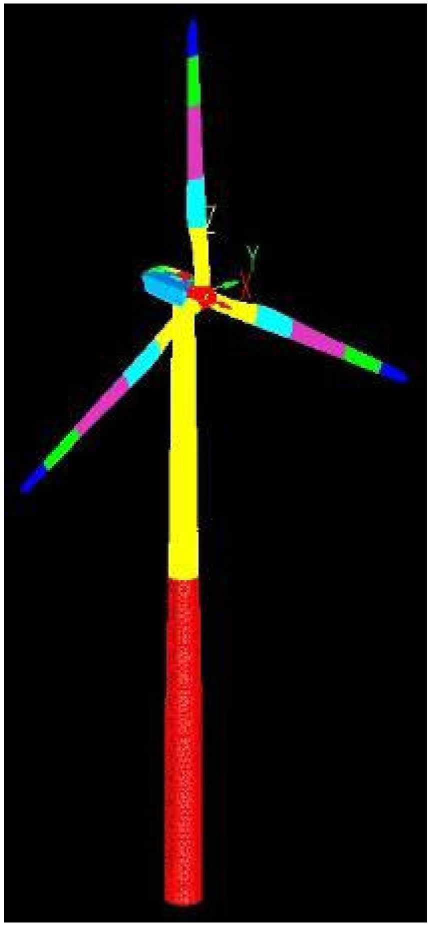
Tower Mesh

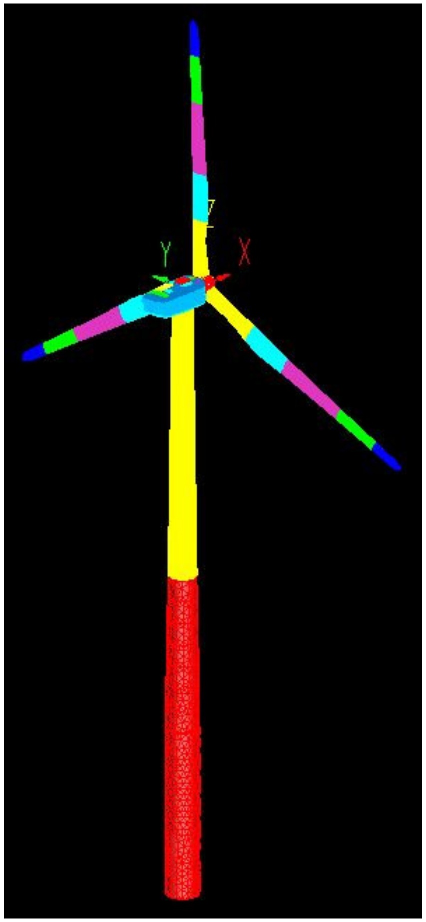


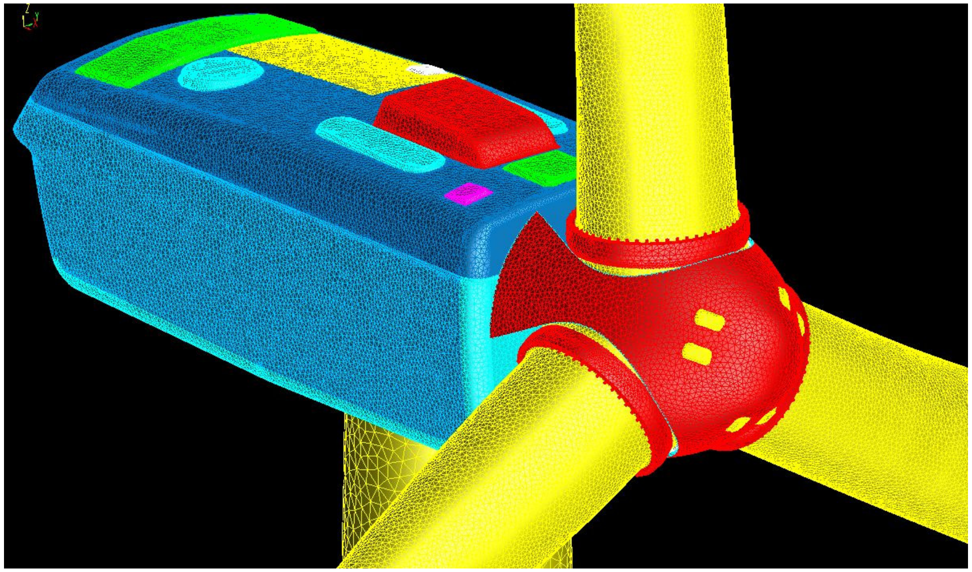


Generate Geometry Input

Windmill Mesh





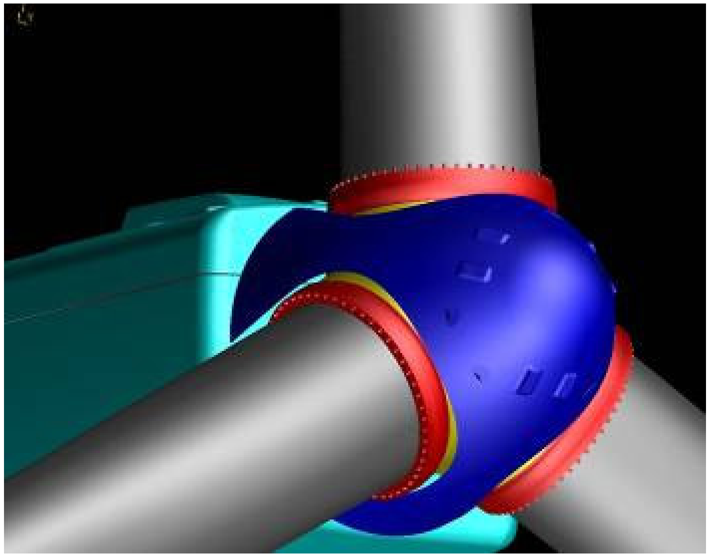


95% of imported models were rebuilt from basic entities such as points and splines!

Meshes of different densities can now be easily generated with the reconstructed geometry.

Generate Geometry Input
Actual vs. ACAD Model

Actual GE Wind Turbine



ACAD Model

Generate Geometry Input

Meshes Statistics

No. of facets	Mesh 1 (Coarse)	Mesh 2 (Medium)	Mesh 3 (Fine)
Nose Cone	2,641	7,293	15,543
Hub & Blades	56,586	140,514	279,284
Nacelle	18,774	45,588	86,098
Tower (fixed mesh)	22,730	22,730	22,730
Total	100,731	216,125	403,655

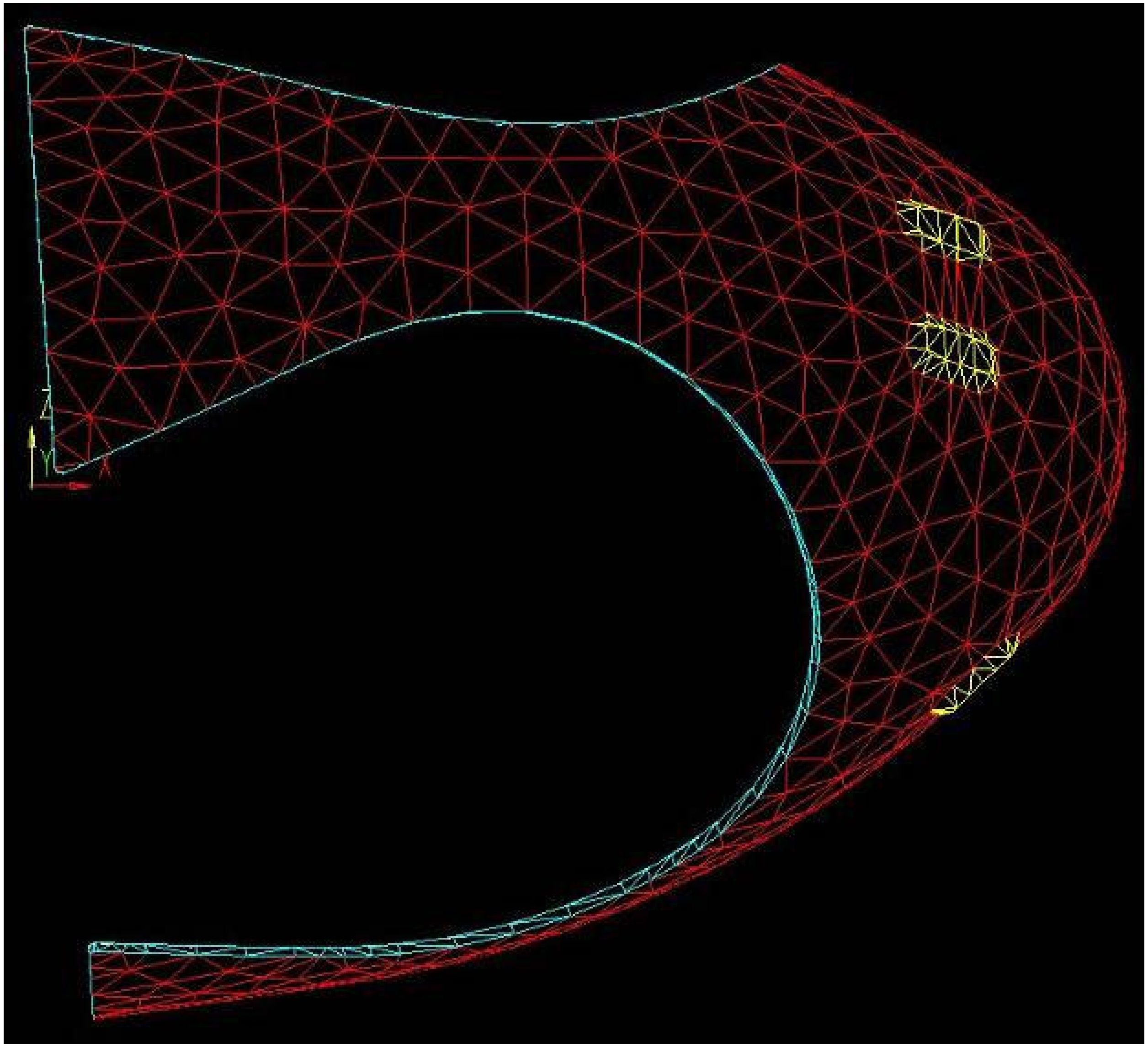
Generate Geometry Input

Meshes Statistics

	Mesh 1 (Coarse)	Mesh 2 (Medium)	Mesh 3 (Fine)
L-band (1.5 GHz)	Min: λ/6 Mean: λ/4.5 Max: λ/3	Min: λ/14.4 Mean: λ/10.8 Max: λ/7.2	Min: λ/23.2 Mean: λ/17.4 Max: λ/11.6
S-band (3.6 GHz)	Min: λ/2.4 Mean: λ/1.8 Max: λ/1.2	Min: λ/6 Mean: λ/4.5 Max: λ/3	Min: λ/9.3 Mean: λ/6.95 Max: λ/4.6
C-band (5.8 GHz)	Min: λ/1.5 Mean: λ/1.13 Max: λ/0.75	Min: λ/3.6 Mean: λ/2.7 Max: λ/1.8	Min: λ/6 Mean: λ/4.5 Max: λ/3
X-band (9.7 GHz)	Min: λ/0.9 Mean: λ/0.68 Max: λ/0.45	Min: λ/2.16 Mean: λ/1.62 Max: λ/1.08	Min: λ/3.48 Mean: λ/2.61 Max: λ/1.74

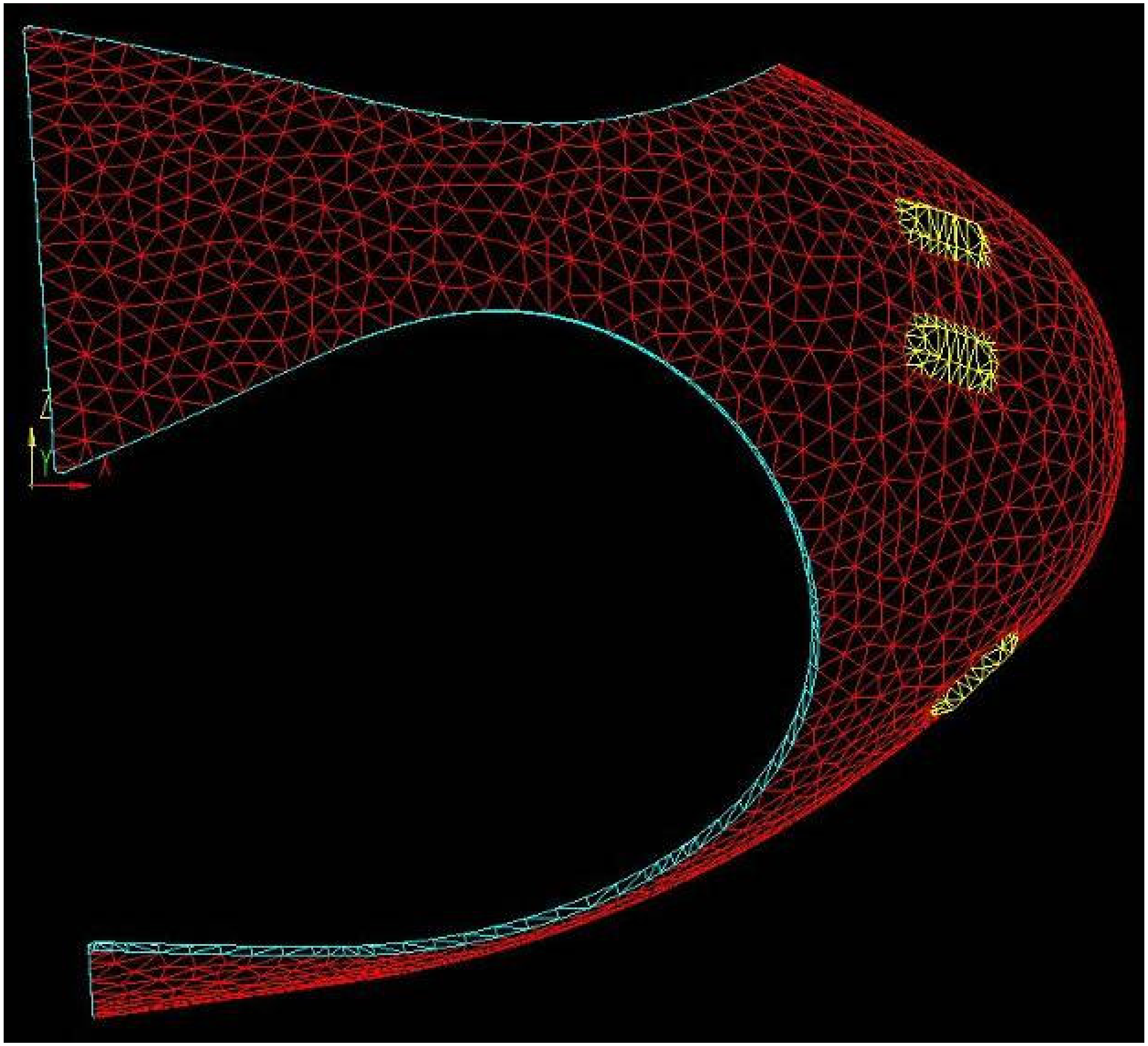
Generate Geometry Input

Nose Cone Coarse Mesh



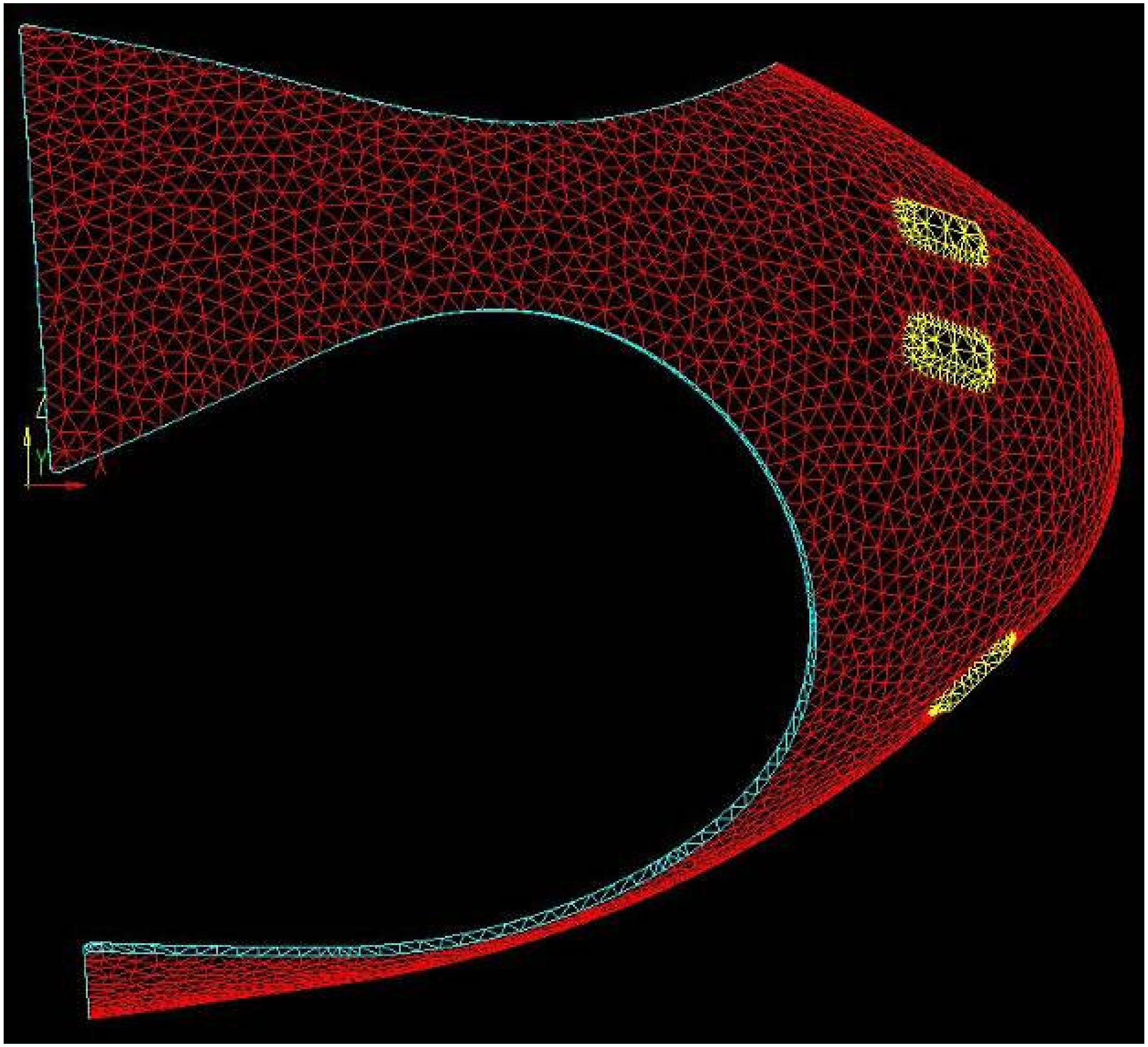
Generate Geometry Input

Nose Cone Medium Mesh



Generate Geometry Input

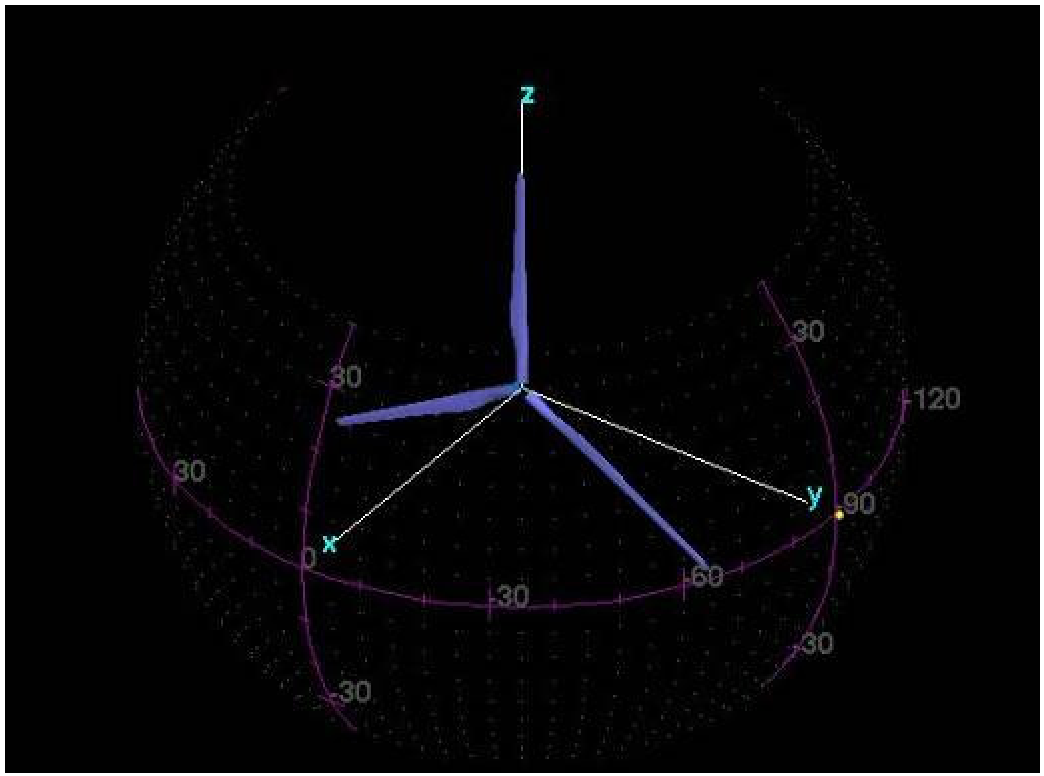
Nose Cone Fine Mesh



Run CEM Code - Xpatch

Blade Rotational Symmetry

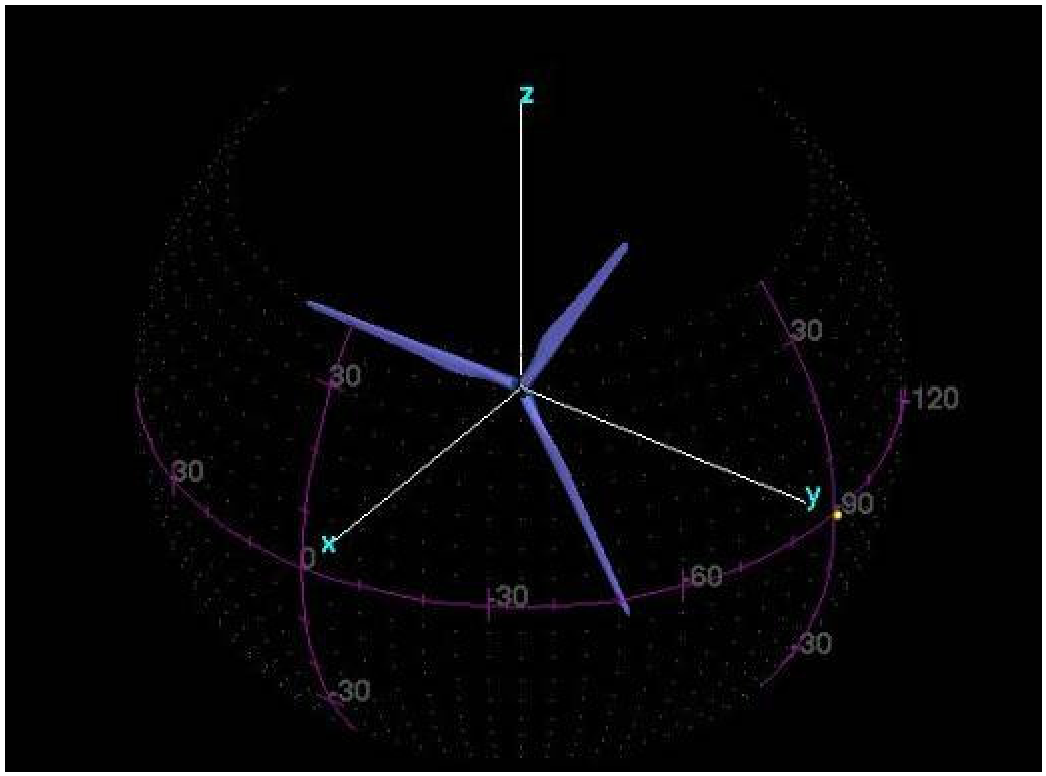
Need to compute only 0° to 120° rotation angles.



0° Rotation Angle

Blade Rotational Symmetry

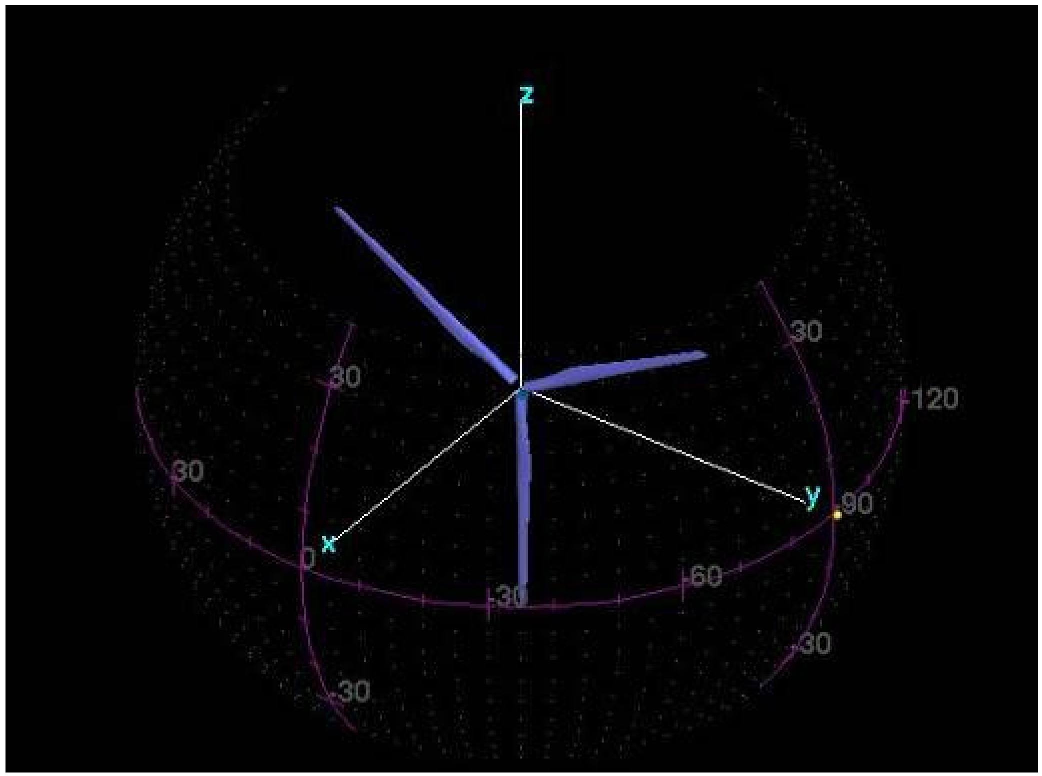
Need to compute only 0° to 120° rotation angles.



30° Rotation Angle

Blade Rotational Symmetry

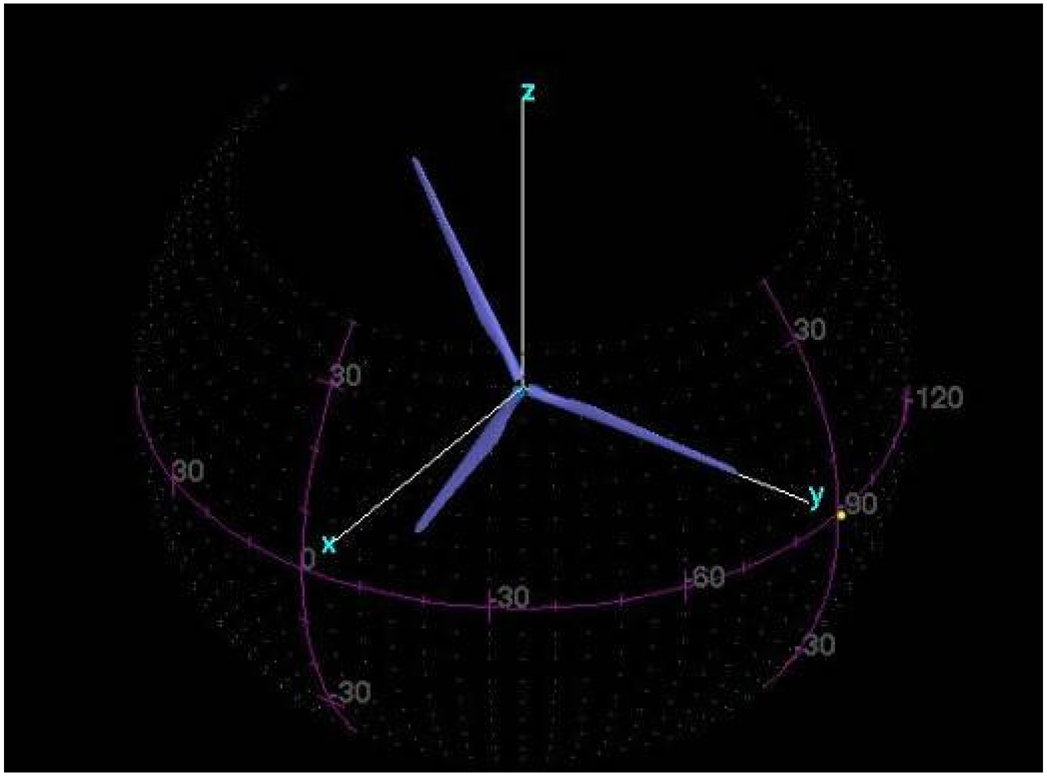
Need to compute only 0° to 120° rotation angles.



60° Rotation Angle

Blade Rotational Symmetry

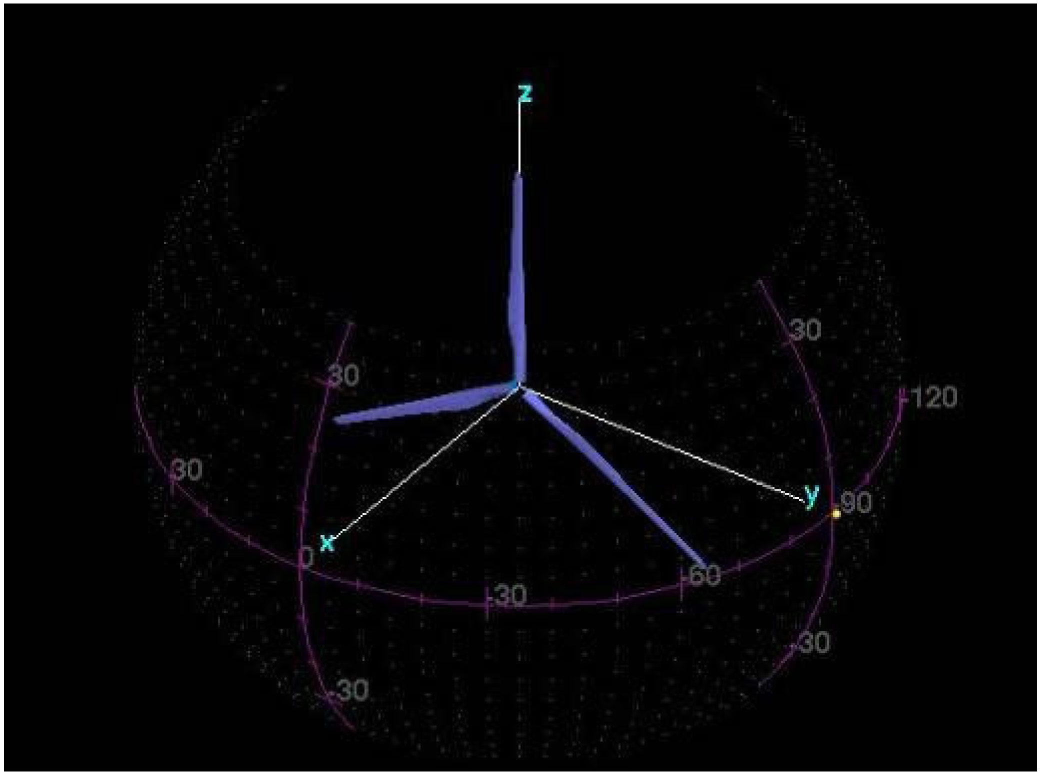
Need to compute only 0° to 120° rotation angles.



90° Rotation Angle

Blade Rotational Symmetry

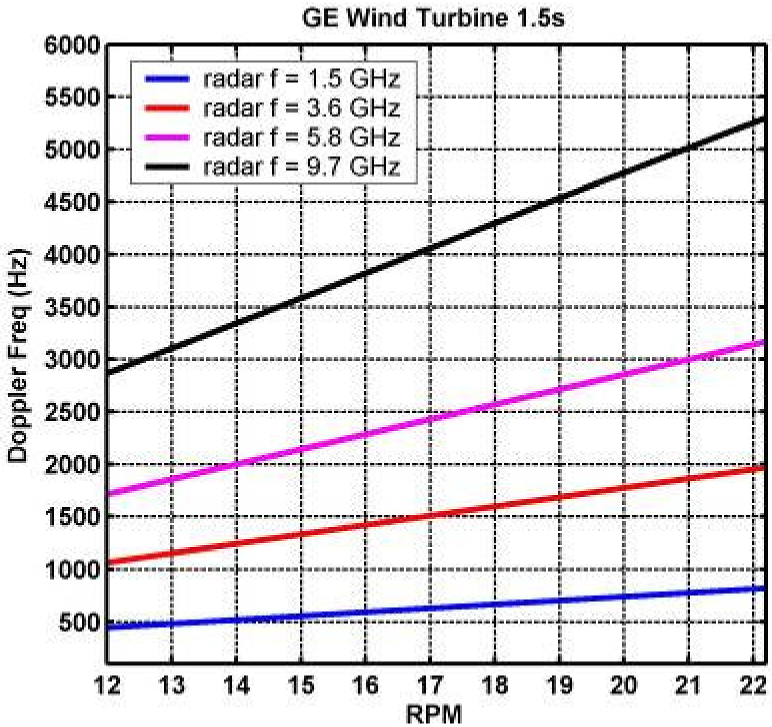
Need to compute only 0° to 120° rotation angles.



120° Rotation Angle

Blade Rotation Minimum Requirements

- To capture multi-bounces, sampling rate needs to be at least twice the Nyquist sampling rate.
- RPM can cause significant change in Doppler Frequency!



$$\text{Doppler Freq} = \frac{2 \text{ x Radial Velocity}}{\text{Wavelength}}$$

- **Nyquist sampling rate**
  - L-band: 1,500 angles
  - S-band: 3,428 angles
  - C-band: 6,000 angles
  - X-band: 12,000 angles
- **Computed *sampling rate***
  - L-band: **4,800** angles (every 0.025°)
  - S-band: **6,000** angles (every 0.02°)
  - C-band: **12,000** angles (every 0.01°)
  - X-band: **24,000** angles (every 0.005°)
    - Still being computed

Computational Matrix

SGI Origin 3900 for Coarse Mesh at 2x Nyquist Rate

Freq \ EL°	-10º	-5º	0º	5º	10º
L-band AZ° *4,801 runs per (EL,AZ)* *40 CPUs* *7 minutes/run*	0 (14 hrs) 46 (14 hrs) 100 (14 hrs) 170 (14 hrs) (2.3 days)	0 (14 hrs) 46 (14 hrs) 100 (14 hrs) 170 (14 hrs) (2.3 days)	0 (14 hrs) 46 (14 hrs) 100 (14 hrs) 170 (14 hrs) (2.3 days)	0 (14 hrs) 46 (14 hrs) 100 (14 hrs) 170 (14 hrs) (2.3 days)	0 (14 hrs) 46 (14 hrs) 100 (14 hrs) 170 (14 hrs) (2.3 days)
S-band AZ° *6,001 runs per (EL,AZ)* *60 CPUs* *40 minutes/run*	10 (24 hrs) 92 (24 hrs) 137 (24 hrs) 188 (24 hrs) (4 days)	10 (24 hrs) 92 (24 hrs) 137 (24 hrs) 188 (24 hrs) (4 days)	10 (24 hrs) 92 (24 hrs) 137 (24 hrs) 188 (24 hrs) (4 days)	10 (24 hrs) 92 (24 hrs) 137 (24 hrs) 188 (24 hrs) (4 days)	10 (24 hrs) 92 (24 hrs) 137 (24 hrs) 188 (24 hrs) (4 days)
C-band AZ° *12,001 runs per (EL,AZ)* *120 CPUs* *1.7 hours/run*	10 42 97 359	10 42 97 359	10 (63 hrs) 42 (63 hrs) 97 (63 hrs) 359 (63 hrs) (7 days)	10 42 97 359	10 42 97 359
X-band AZ° *24,001 runs per (EL,AZ)* *4.8 hours/run*	5 96 101 310	5 96 101 310	5 96 101 310	5 96 101 310	5 96 101 310

Validation:
Compare Measured and Xpatch Predicted
RCS vs. Time

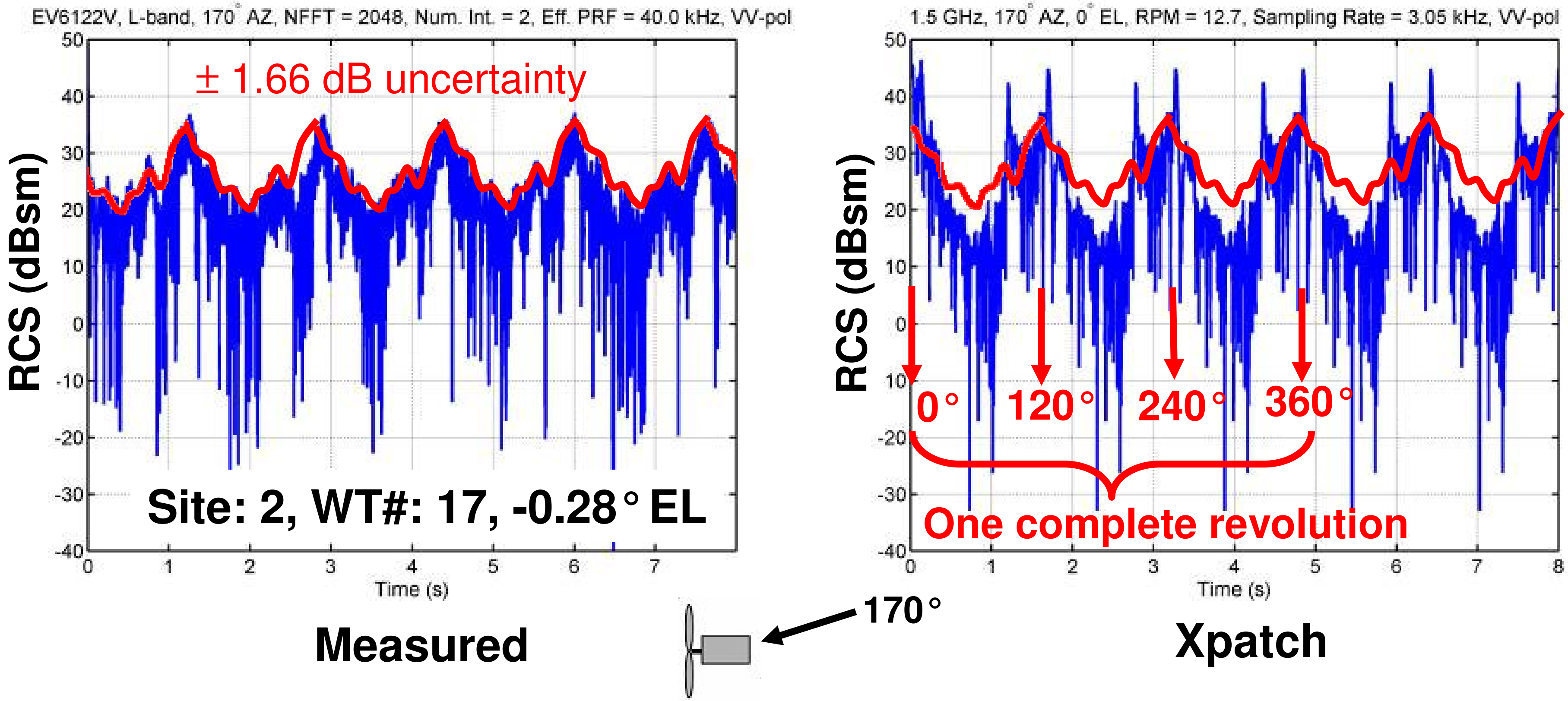
L-Band – Coarse Mesh with 4,800 blade rotations
S-Band – Coarse Mesh with 6,000 blade rotations
C-Band – Coarse Mesh with 12,000 blade rotations

Note: Measured and Predicted data are zero-Doppler filtered

Measured vs. Predicted RCS

L-band, 170° AZ, 0° EL, RPM = 12.7, VV-pol

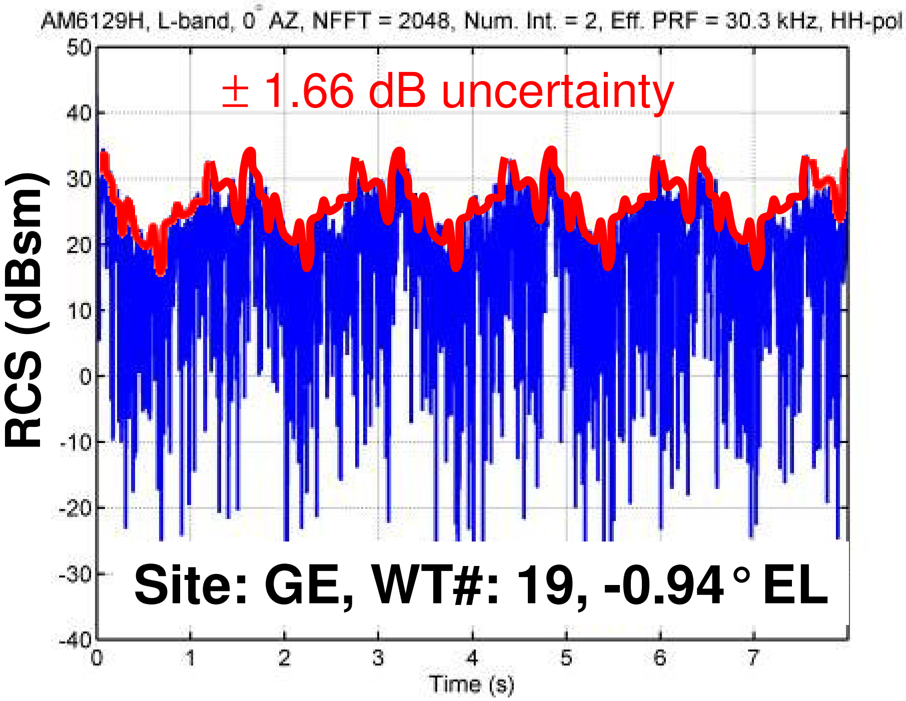
- Prediction captures the measurement pattern
- Predicted RCS levels comparable with measured RCS
- Spikes in the prediction are artifact due to coarse mesh sampling
- Elevation and pitch angles differ for measurement and prediction
- Fiberglass was modeled as metal in prediction



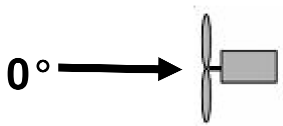
Measured vs. Predicted RCS

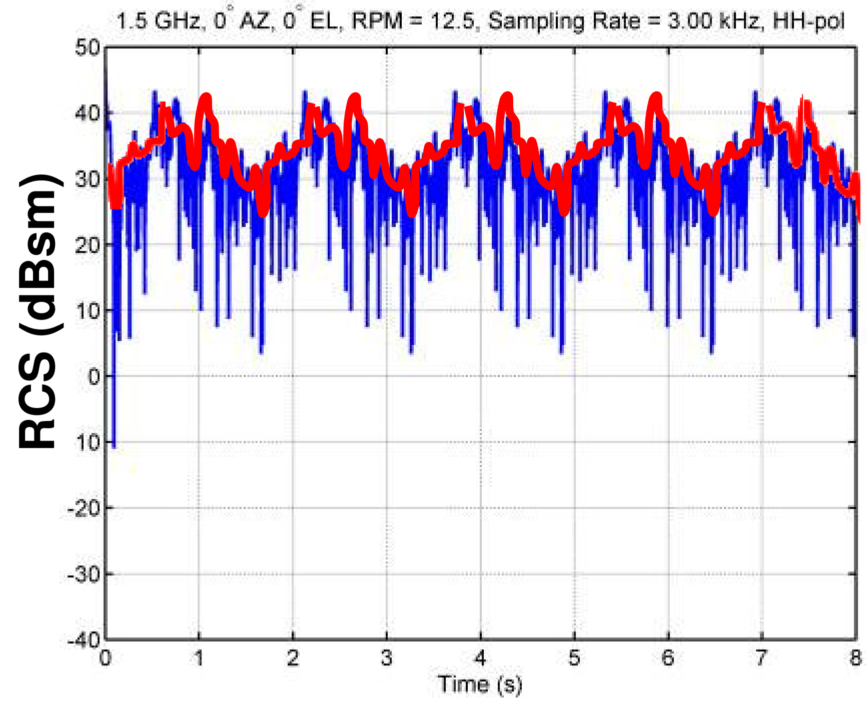
L-band, 0° AZ, 0° EL, RPM = 12.5, HH-pol

- Prediction captures the measurement pattern
- Blades are flexible in measurement but fixed in prediction
- Elevation and pitch angles differ for measurement and prediction.
- Fiberglass was modeled as metal in prediction



Measured



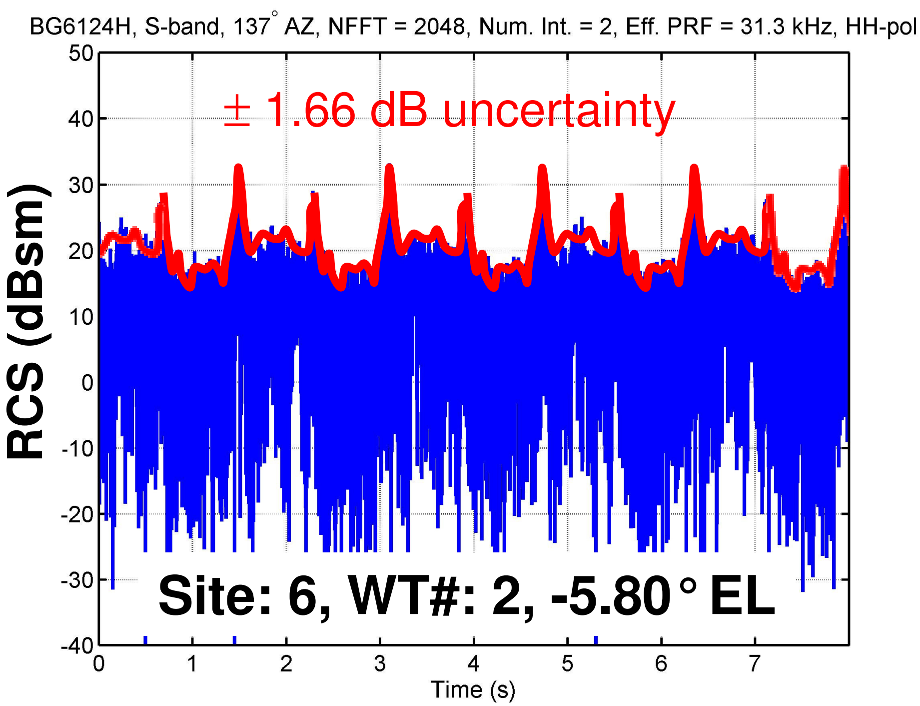


Xpatch

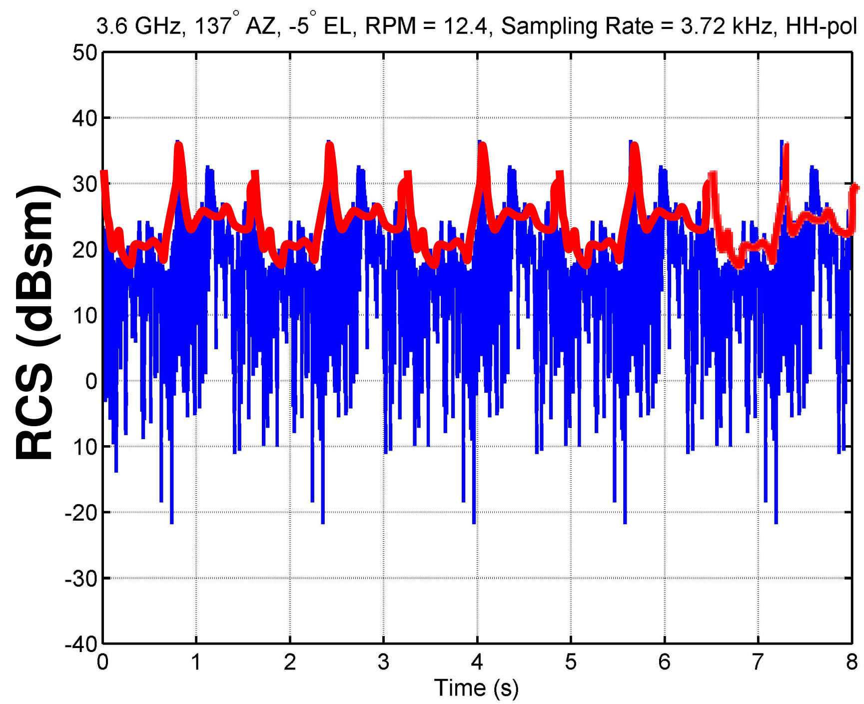
Measured vs. Predicted RCS

S-band, 137° AZ, -5° EL, RPM = 12.4, HH-pol

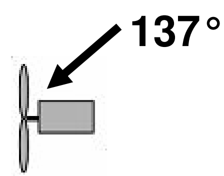
- Prediction captures the measurement pattern
- RCS levels within measurement uncertainty
- Elevation and pitch angles differ for measurement and prediction.
- Fiberglass was modeled as metal in prediction



Measured



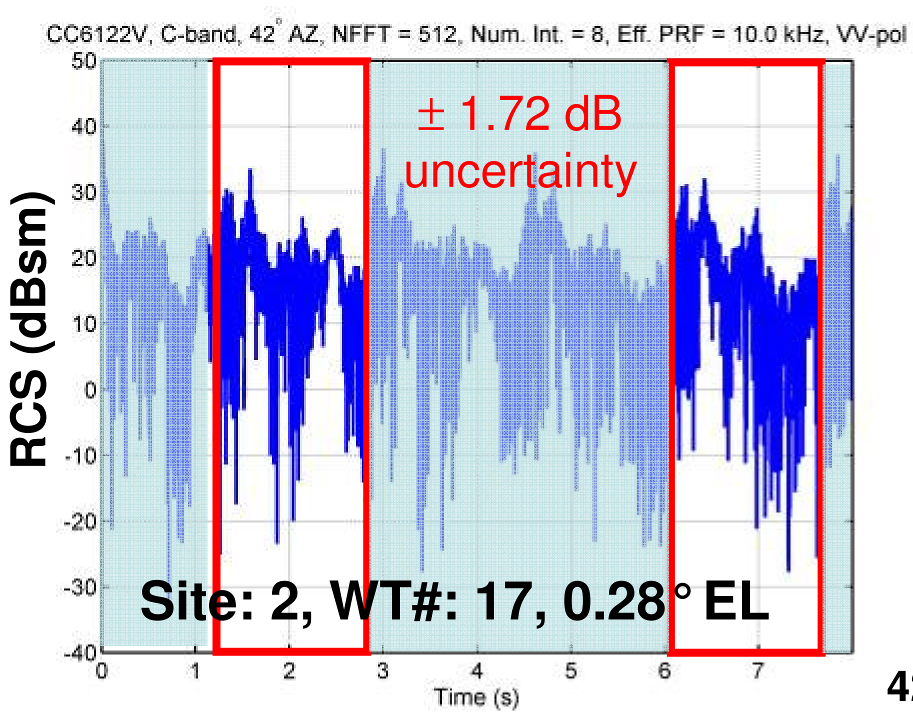
Xpatch



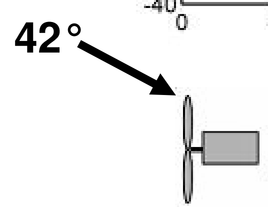
Measured vs. Predicted RCS

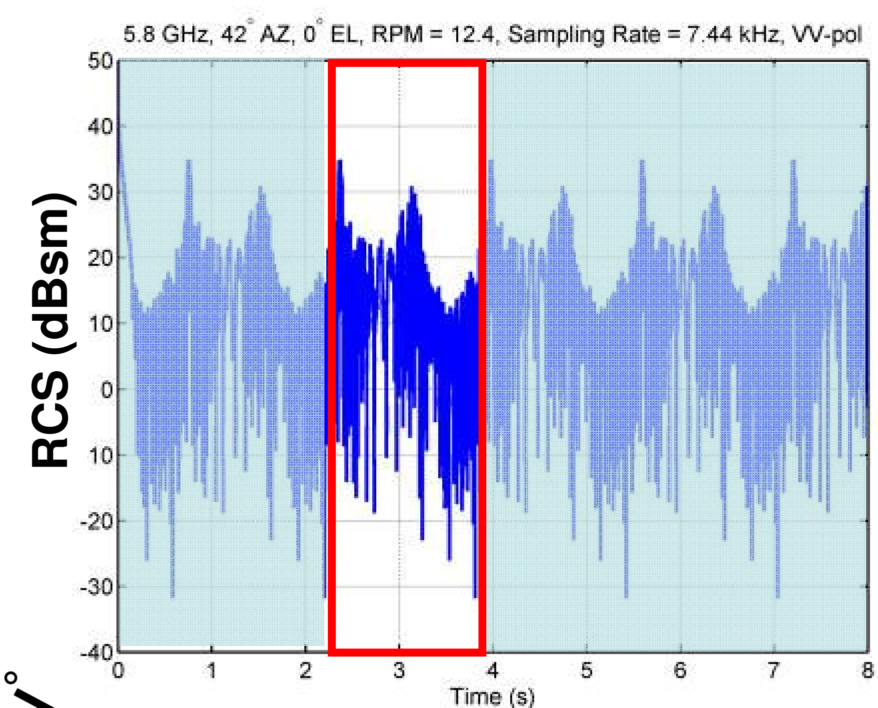
C-band, 42° AZ, 0° EL, RPM = 12.4, VV-pol

- Prediction captures the measurement pattern
- RCS level within measurement uncertainty
- Pitch angles changed during measurement



Measured





Xpatch

Validation: Compare Measured and Xpatch Predicted *Spectrograms*

L-band (1.5 GHz) – Coarse Mesh with 4,800 Blade Rotations

Note: Measured and Xpatch data are zero-Doppler filtered

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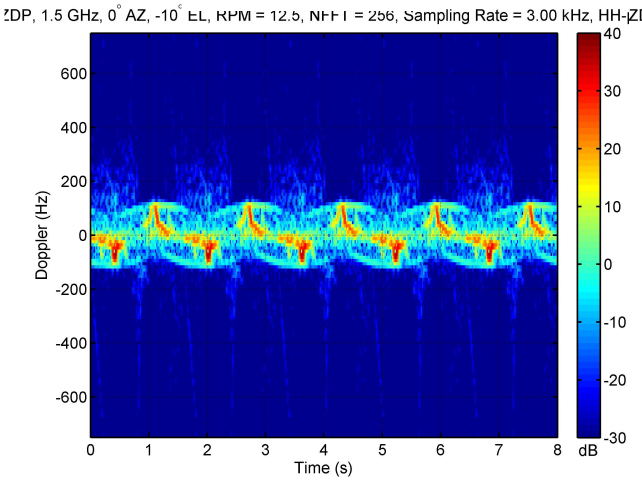
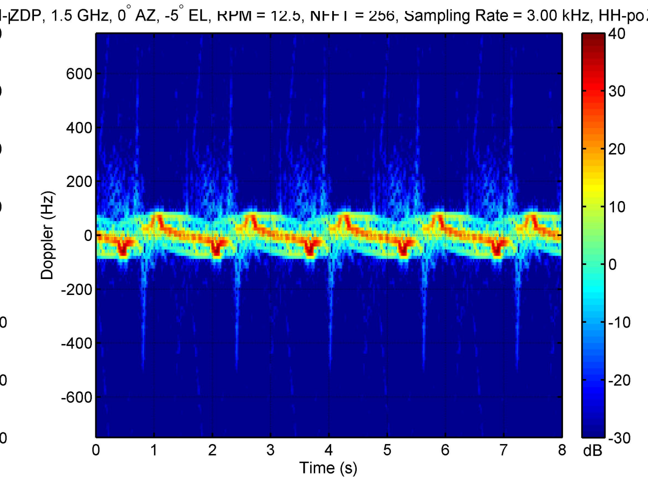
Measured vs. Predicted Spectrograms

L-band, 0° AZ, RPM = 12.5, HH-pol

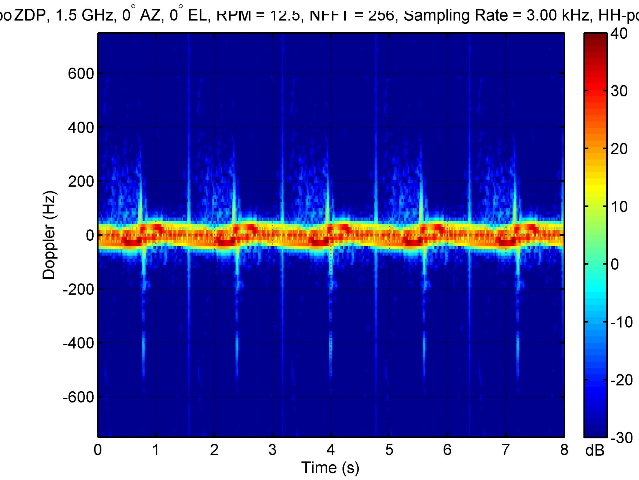
EL = -10°



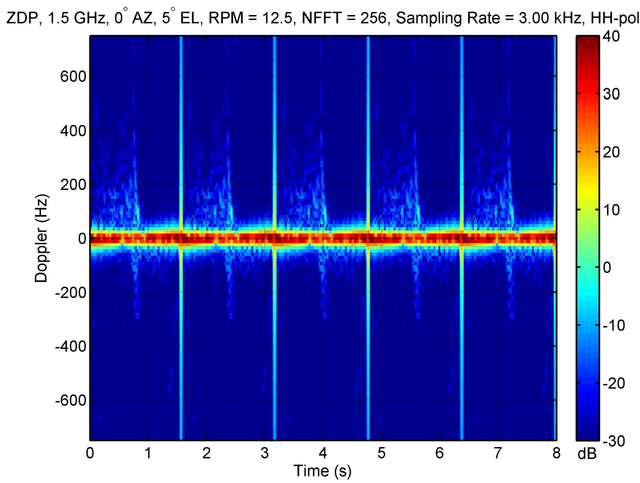
EL = -5°



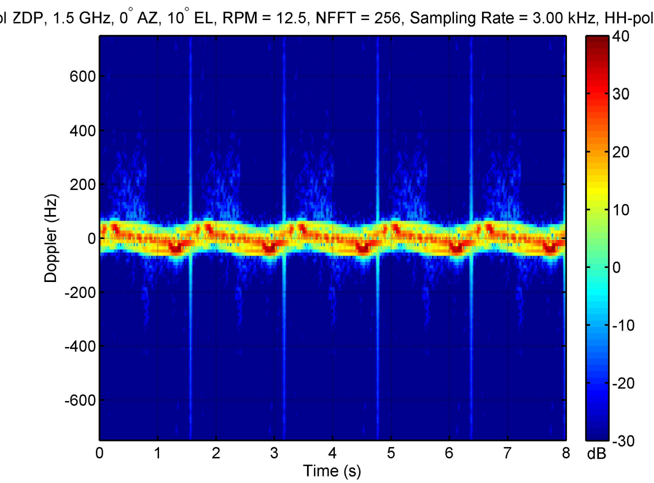
EL = 0°

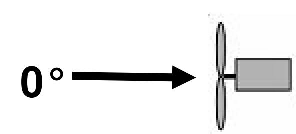


EL = 5°



EL = 10°



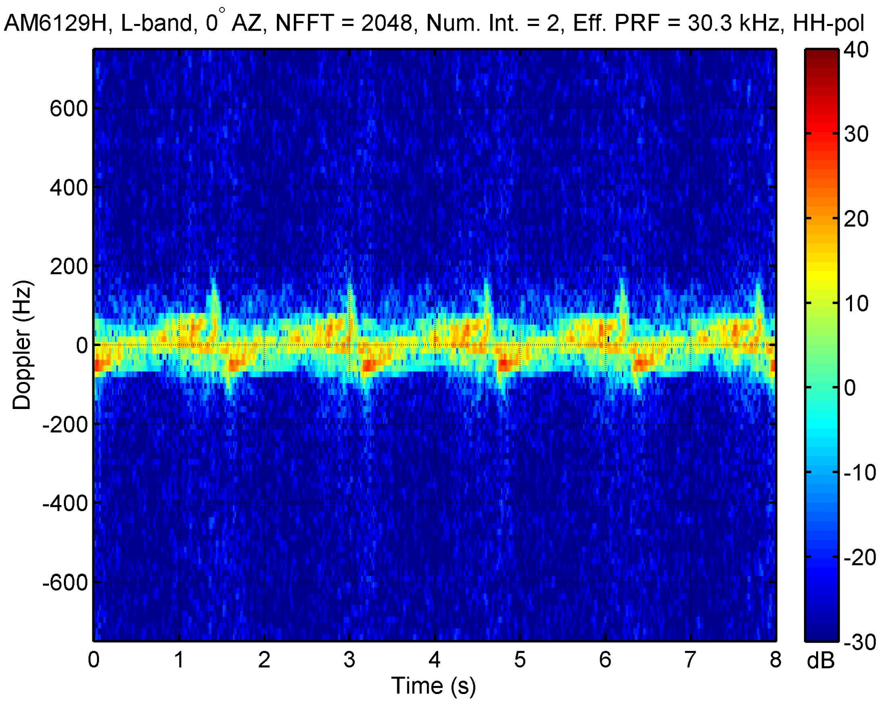


Xpatch Prediction

Measured vs. Predicted Spectrograms

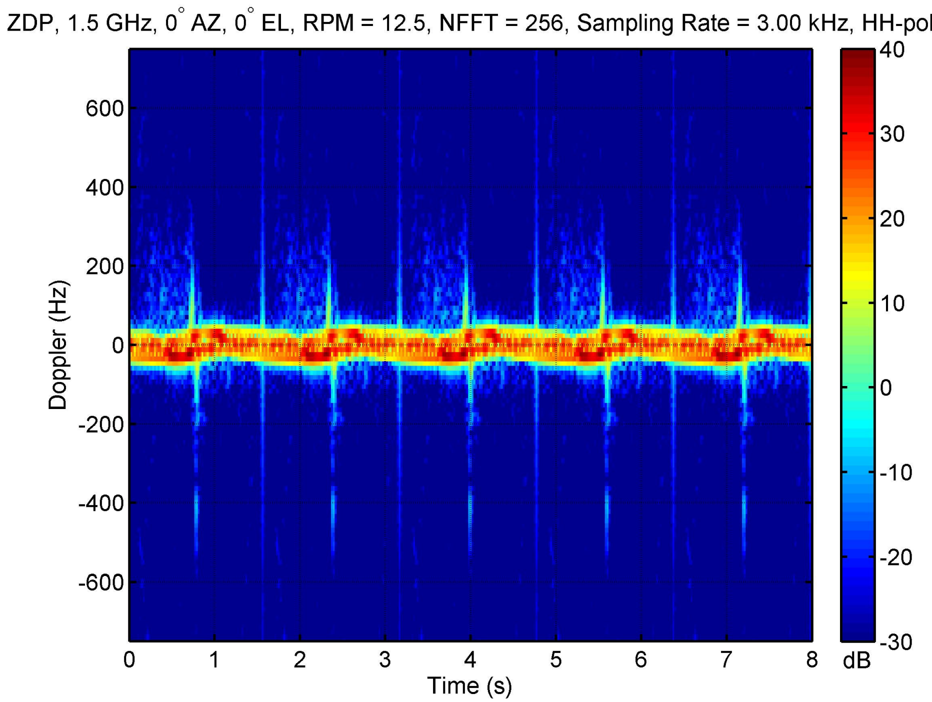
L-band, 0° AZ, 0° EL, RPM = 12.5, HH-pol

Site: GE, WT#: 19, EL = -0.94°

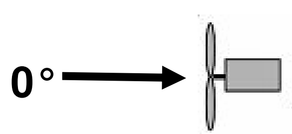


Measurement

EL = 0°



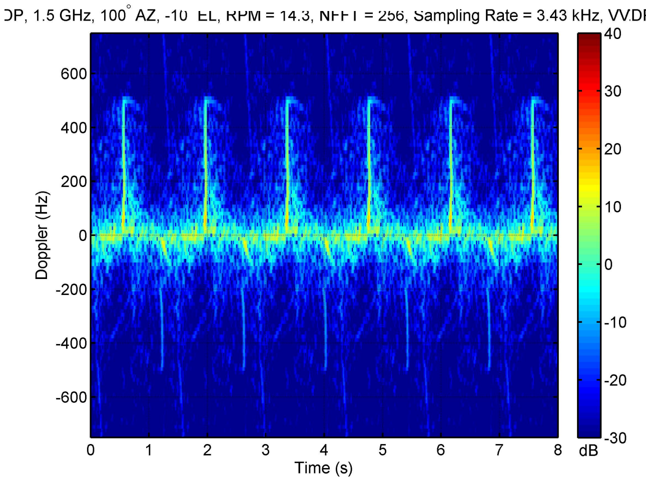
Xpatch



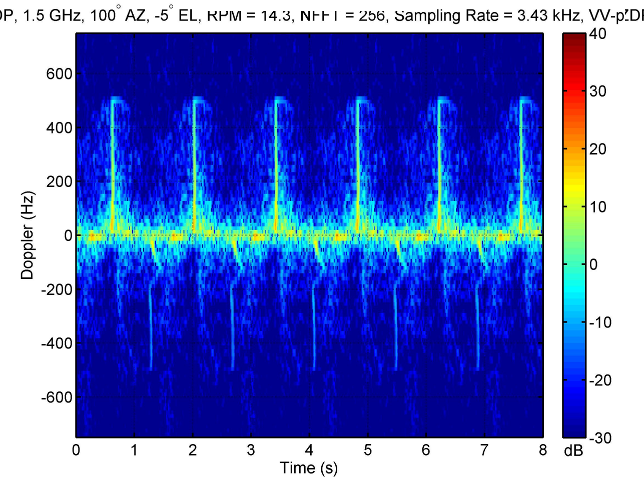
Measured vs. Predicted Spectrograms

L-band, 100° AZ, RPM = 14.3, VV-pol

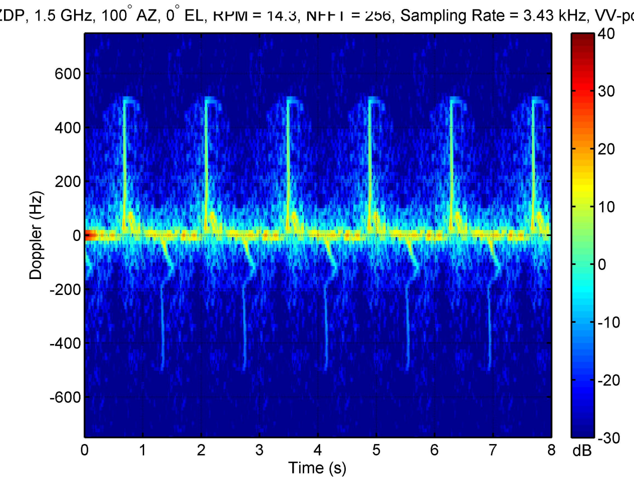
EL = -10°



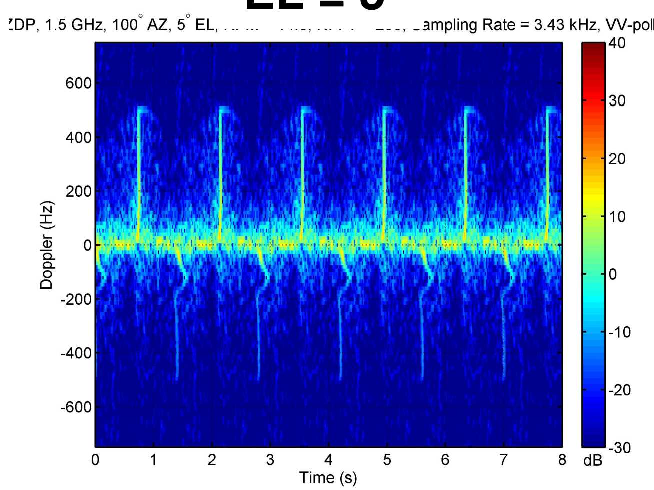
EL = -5°



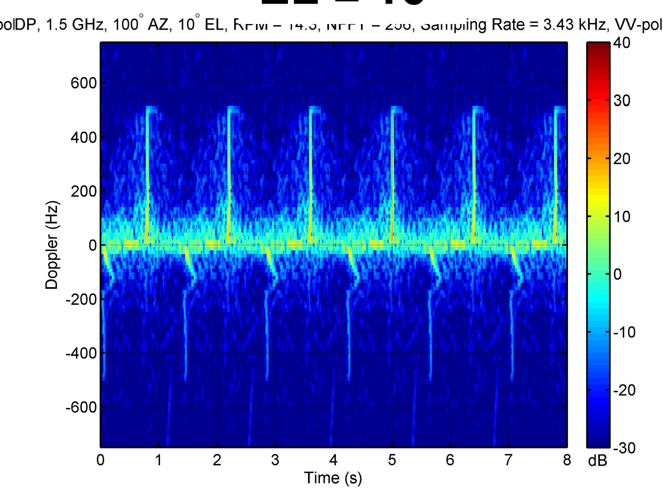
EL = 0°

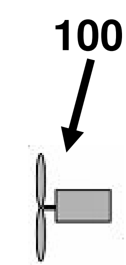


EL = 5°



EL = 10°



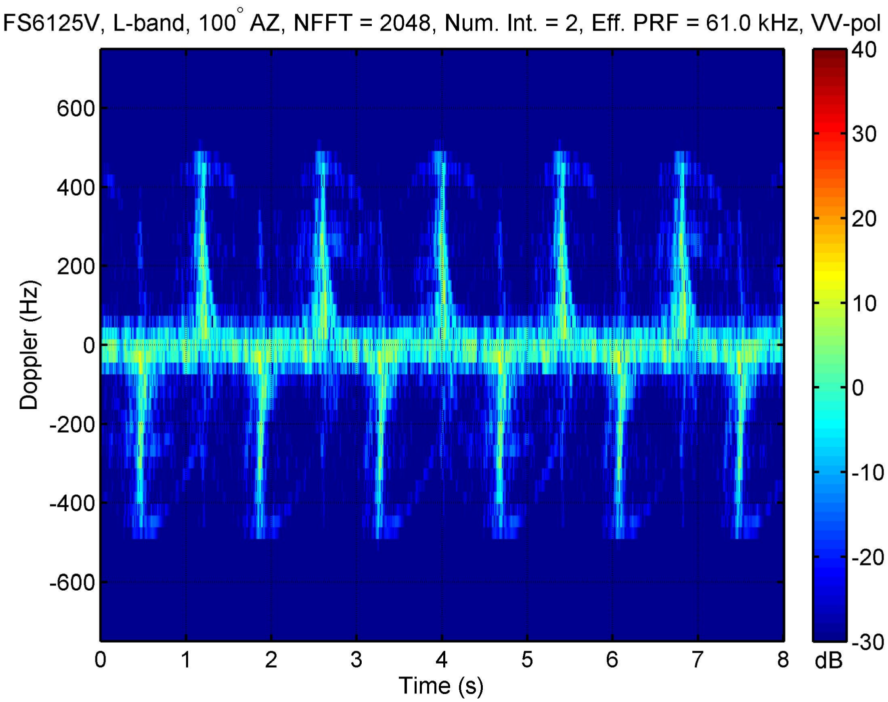


Xpatch Prediction

Measured vs. Predicted Spectrograms

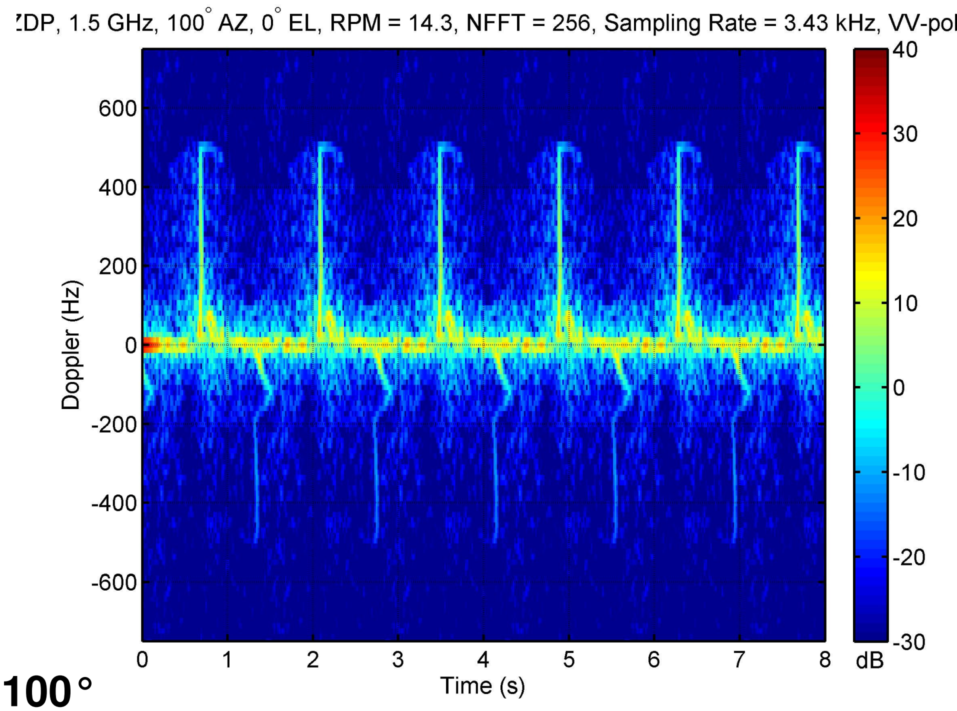
L-band, 100° AZ, 0° EL, RPM = 14.3, VV-pol

Site: GE, WT#: 12, EL = -2.60°



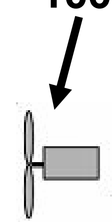
Measurement

EL = 0°



Xpatch

100°



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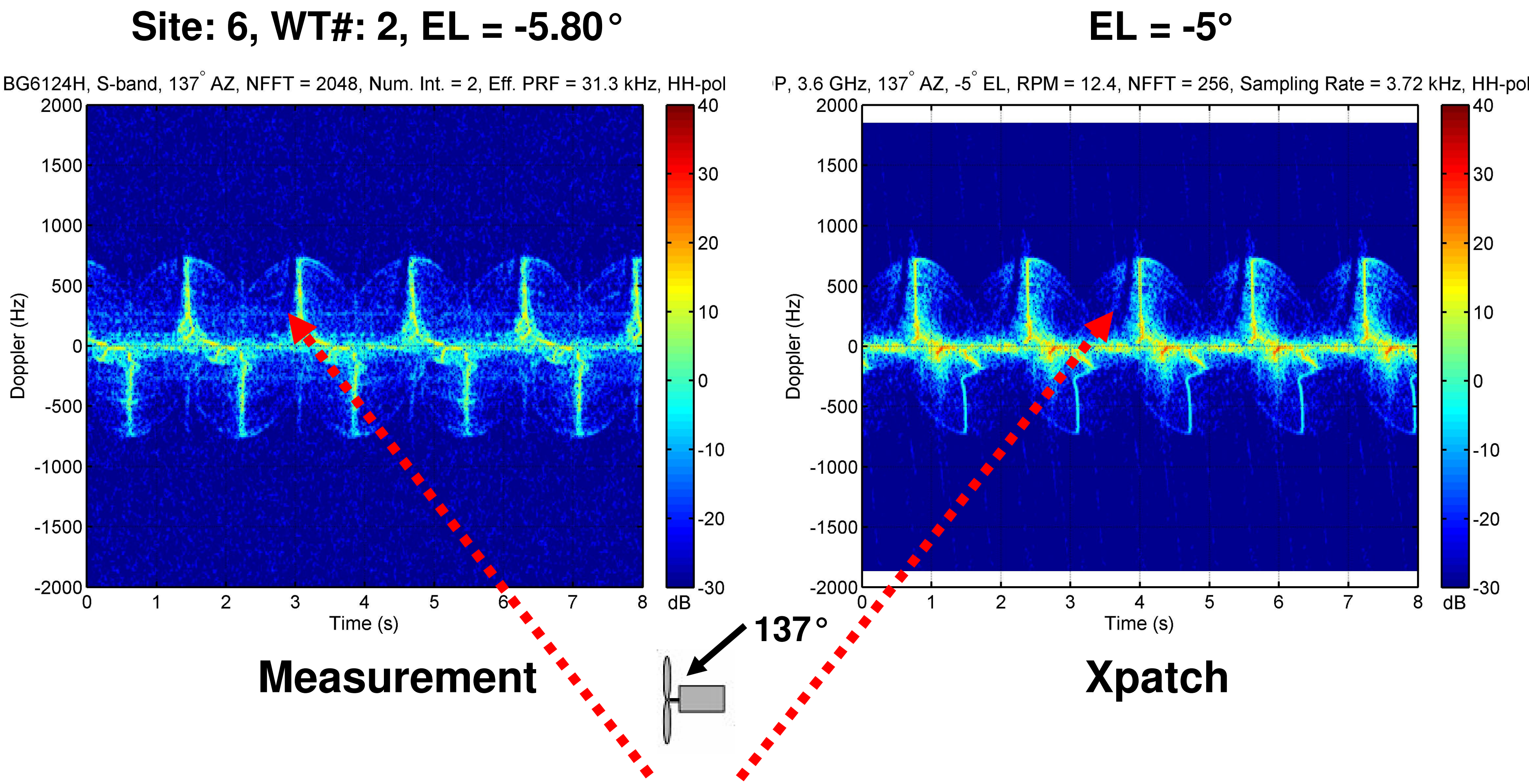
Measured vs. Predicted Spectrograms

S-band, 137° AZ, -5° EL, RPM = 12.4, HH-pol

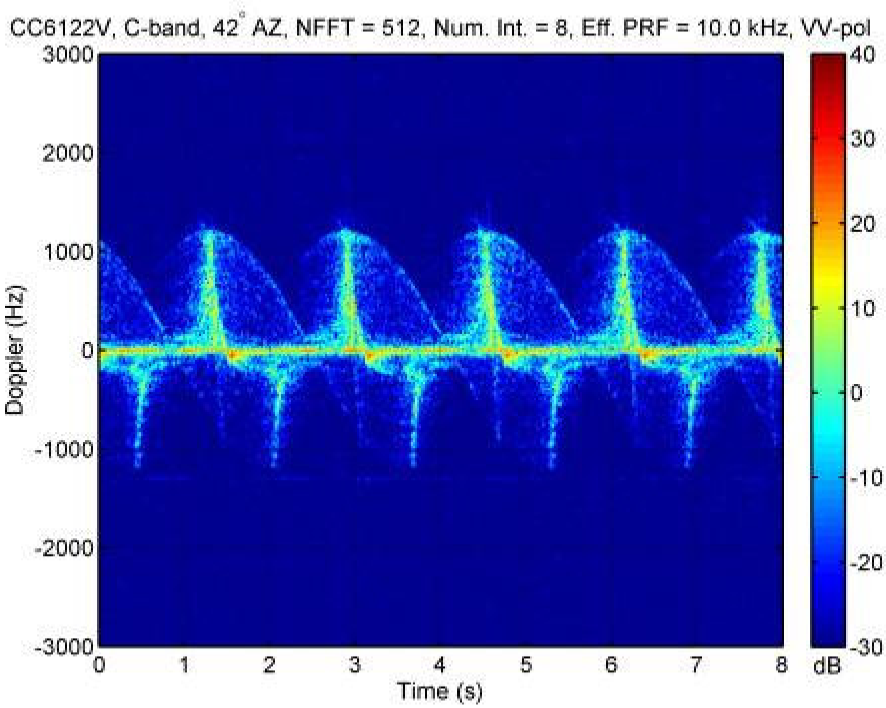


Note the shadowed regions in the spectrogram

Measured vs. Predicted Spectrograms

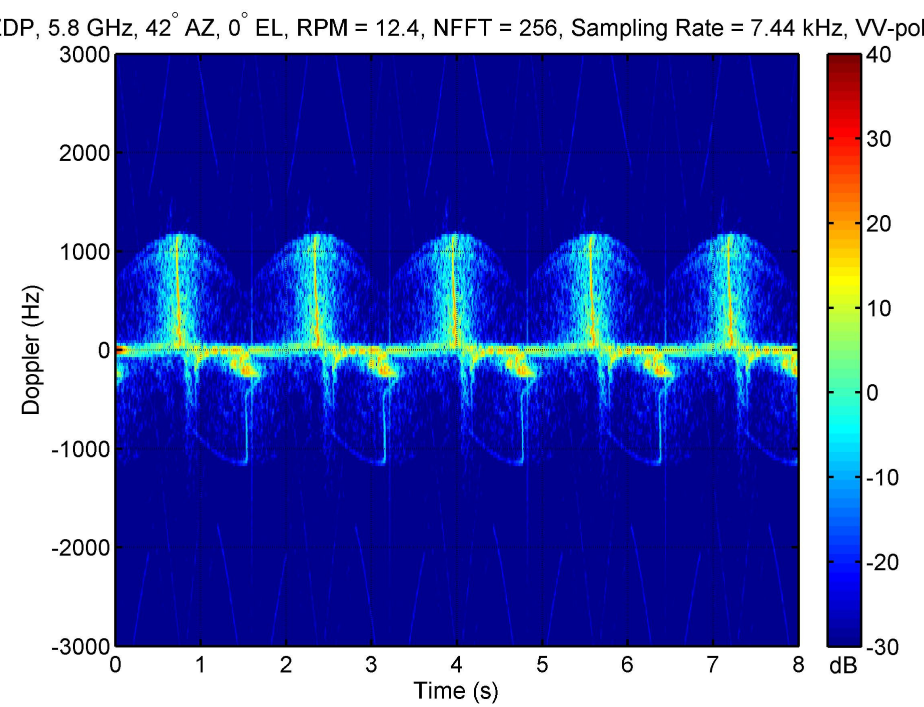
C-band, 42° AZ, 0° EL, RPM = 12.4, VV-pol

Site: 2, WT#: 17, EL= -0.28°

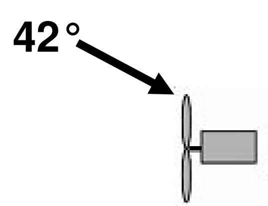


Measurement

EL = 0°



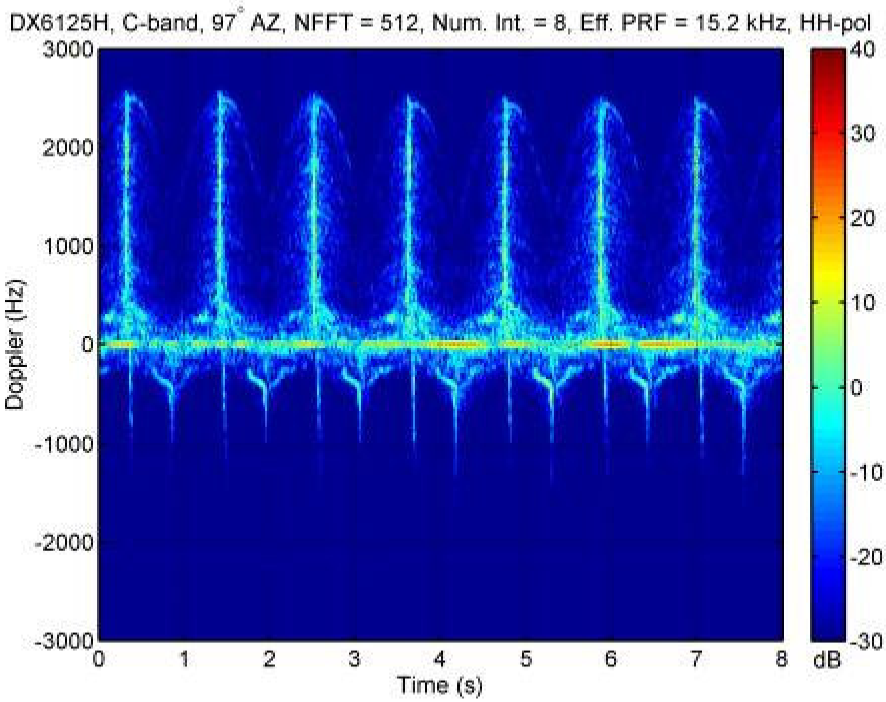
Xpatch



Measured vs. Predicted Spectrograms

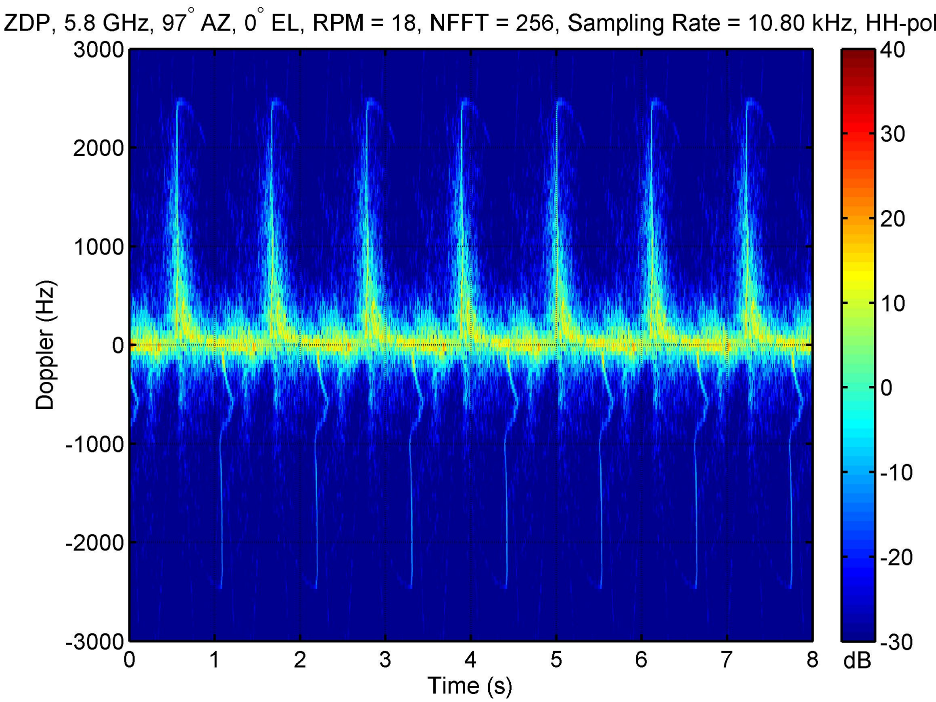
C-band, 97° AZ, 0° EL, RPM = 18.0, HH-pol

Site: GE, WT#: 12, EL = -2.60°

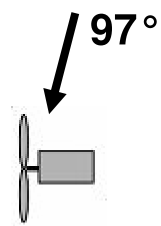


Measurement

EL = 0°



Xpatch



Trade Study:
Compare Effects of Mesh Density

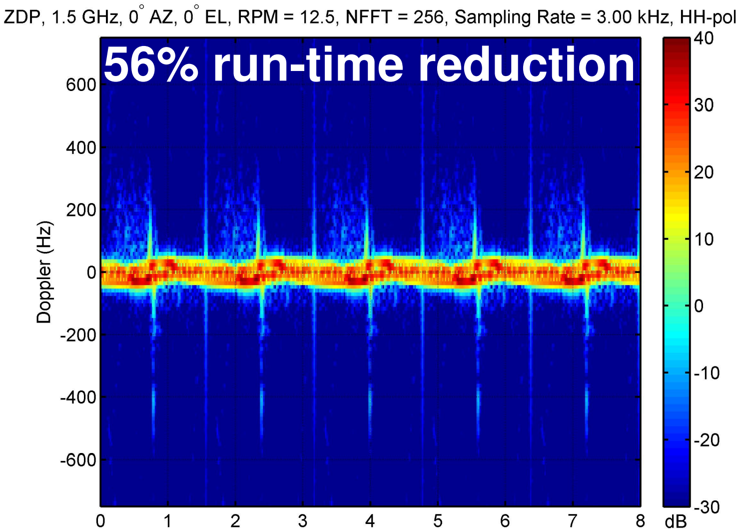
L-Band – 4,800 Blade Rotations

S-Band – 6,000 Blade Rotations

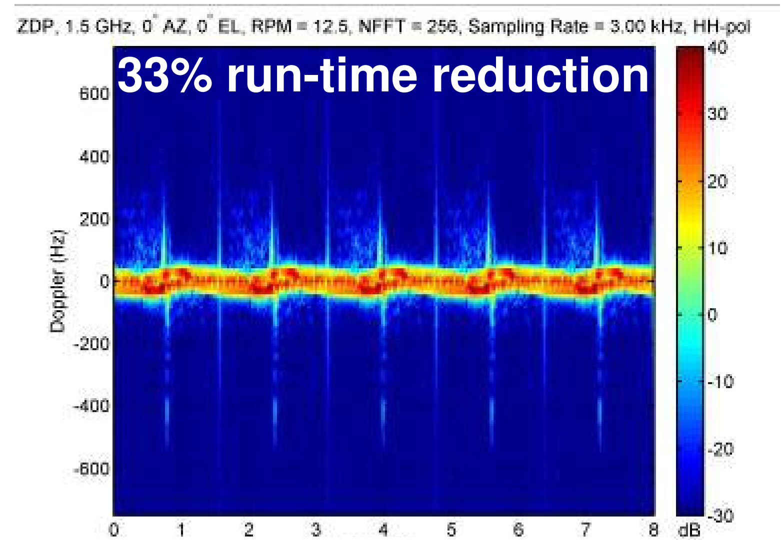
C-Band – 12,000 Blade Rotations

Mesh Comparison

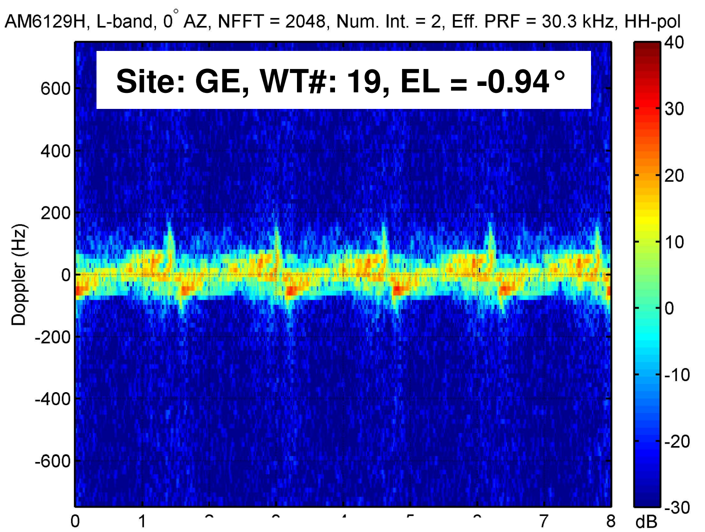
L-band, 0° AZ, 0° EL, HH-pol



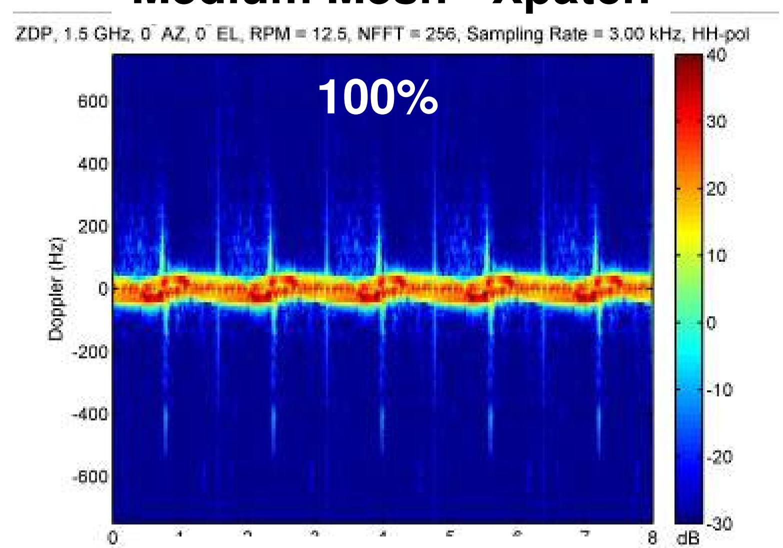
Coarse Mesh - Xpatch



Medium Mesh - Xpatch



Measurement



Fine Mesh - Xpatch

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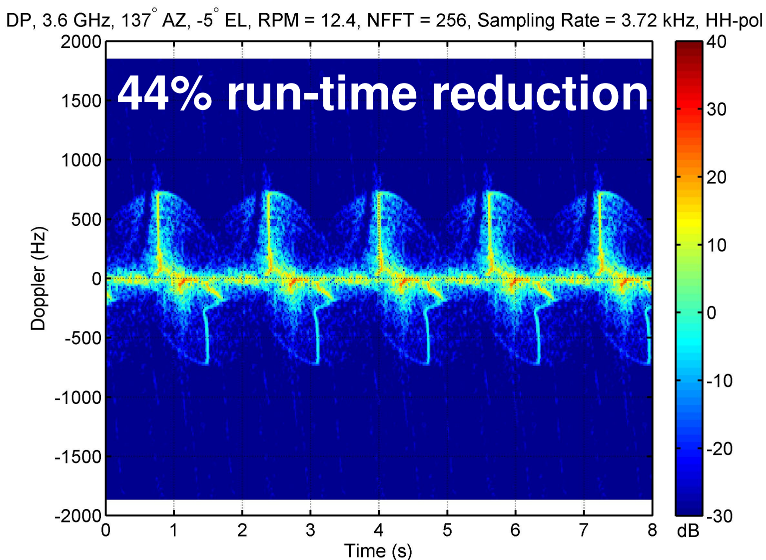
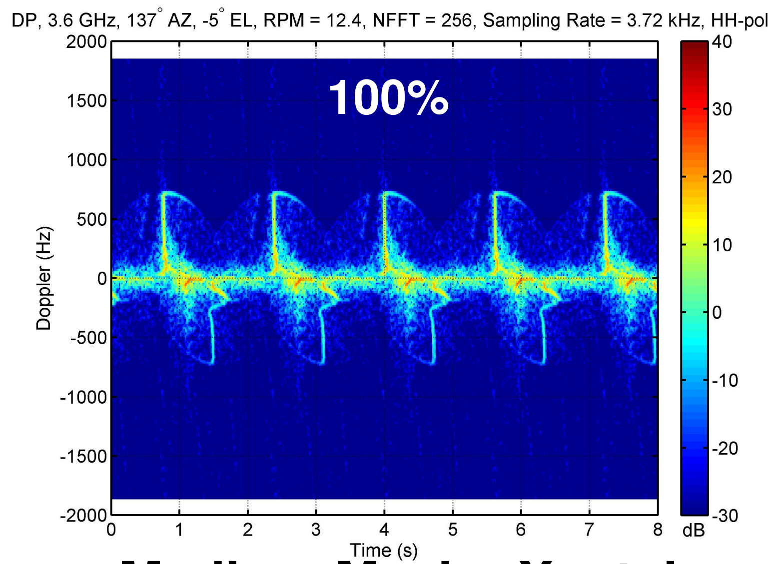
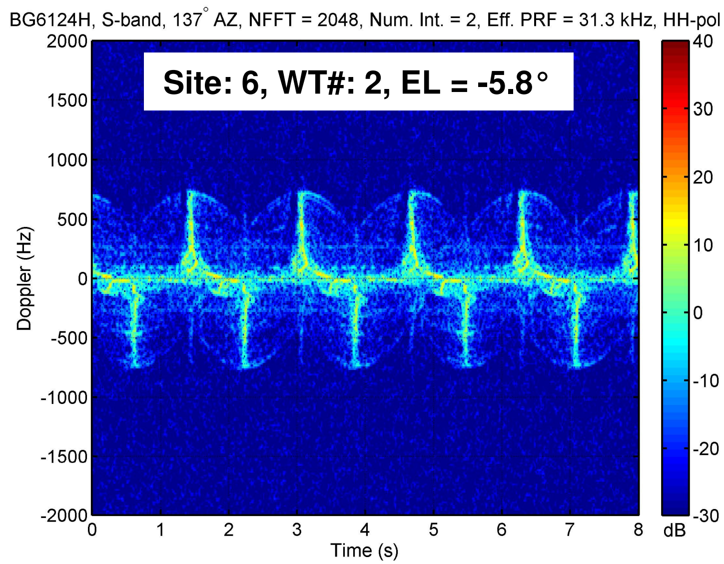
Mesh Comparison
S-band, 137° AZ, 0° EL, HH-pol



Coarse Mesh - Xpatch



Medium Mesh - Xpatch



Measurement

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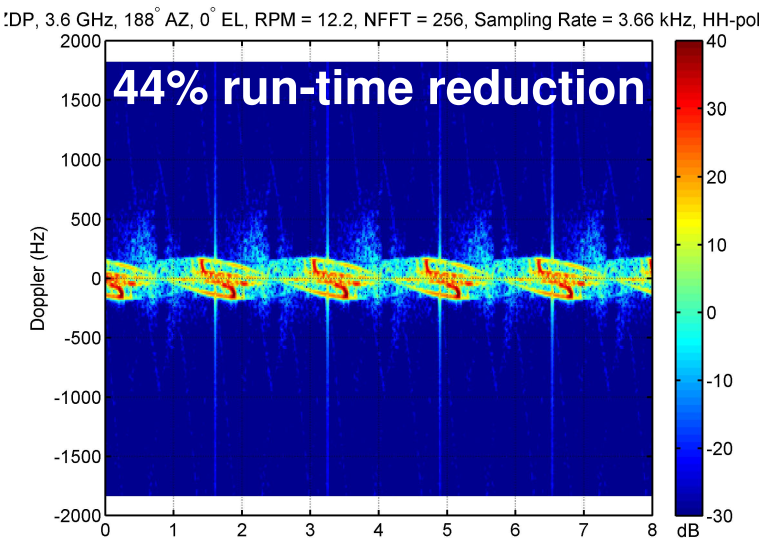
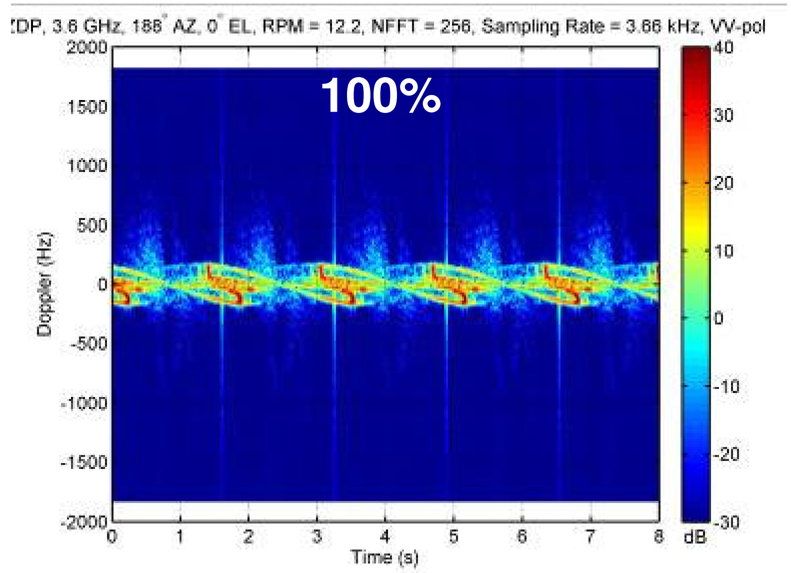
Mesh Comparison

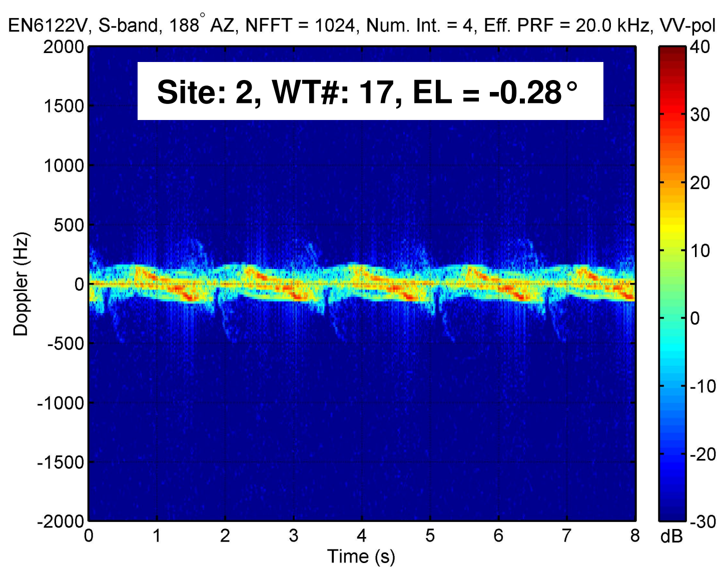
S-band, 188° AZ, 0° EL, VV-pol



Coarse Mesh - Xpatch



Medium Mesh - Xpatch



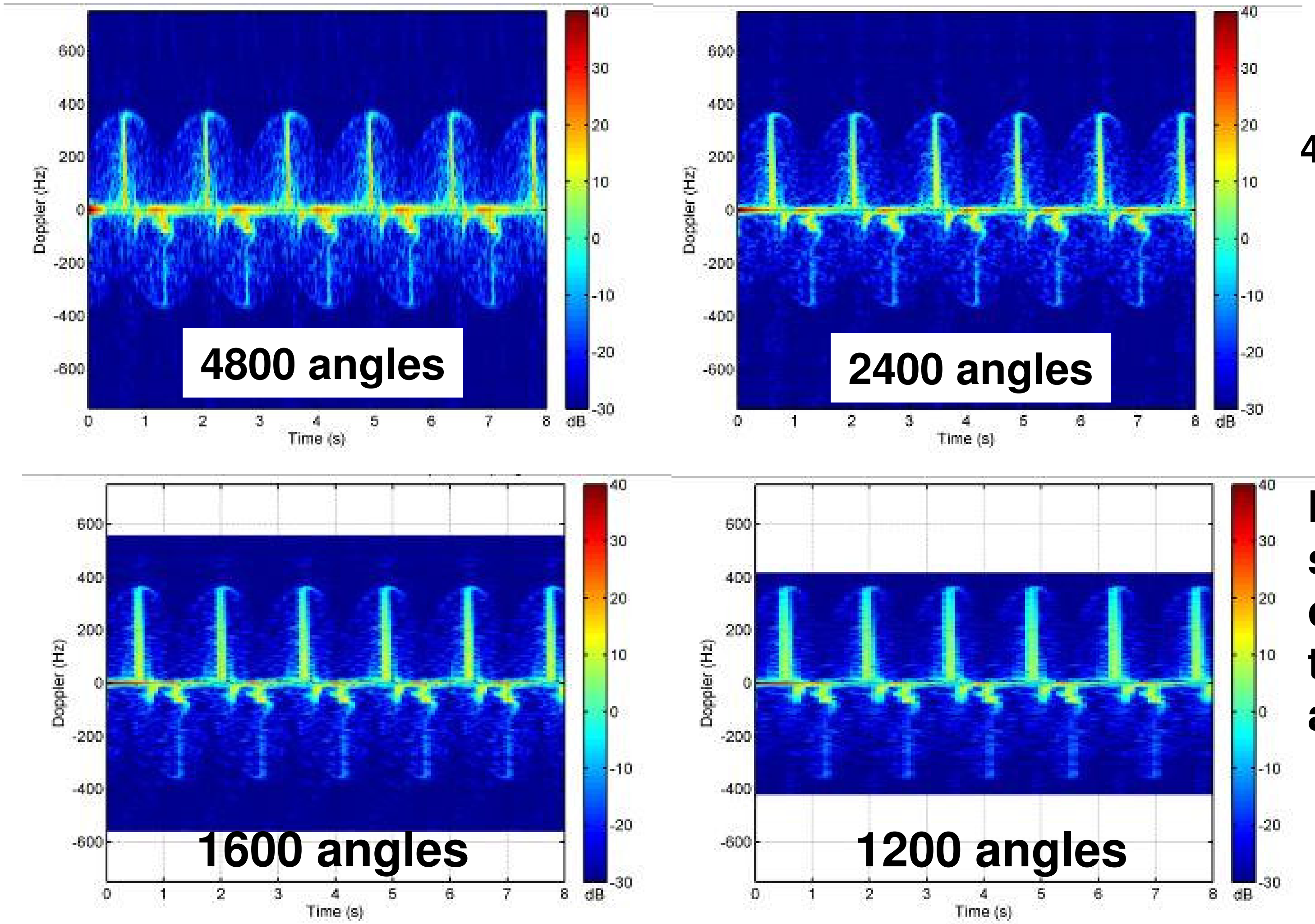
Measurement

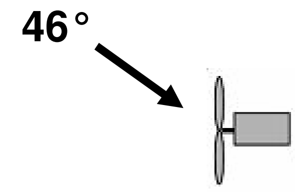
Trade Study:
Blade Rotation Angle Sampling Rates

L-Band – Coarse Mesh
S-Band – Coarse Mesh
C-Band – Coarse Mesh

Sampling Rate's Effect on Spectrograms

L-band, 46° AZ, 0° EL, RPM = 14.0, VV-pol



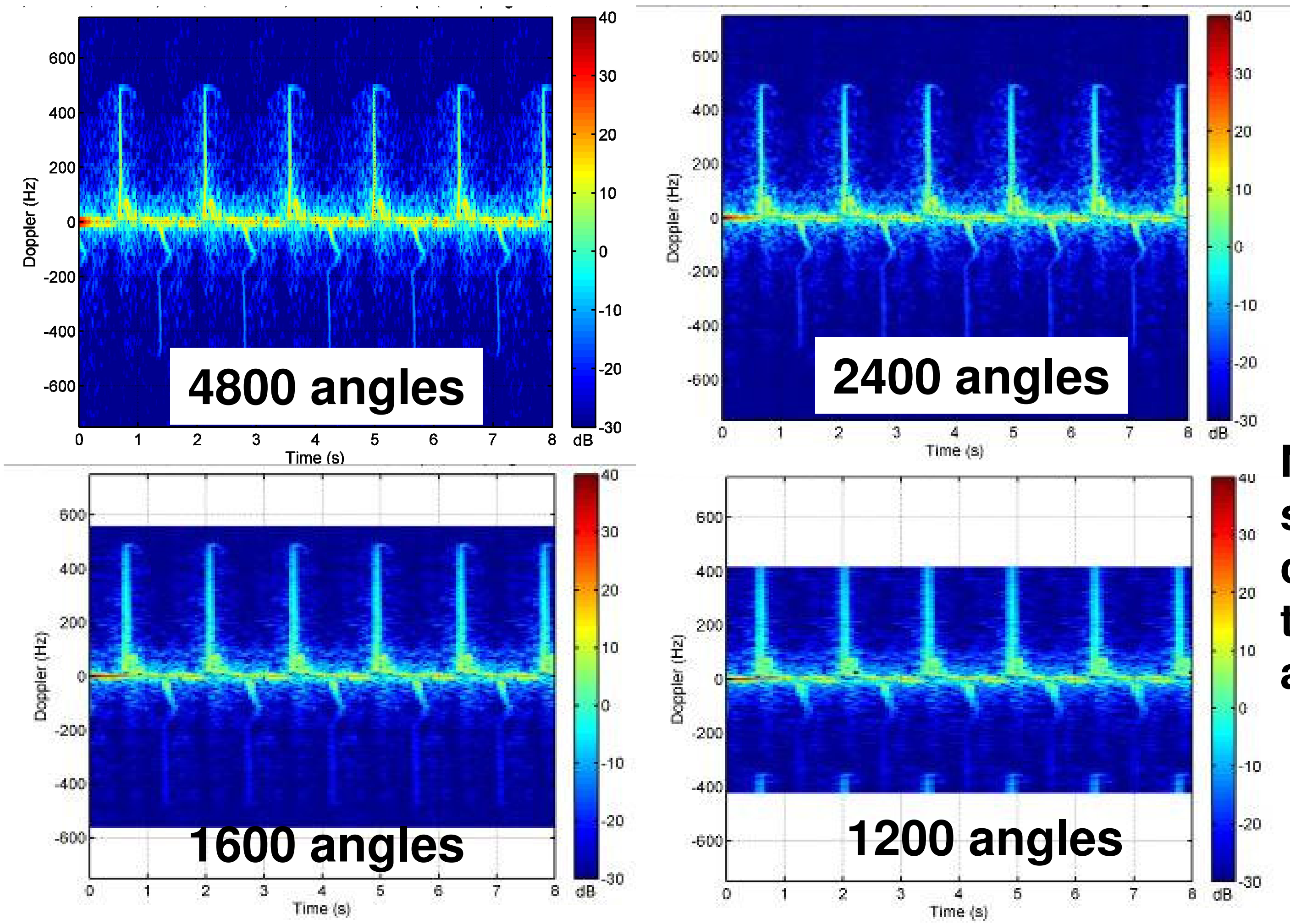


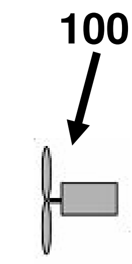
Nyquist sampling corresponds to 1500 angles

- **Sampling more angles captures more higher order interactions**
- **Computation time increases proportionally with number of angles**

Sampling Rate's Effect on Spectrograms

L-band, 100 °AZ, 0° EL, RPM = 14.0, VV-pol





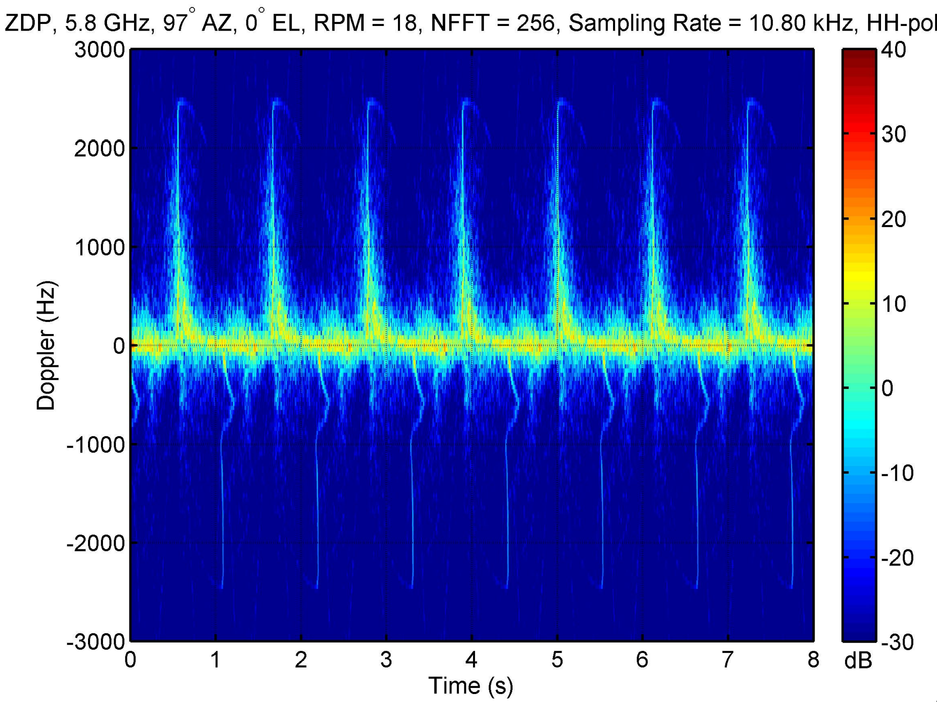
Nyquist sampling corresponds to 1500 angles

- Sampling more angles captures more higher order interactions
- Computation time increases proportionally with number of angles

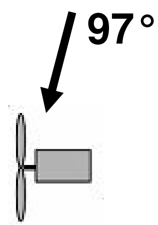
Sampling Rate's Effect on Spectrograms

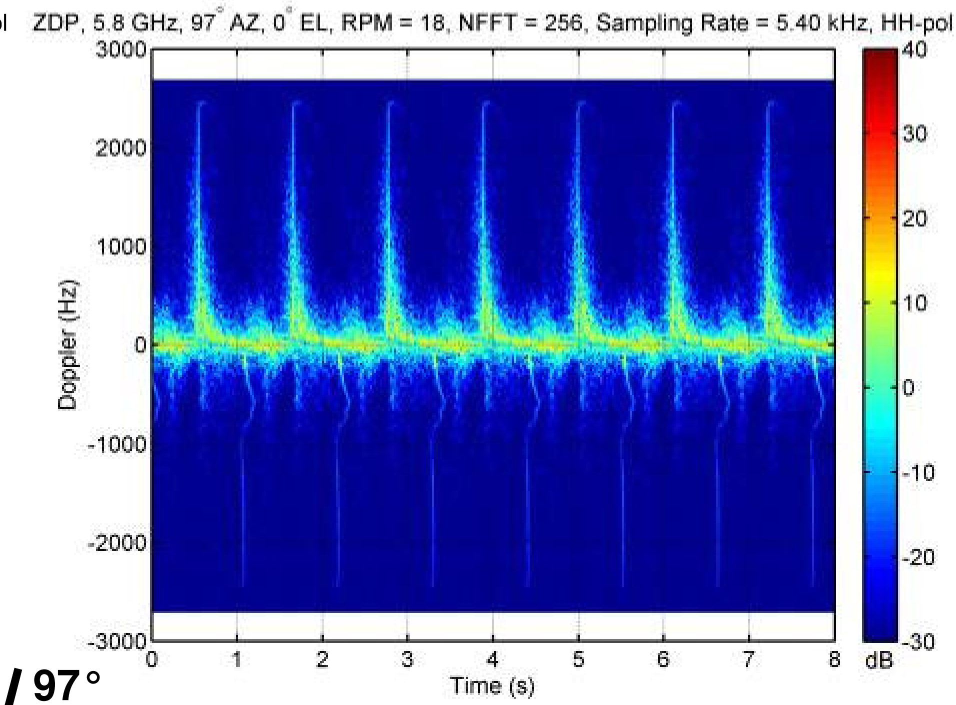
C-band, 97° AZ, 0° EL, RPM = 18.0

Nyquist sampling corresponds to 6000 angles



12000 angles





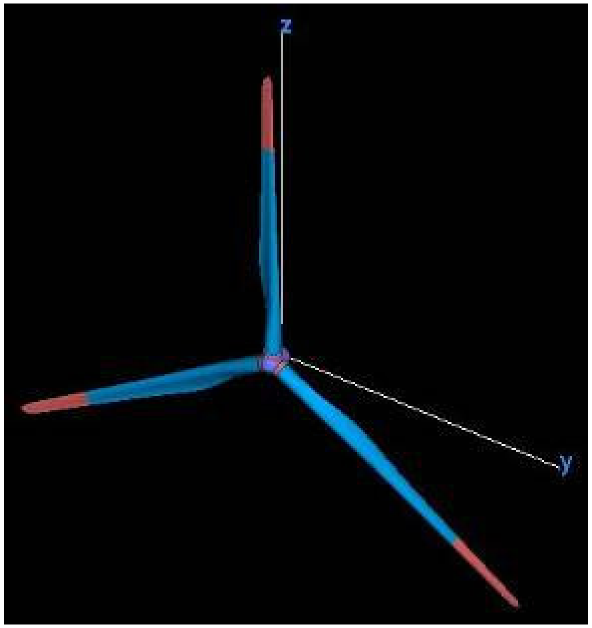
6000 rotations

- Sampling more angles captures more higher order interactions
- Computation time increases proportionally with number of angles

Trade Study:
"Simplified" vs. "True" Windmill

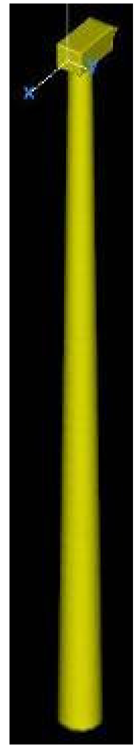
L-band – Coarse Mesh with 4,800 Blade rotations

"Simplified" vs. "True" Windmill
25% Run-Time Reduction



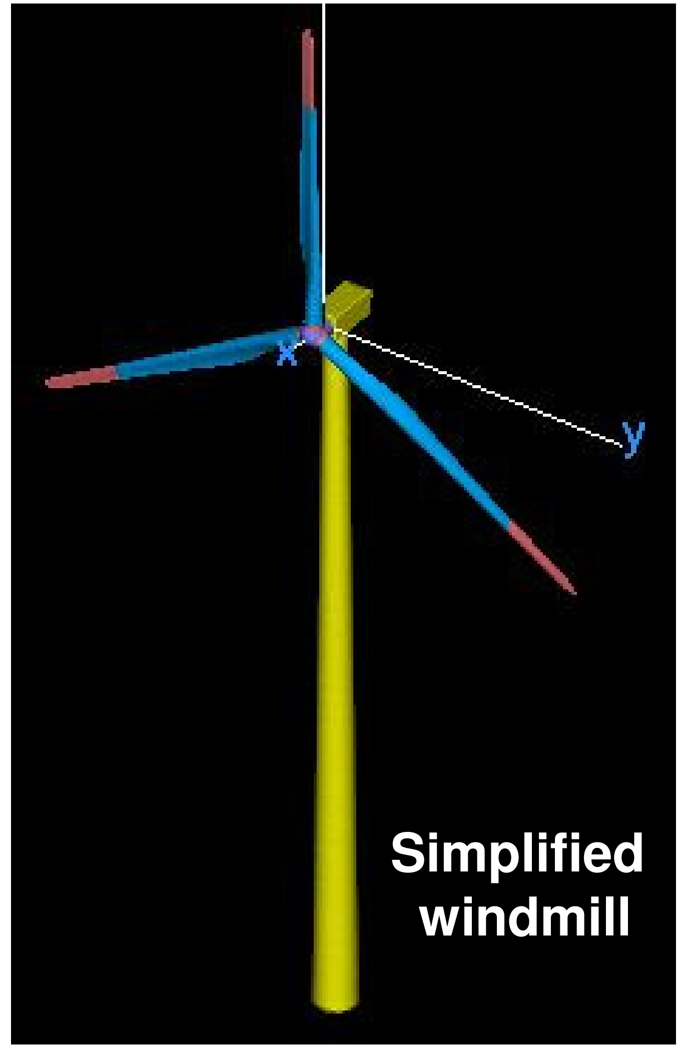
"True" Blades and
"Simplified" Hub

+



"Simplified"
Nacelle & Tower

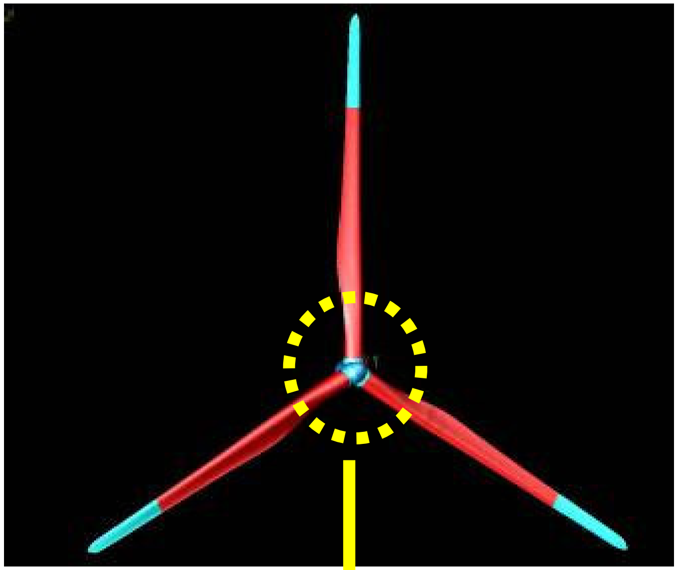
=



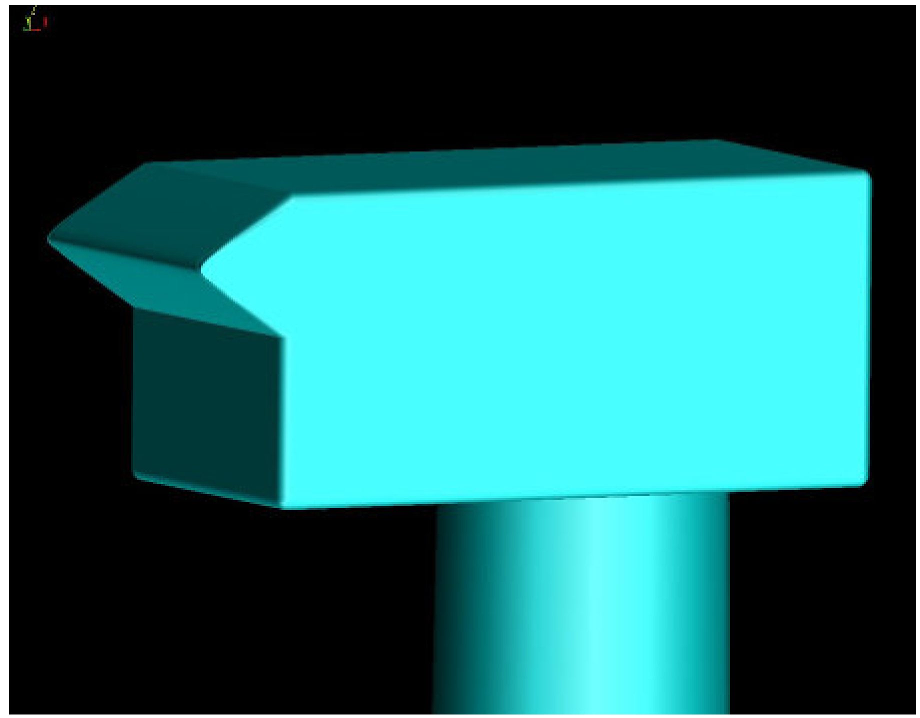
Simplified windmill has 75,984 facets
True windmill has 100,731 facets

“Simplified” vs. “True” Windmill

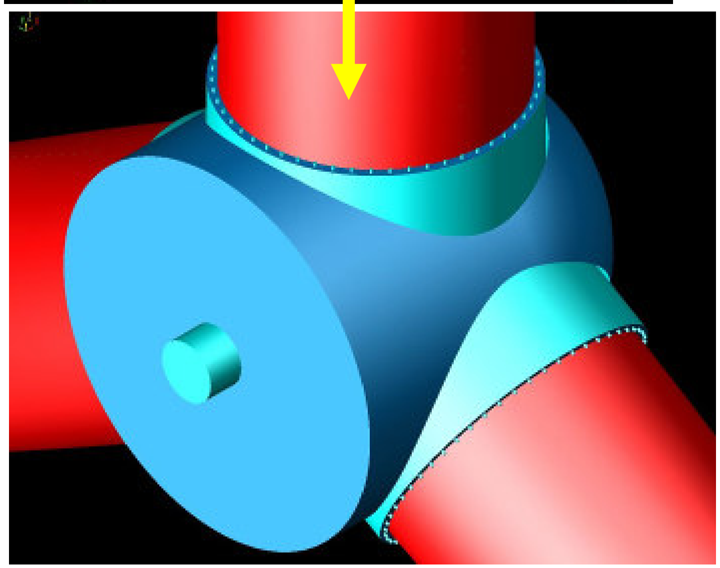
True Blades with Simplified Hub/Nacelle/tower



True Blades with simplified hub



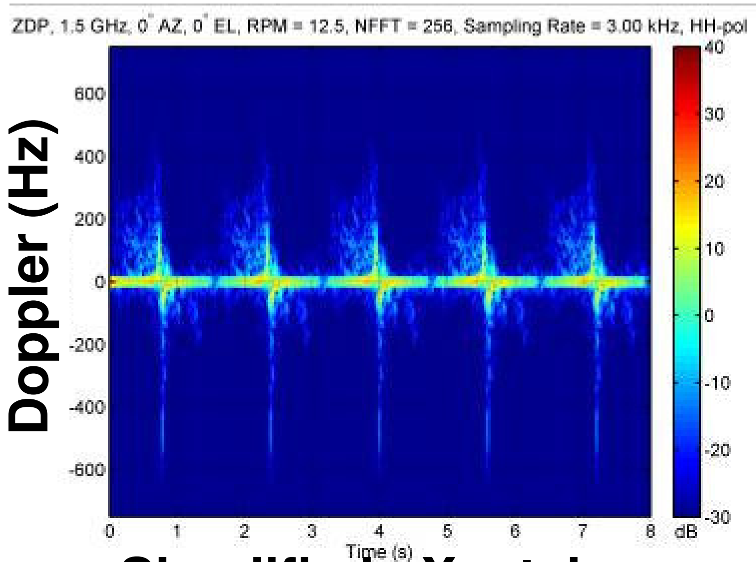
Simplified Nacelle and Tower



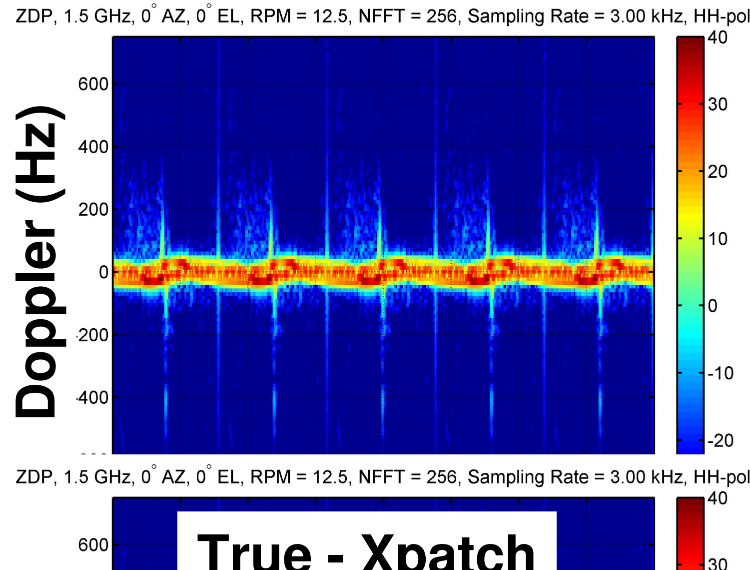
Simplified Hub

"Simplified" vs. "True" Windmill

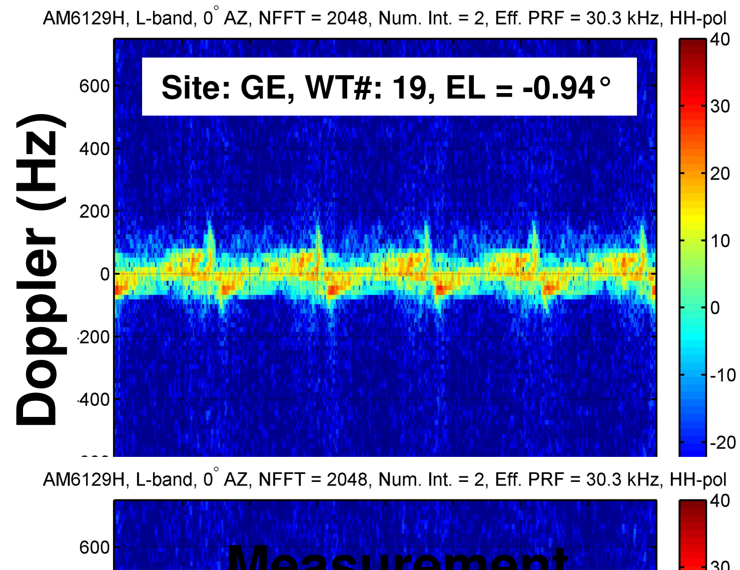
L-band, 0° AZ, 0° EL, RPM = 12.5, HH-pol



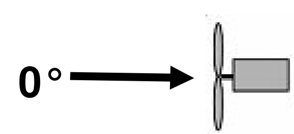
Simplified - Xpatch



True - Xpatch



Measurement



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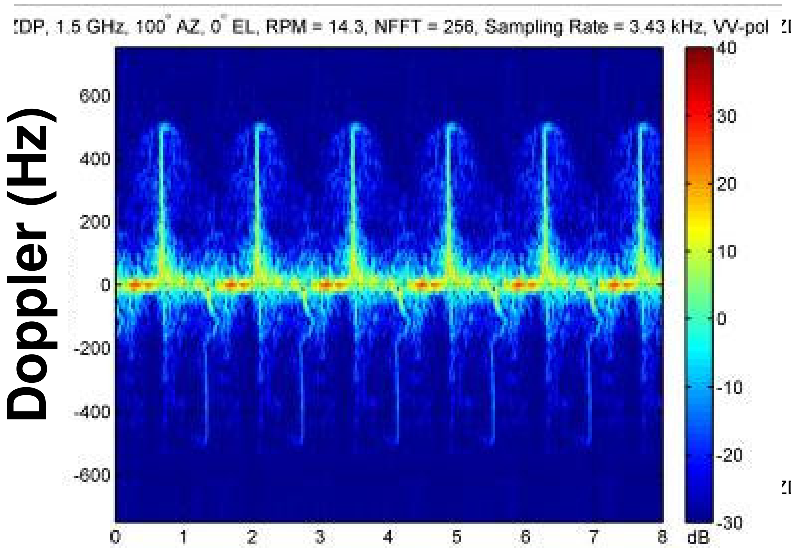
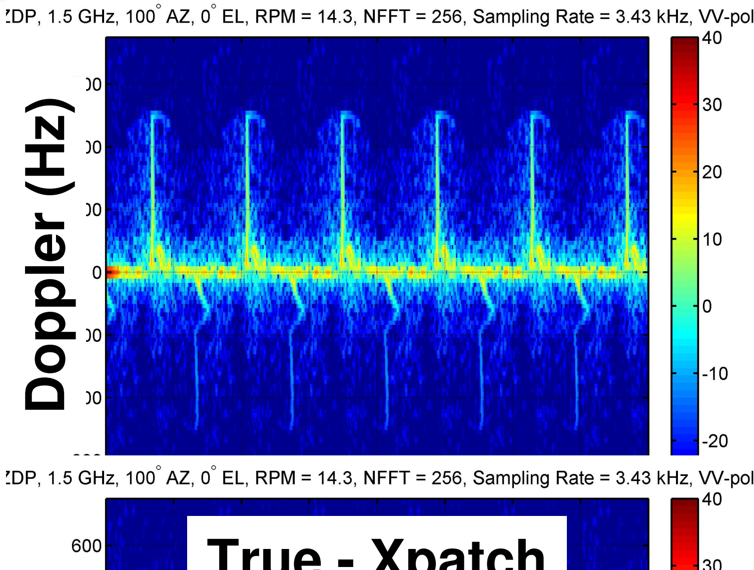
"Simplified" vs. "True" Windmill

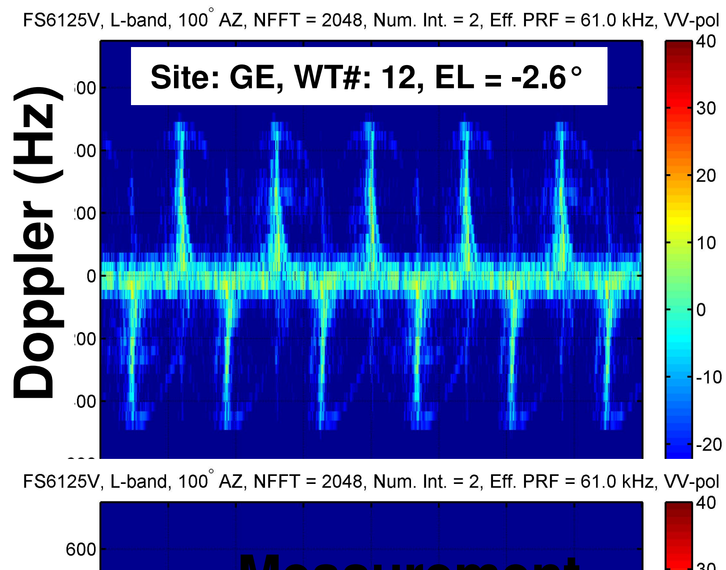
L-band, 100° AZ, 0° EL, RPM = 14.3, VV-pol



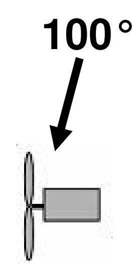
Simplified - Xpatch



True - Xpatch



Measurement



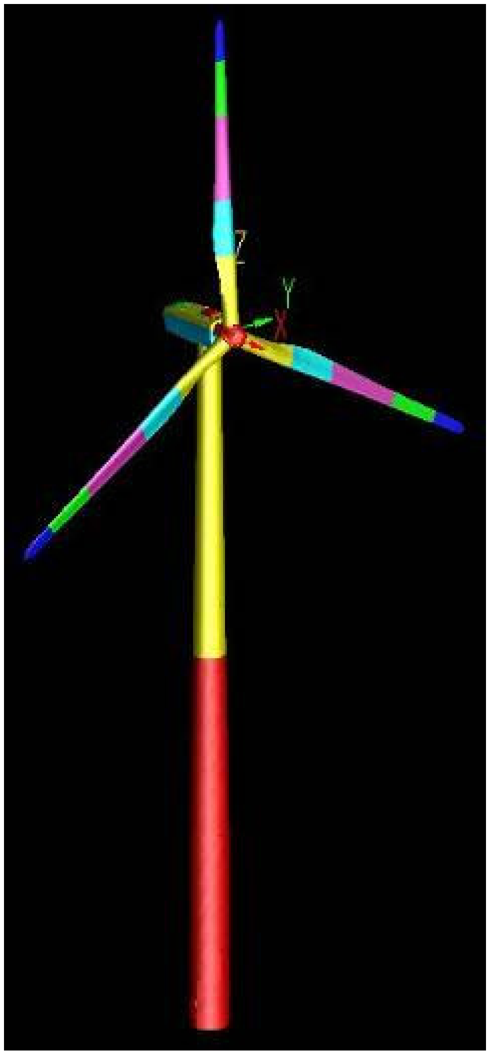
Trade Study:
Entire Geometry vs.
Only Rotational Components

L-band (1.5 GHz); Coarse Mesh; 4,800 rotations

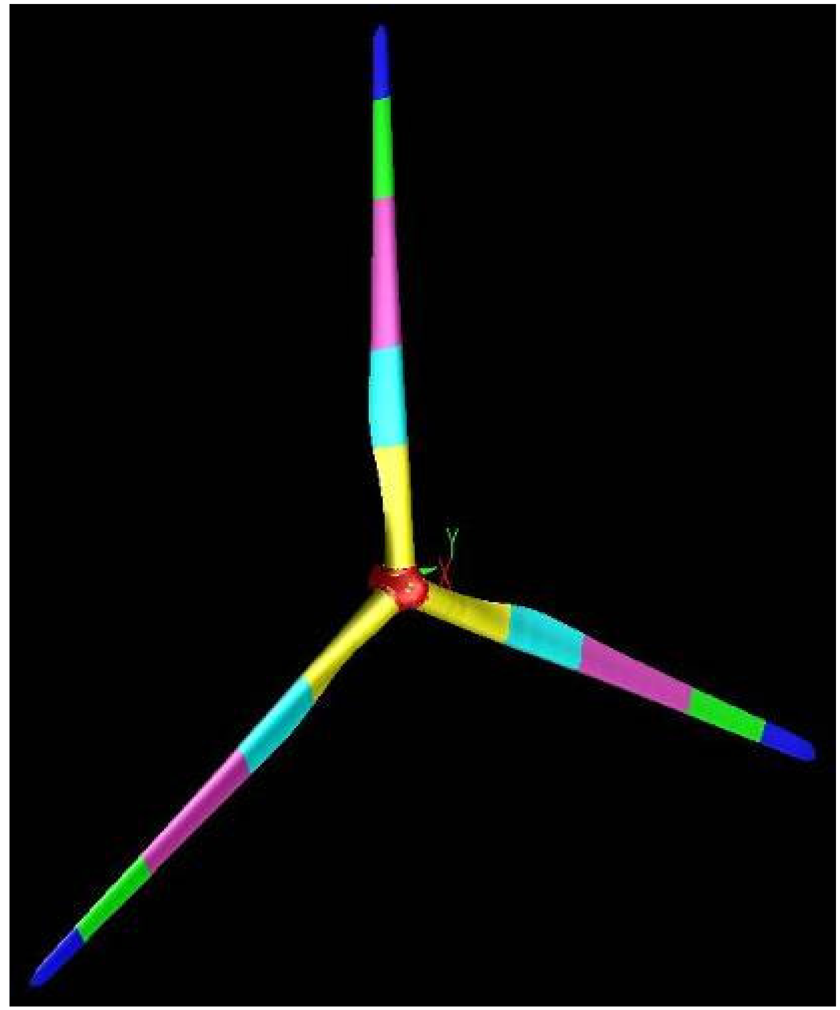
S-band (3.6 GHz); Coarse Mesh; 6,000 rotations

C-band (5.8 GHz); Coarse Mesh; 12,000 rotations

Entire Windmill vs. Only Rotational Parts



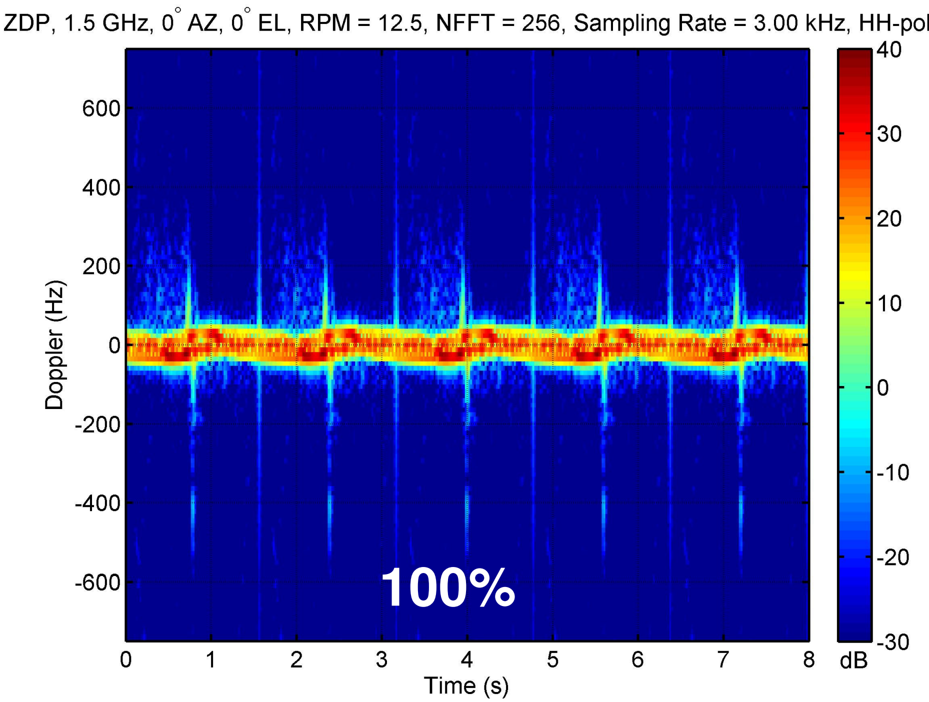
Entire Geometry

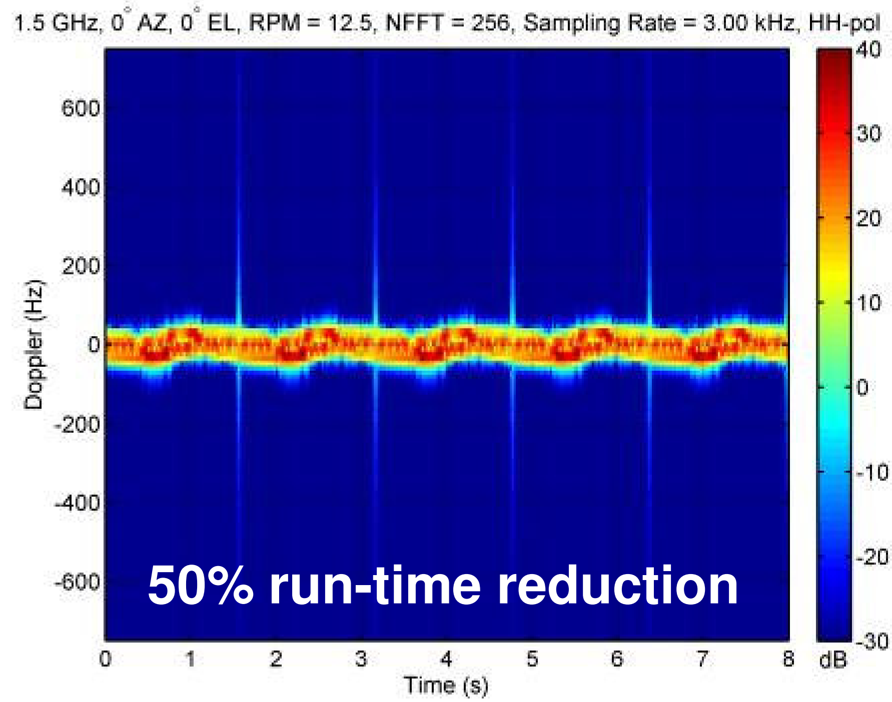


Blades, Hub, and Nose Cone

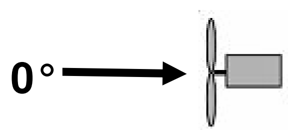
Entire Windmill vs. Only Rotational Parts
L-band, 0° AZ, 0° EL, RPM = 12.5, HH-pol

Spectrogram missing interaction between blades and tower





Entire Geometry | **Hub, Blades, and Nose Cone**



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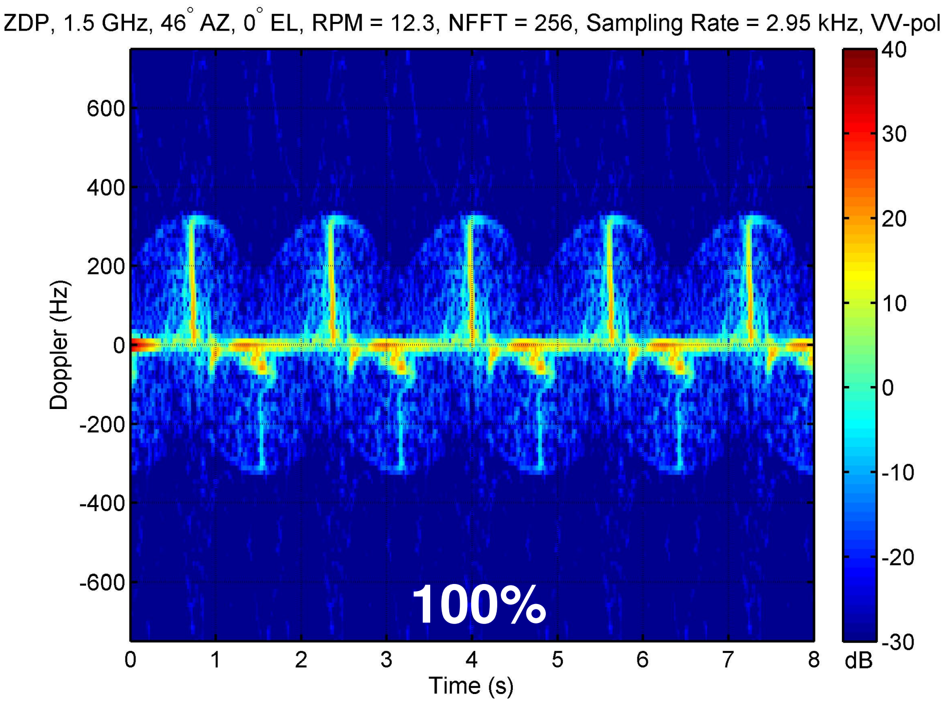
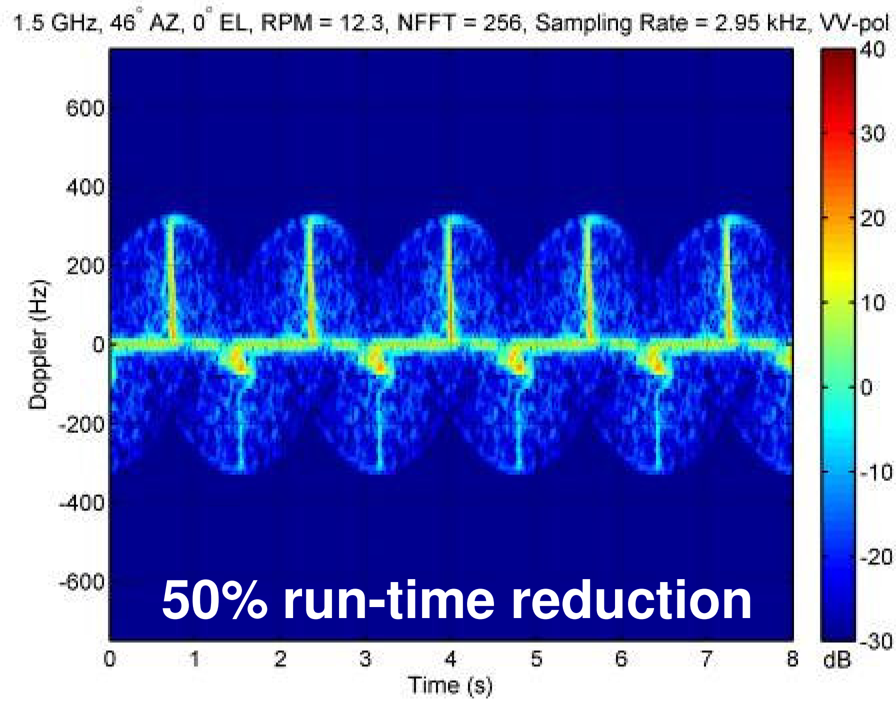
Entire Windmill vs. Only Rotational Parts

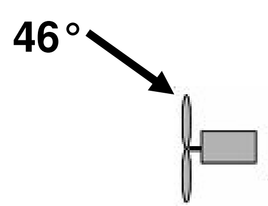
L-band, 46° AZ, 0° EL, RPM = 12.3, VV-pol

Spectrogram missing interaction between blades and tower





Entire Geometry

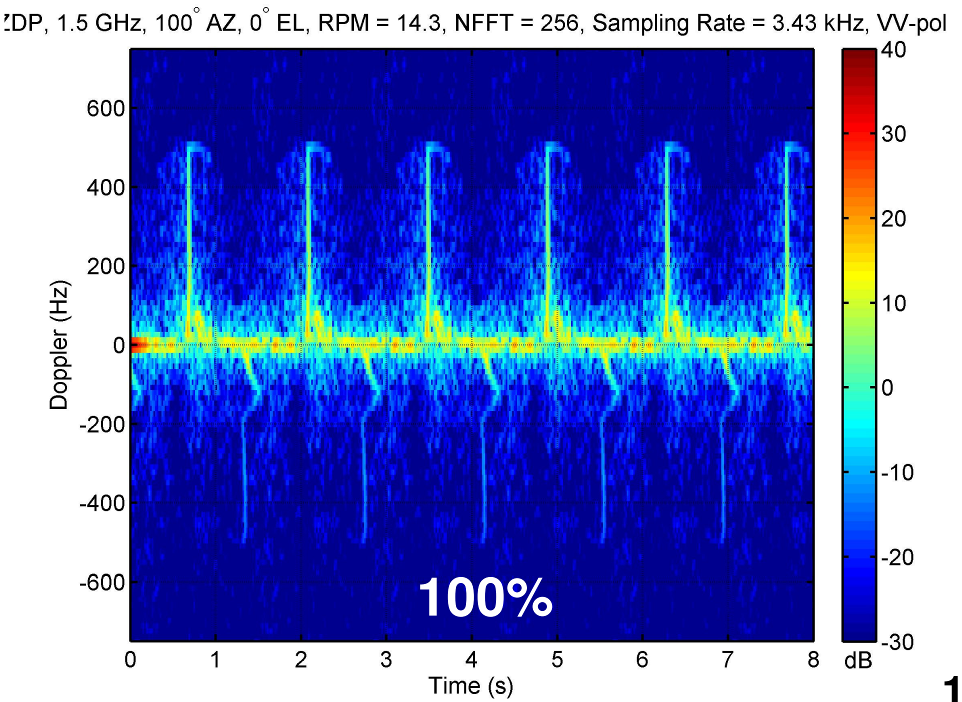


Hub, Blades, and Nose Cone

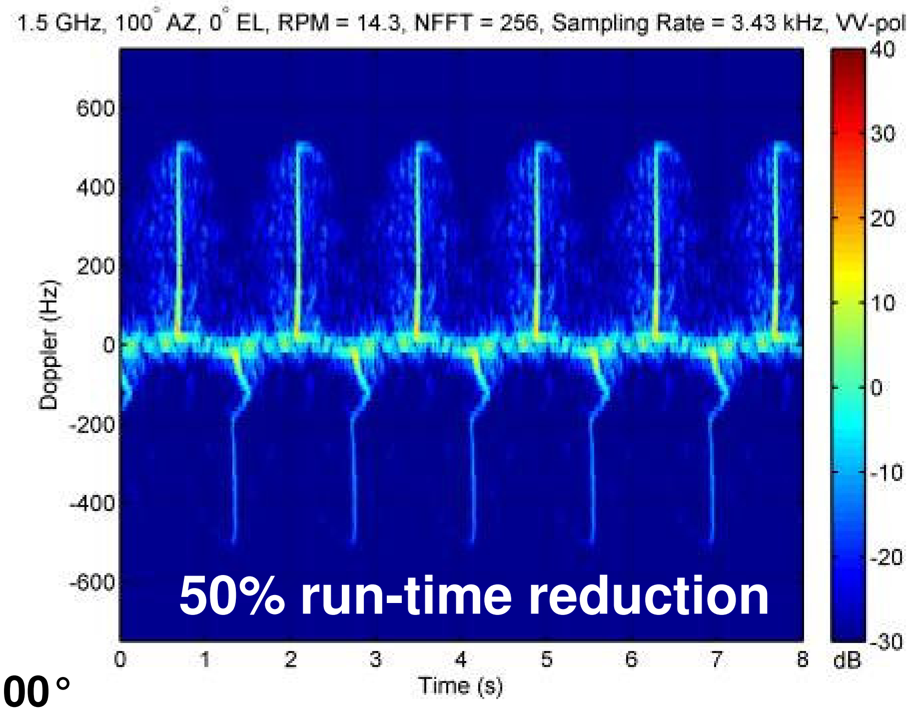
Entire Windmill vs. Only Rotational Parts

L-band, 100° AZ, 0° EL, RPM = 14.3, VV-pol

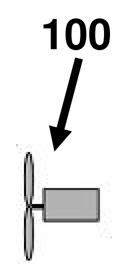
Spectrogram missing interaction between blades and tower



Entire Geometry



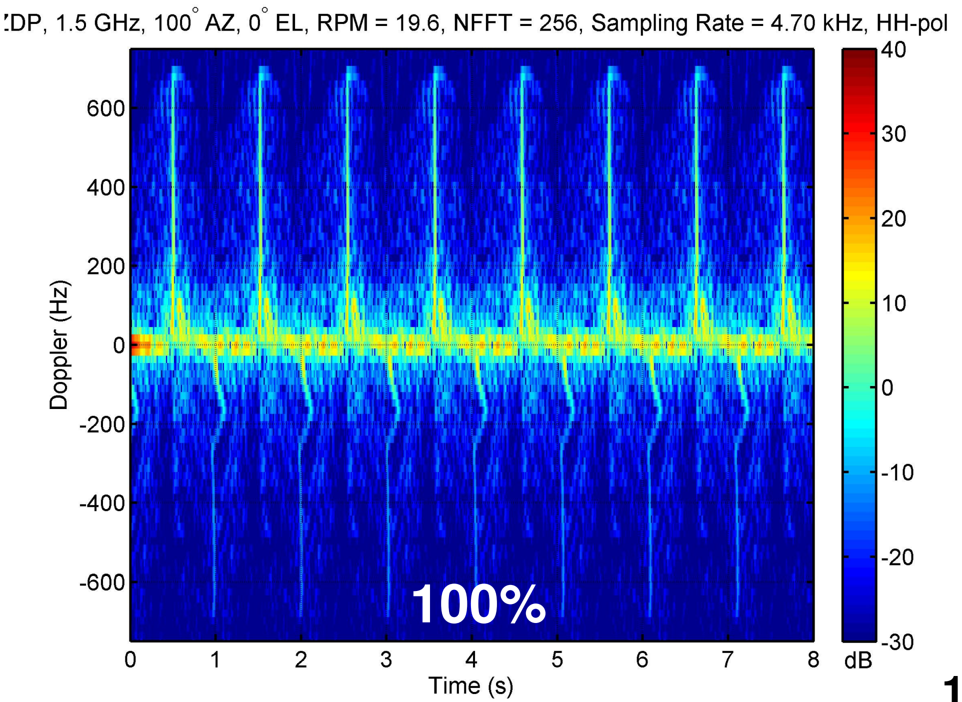
Hub, Blades, and Nose Cone

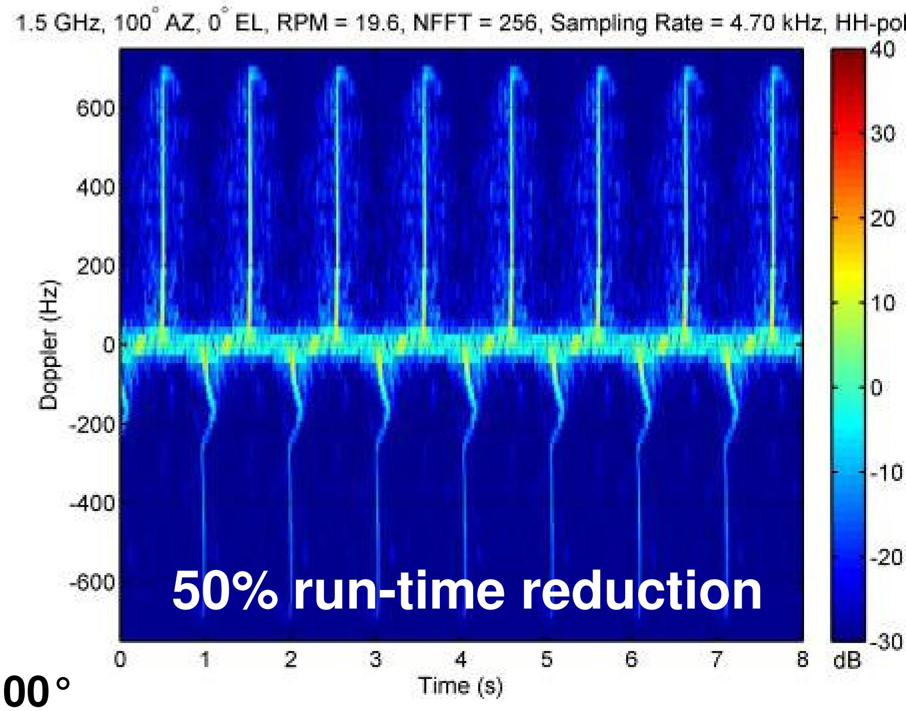


Entire Windmill vs. Only Rotational Parts

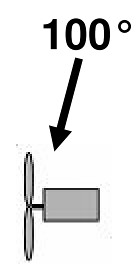
L-band, 100° AZ, 0° EL, RPM = 19.6, HH-pol

Spectrogram missing interaction between blades and tower





Entire Geometry

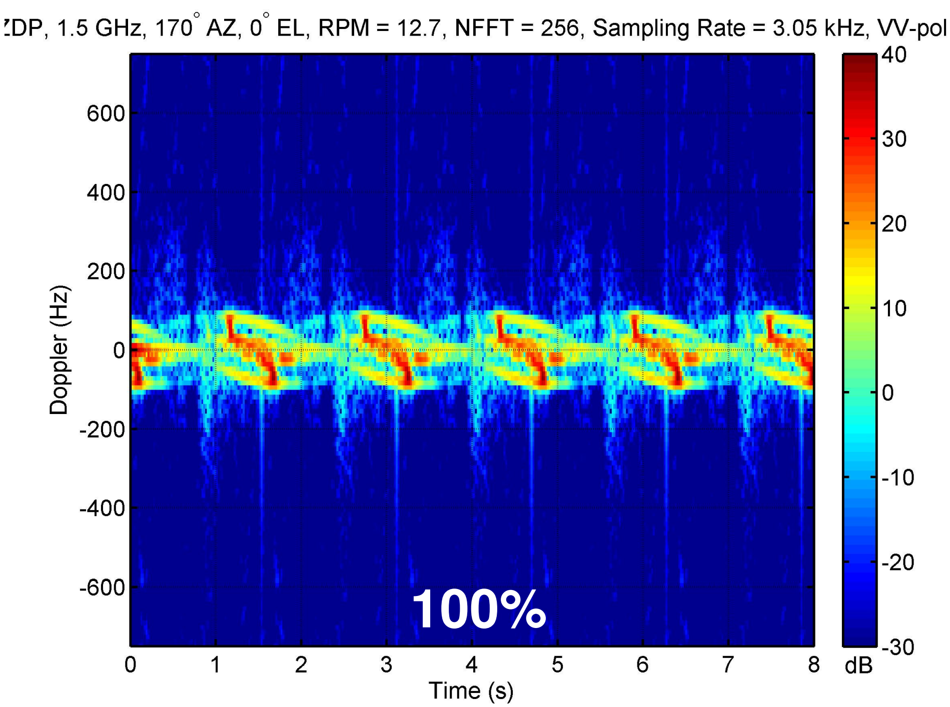


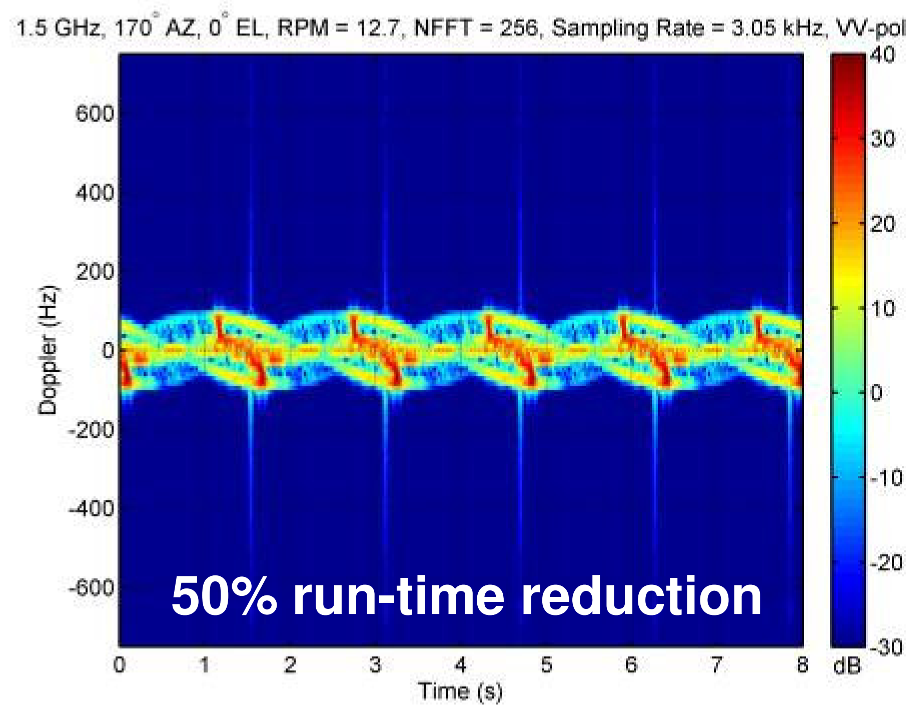
Hub, Blades, and Nose Cone

Entire Windmill vs. Only Rotational Parts

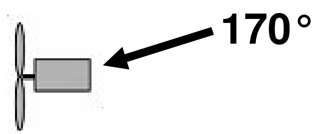
L-band, 170° AZ, 0° EL, RPM = 12.7, VV-pol

Spectrogram missing interaction between blades and tower





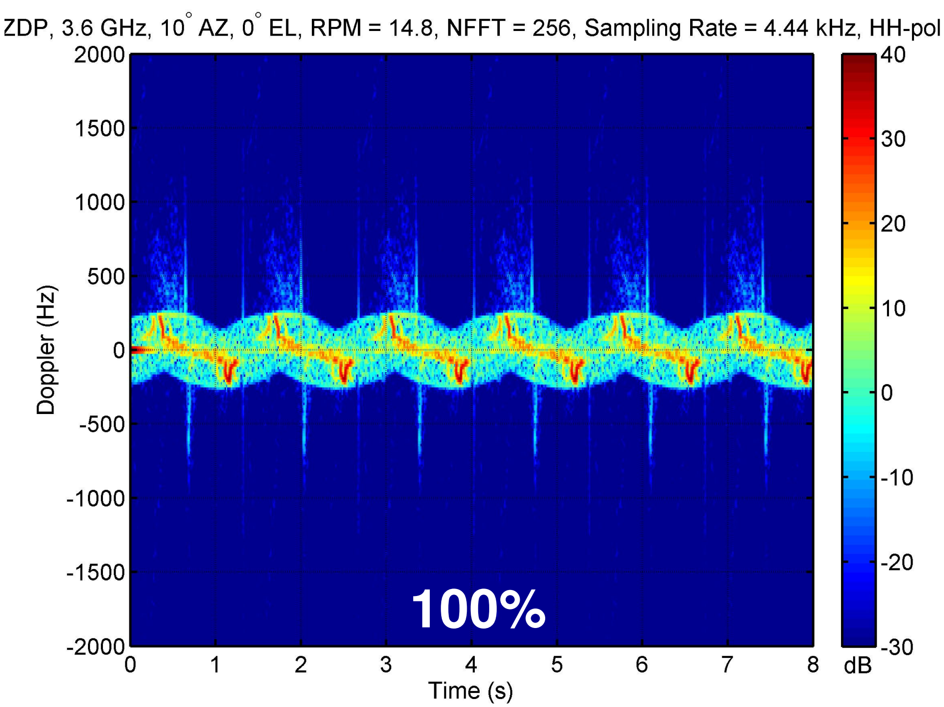
Entire Geometry **Hub, Blades, and Nose Cone**



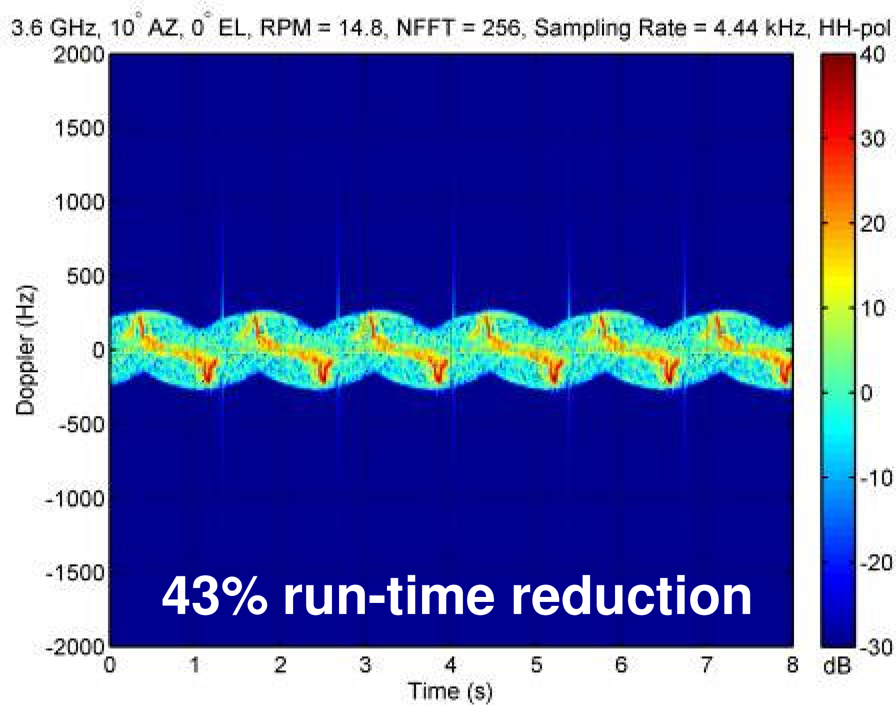
Entire Windmill vs. Only Rotational Parts

S-band, 10° AZ, 0° EL, RPM = 14.8, HH-pol

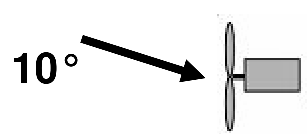
Spectrogram missing interaction between blades and tower



Entire Geometry



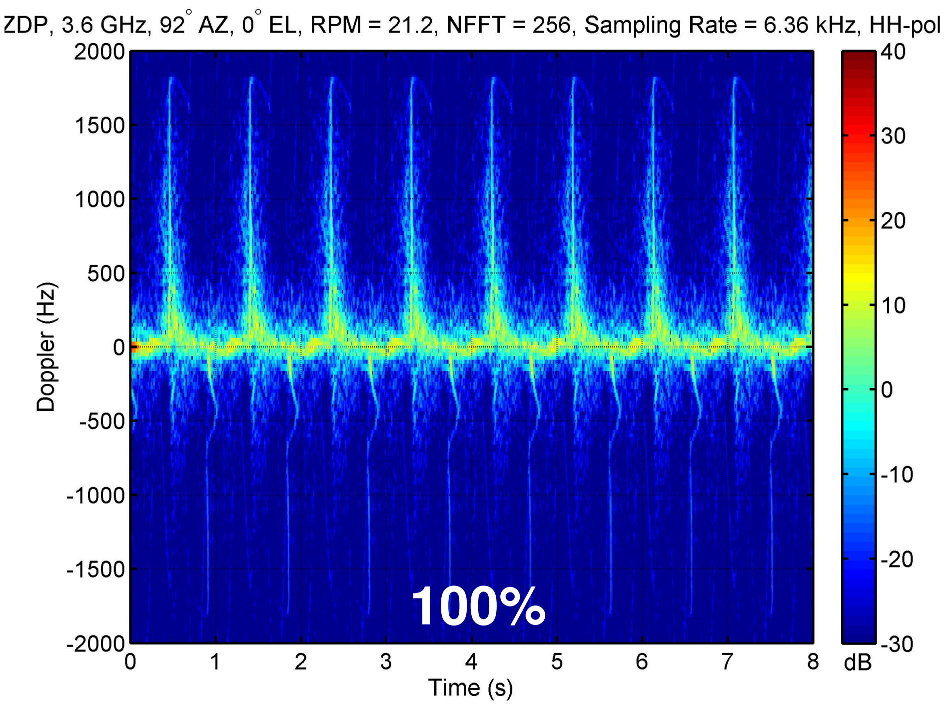
Hub, Blades, and Nose Cone



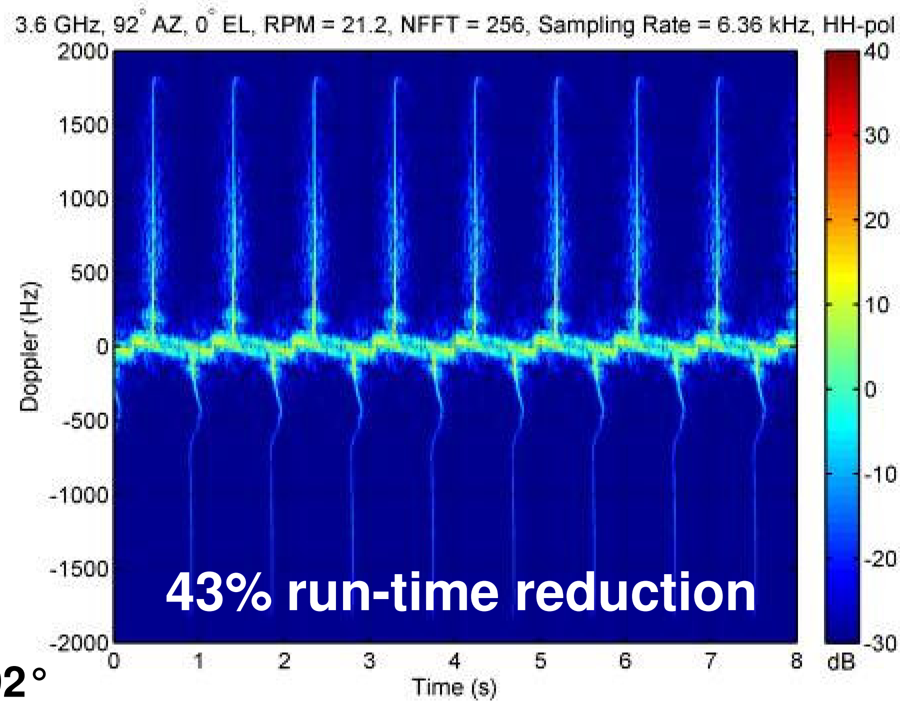
Entire Windmill vs. Only Rotational Parts

S-band, 92° AZ, 0° EL, RPM = 21.2, HH-pol

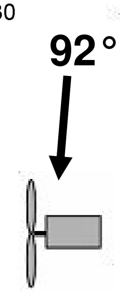
Spectrogram missing interaction between blades and tower



Entire Geometry



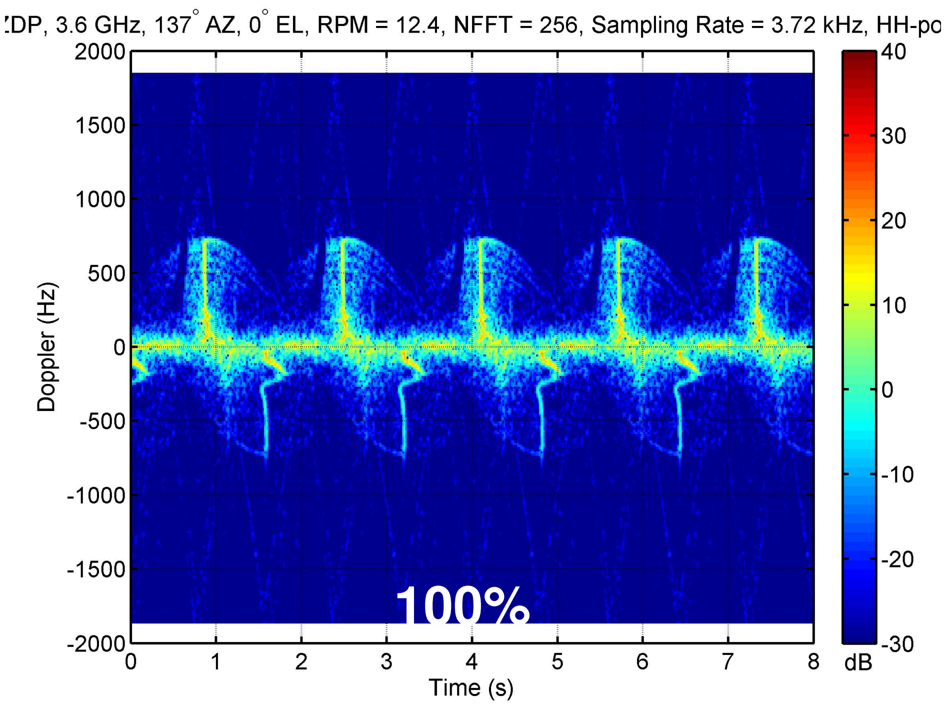
Hub, Blades, and Nose Cone



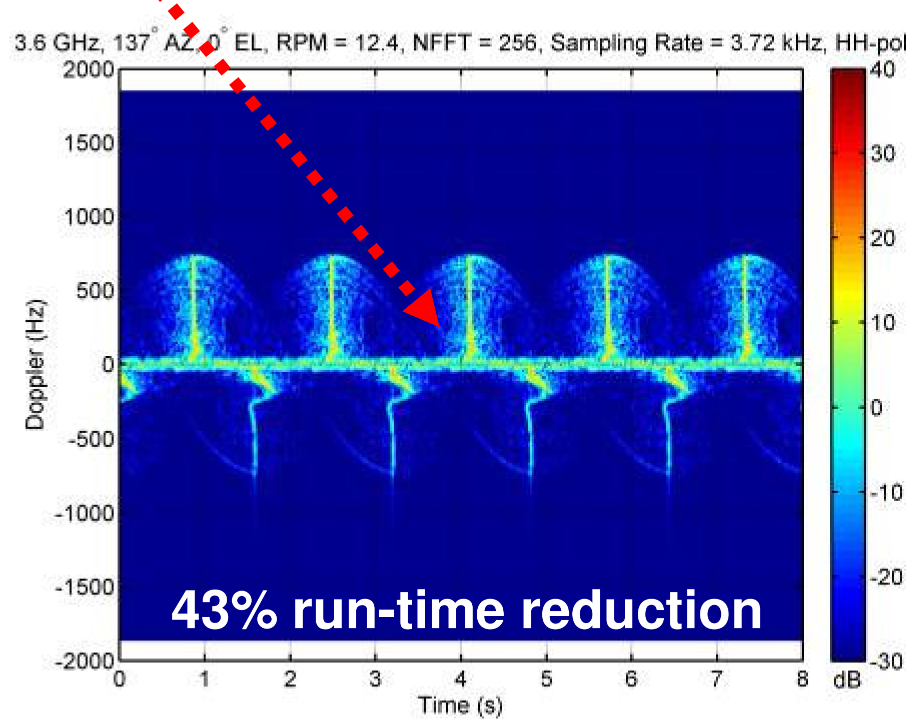
Entire Windmill vs. Only Rotational Parts

S-band, 137° AZ, 0° EL, RPM = 12.4, HH-pol

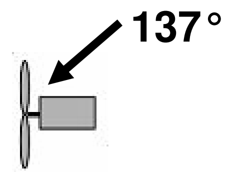
Note the shadowed regions do not appear without the tower



Entire Geometry



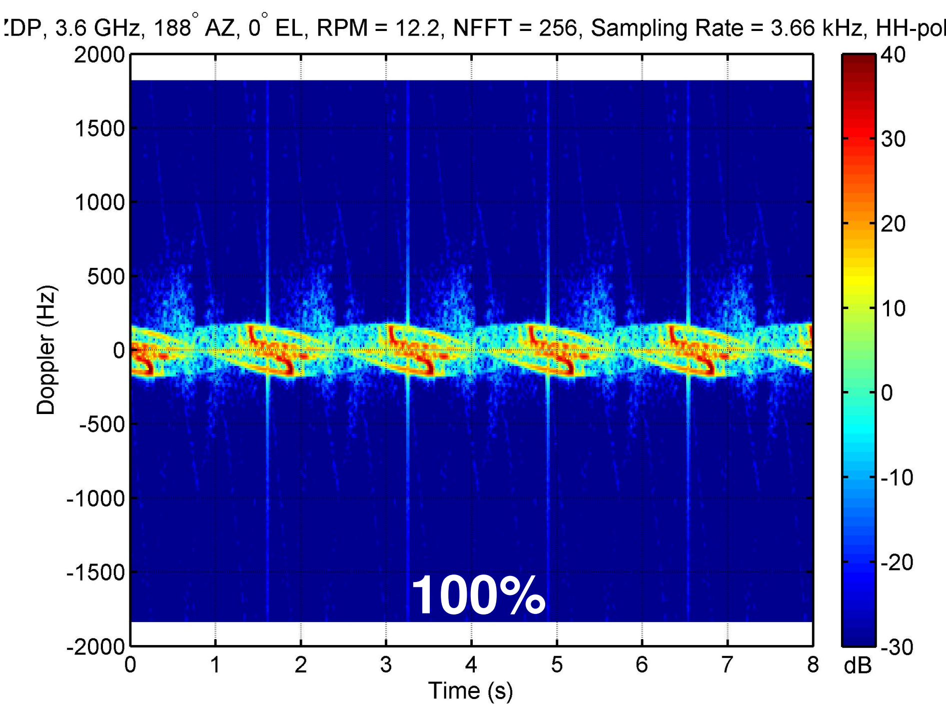
Hub, Blades, and Nose Cone

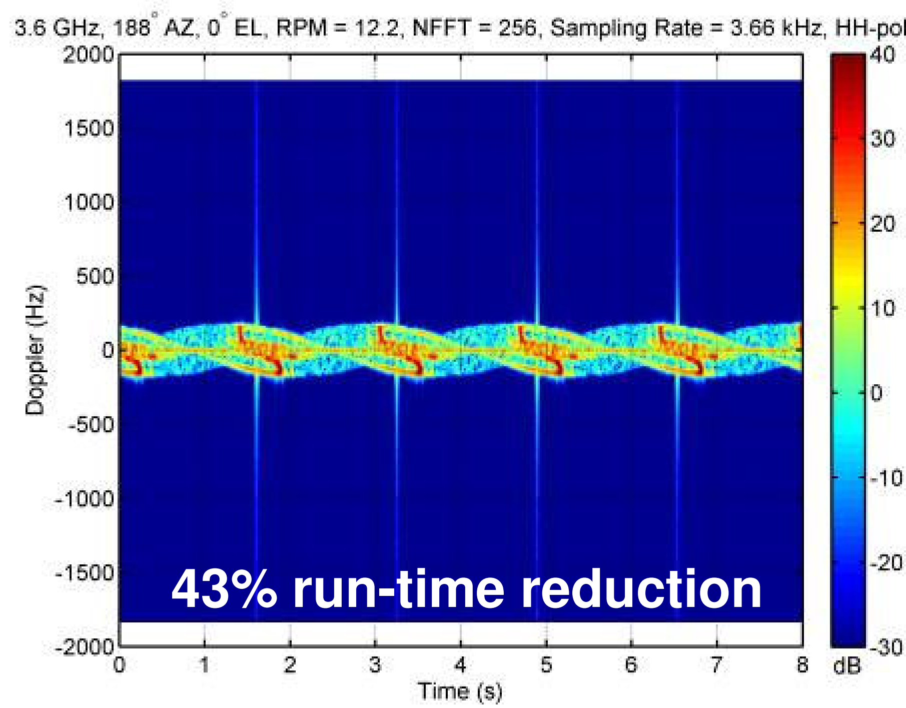


Entire Windmill vs. Only Rotational Parts

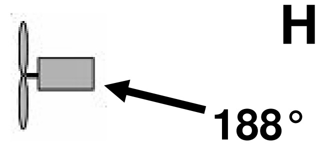
S-band, 188° AZ, 0° EL, RPM = 12.2, HH-pol

Spectrogram missing interaction between blades and tower





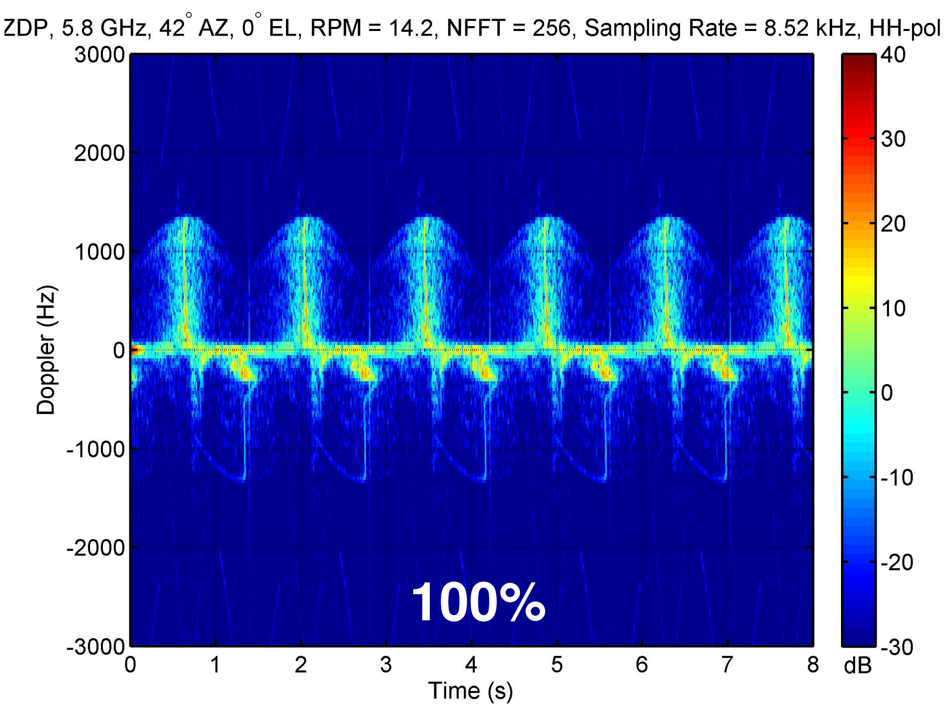
Entire Geometry | **Hub, Blades, and Nose Cone**

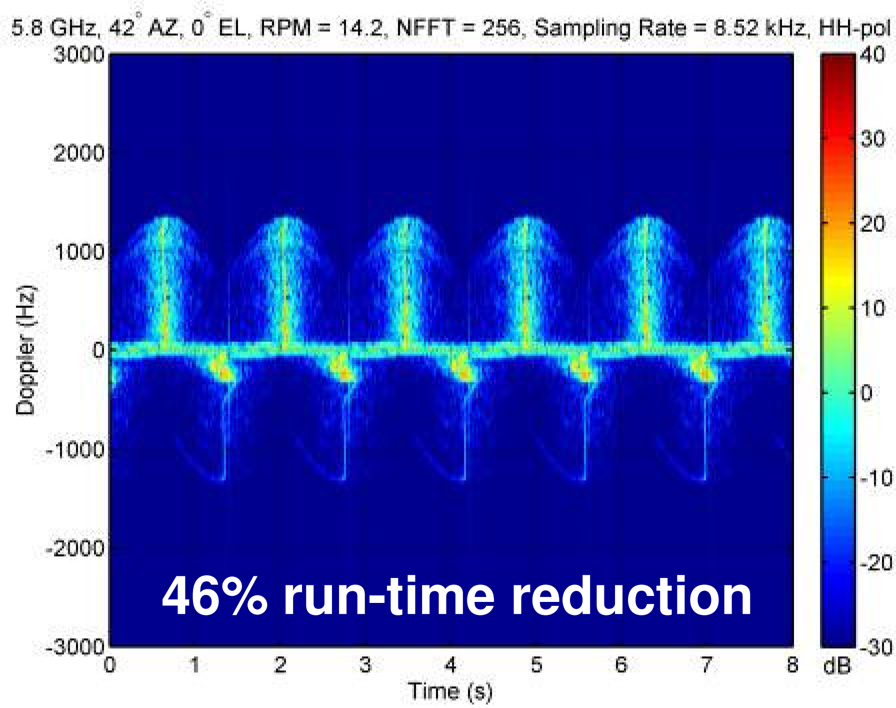


Entire Windmill vs. Only Rotational Parts

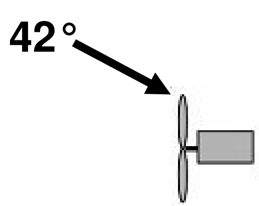
C-band, 42° AZ, 0° EL, RPM = 14.2, HH-pol

Spectrogram missing interaction between blades and tower





Entire Geometry

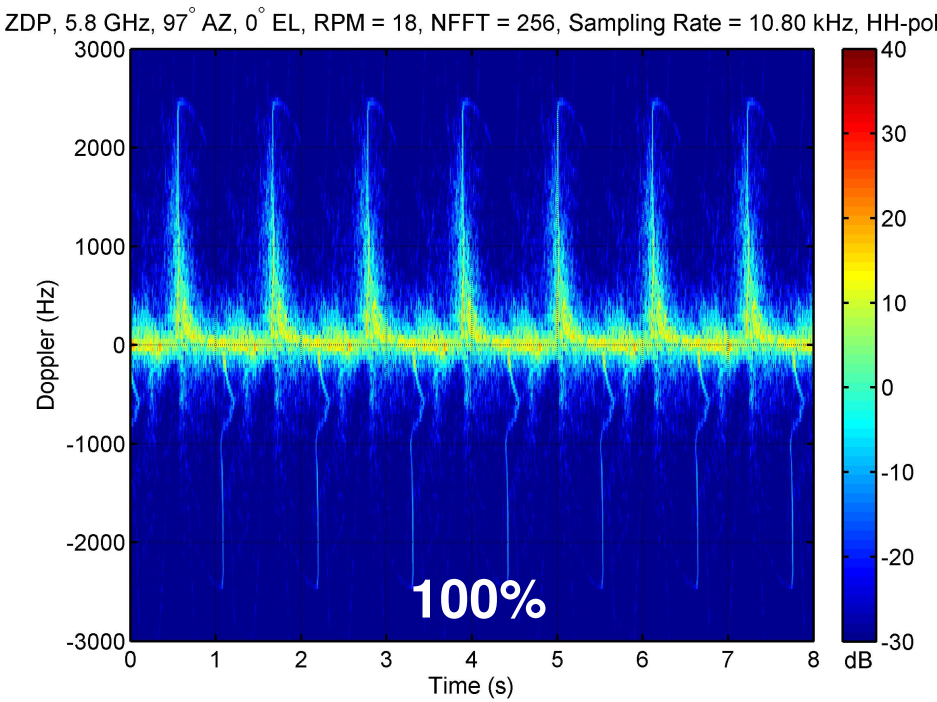


Hub, Blades, and Nose Cone

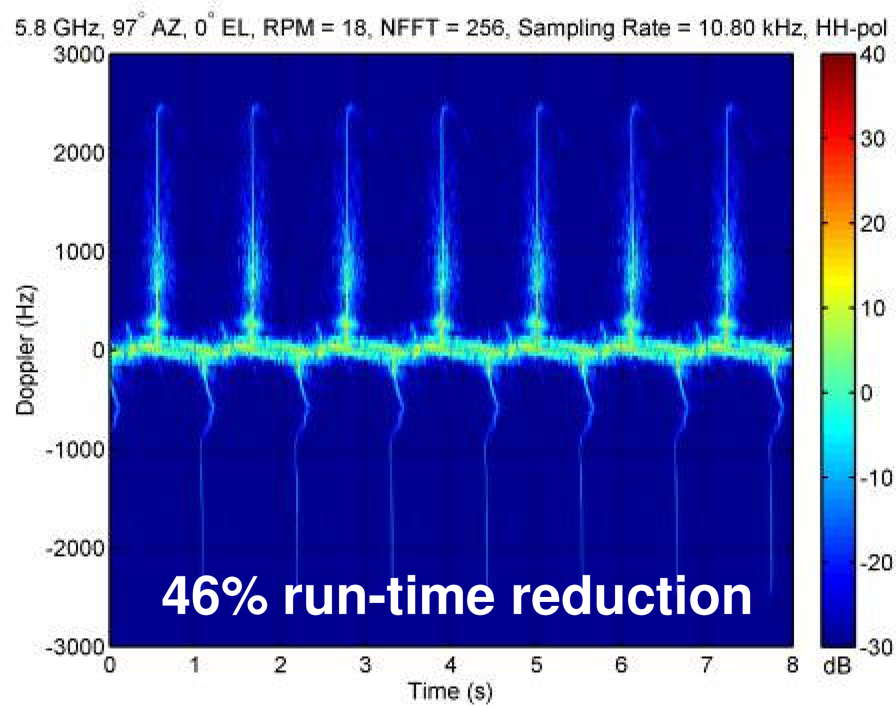
Entire Windmill vs. Only Rotational Parts

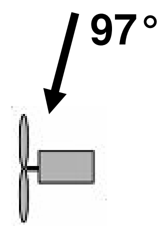
C-band, 97° AZ, 0° EL, RPM = 18.0, HH-pol

Spectrogram missing interaction between blades and tower



Entire Geometry



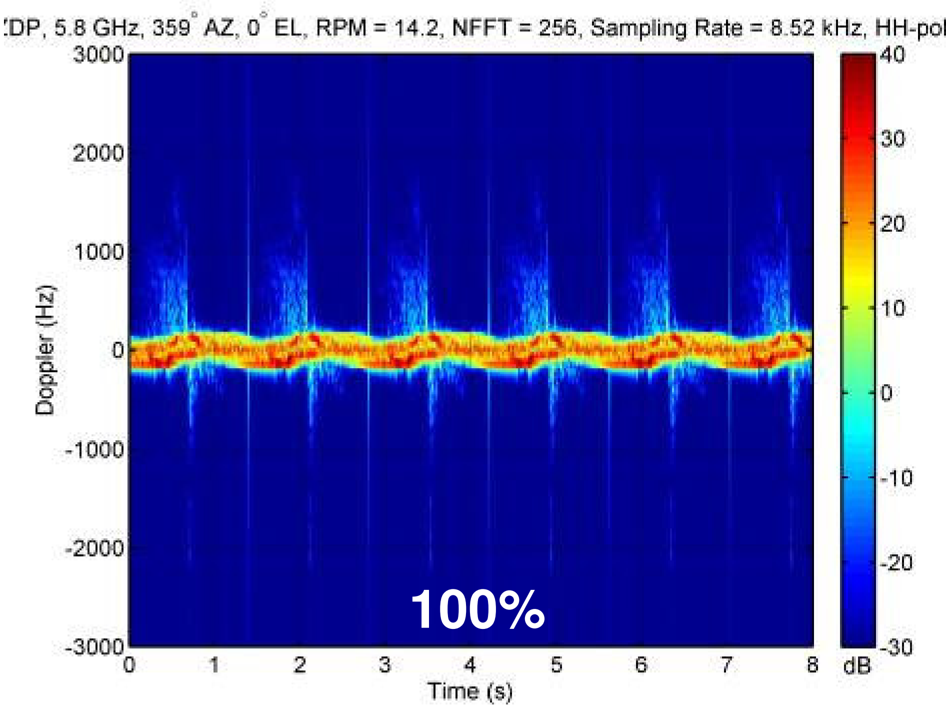


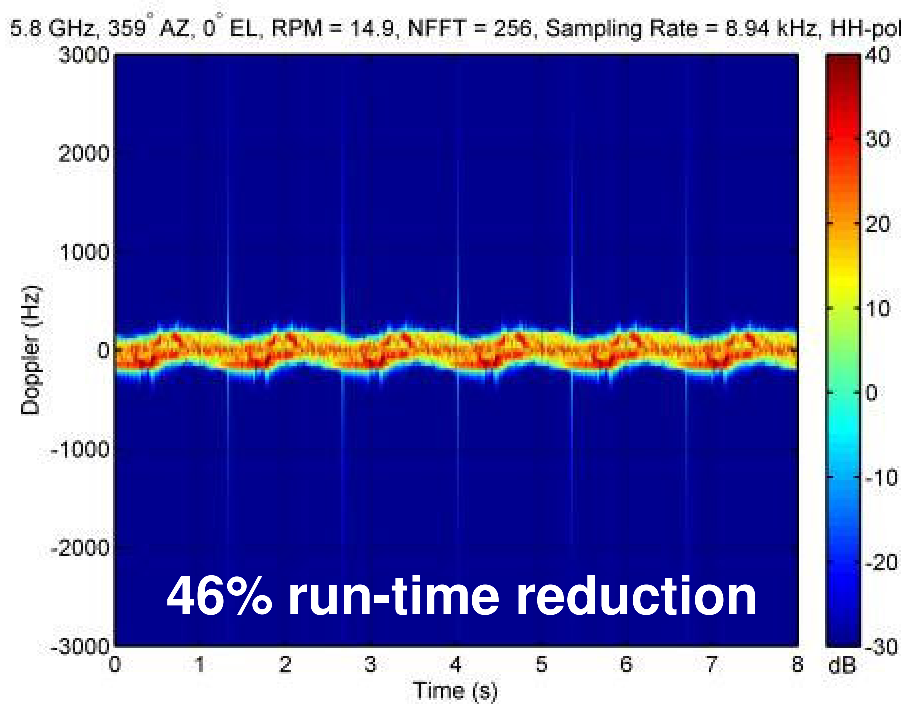
Hub, Blades, and Nose Cone

Entire Windmill vs. Only Rotational Parts

C-band, 359° AZ, 0° EL, RPM = 14.9, VV-pol

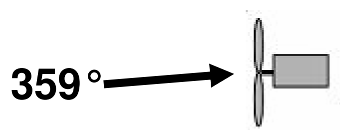
Spectrogram missing interaction between blades and tower





Entire Geometry

Hub, Blades, and Nose Cone



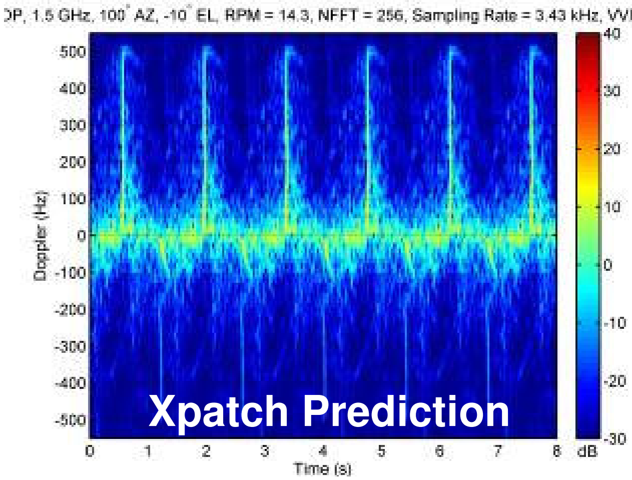
Maximum Doppler Estimation

L-band (1.5 GHz); Coarse Mesh; 4,800 rotations
S-band (3.6 GHz); Coarse Mesh; 6,000 rotations
C-band (5.8 GHz); Coarse Mesh; 12,000 rotations
Maximum Doppler for 12-22 RPM

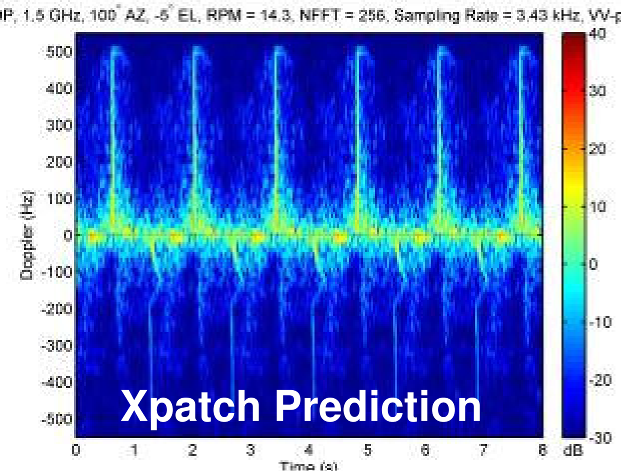
Maximum Doppler Estimation

L-band, 100° AZ, RPM = 14.3, VV-pol

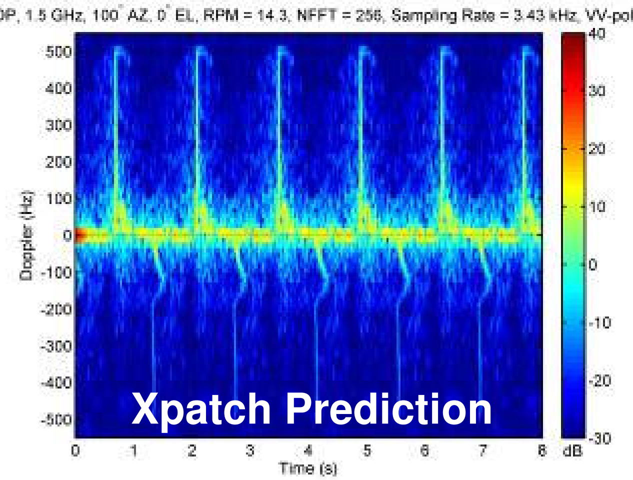
EL = -10°



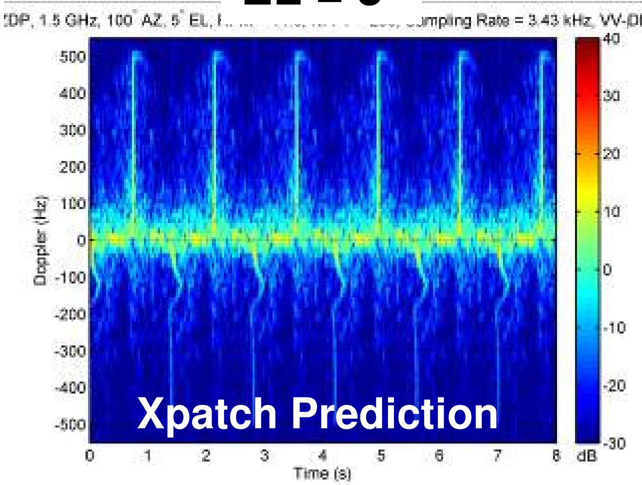
EL = -5°



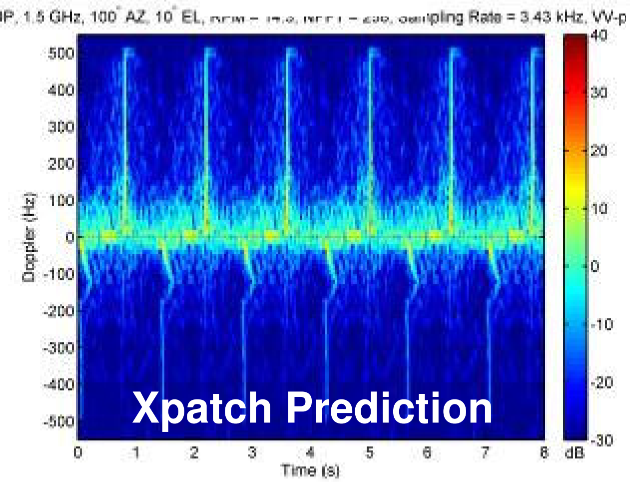
EL = 0°

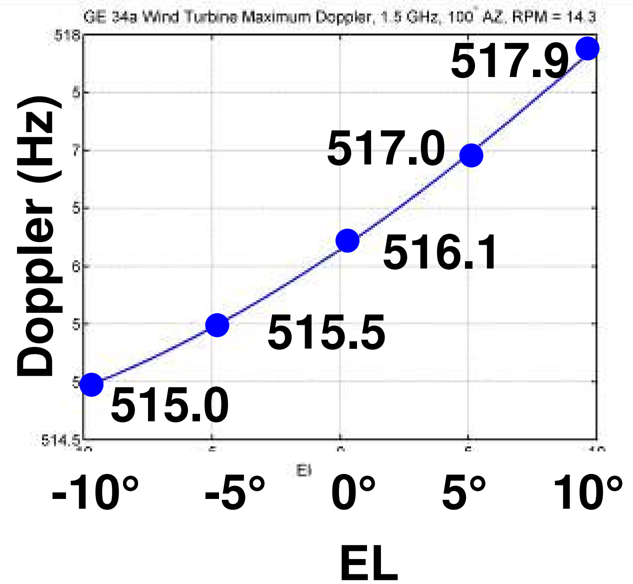


EL = 5°



EL = 10°

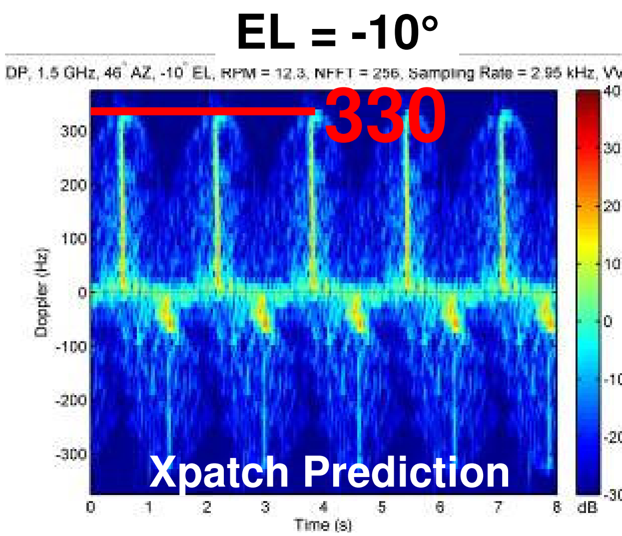


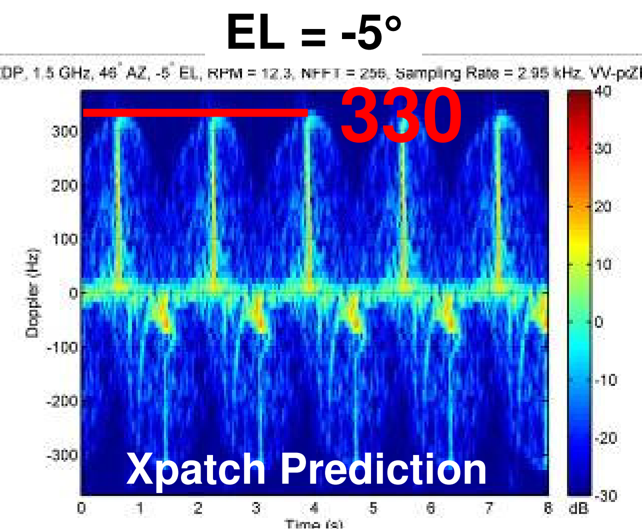


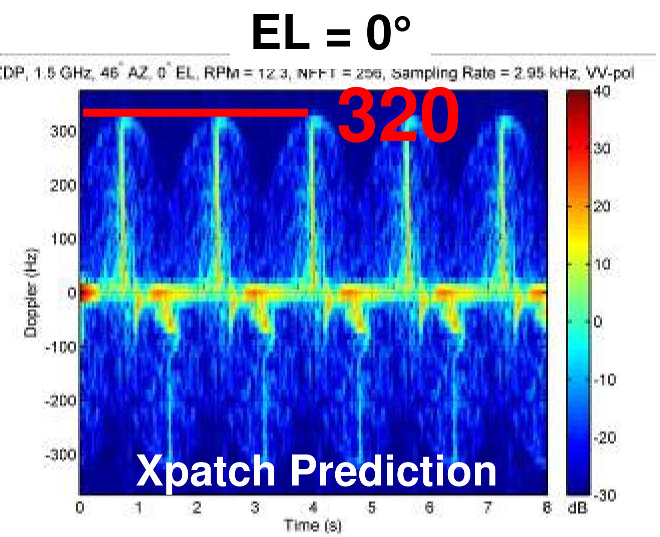
Maximum Doppler estimate accurate near 90° AZ

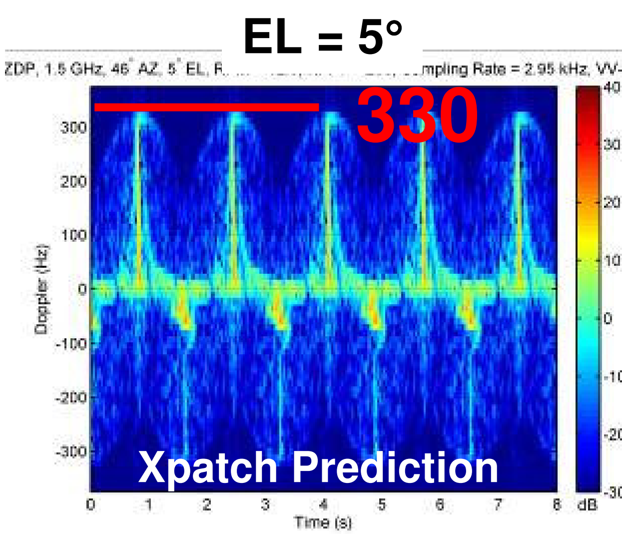
Maximum Doppler Estimation

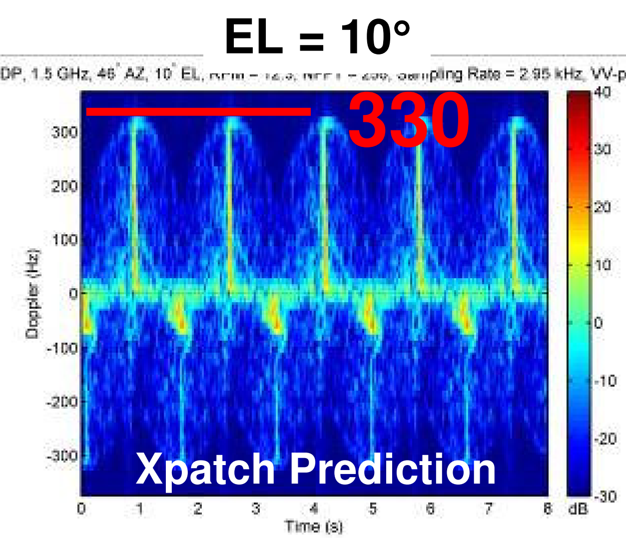
L-band, 46° AZ, RPM = 12.3, VV-pol

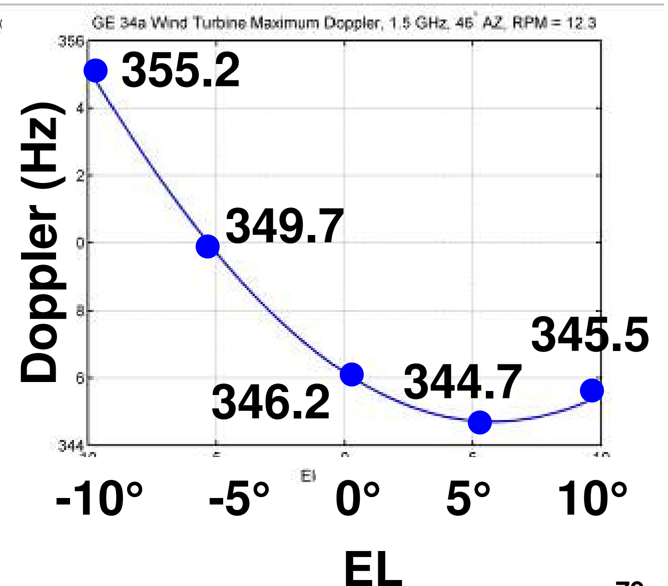










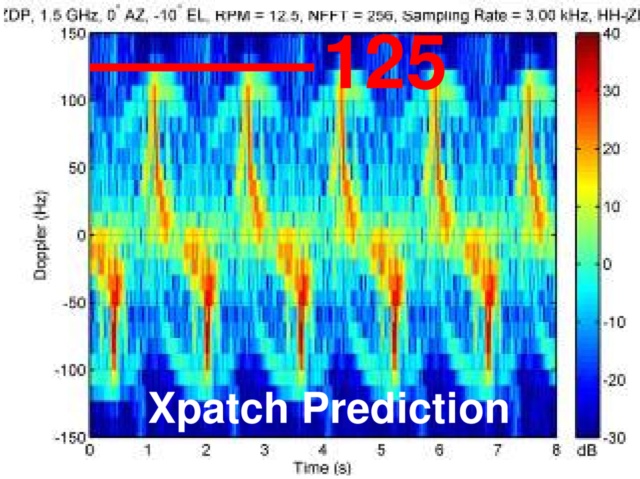


Maximum Doppler estimate reasonable near 45° AZ

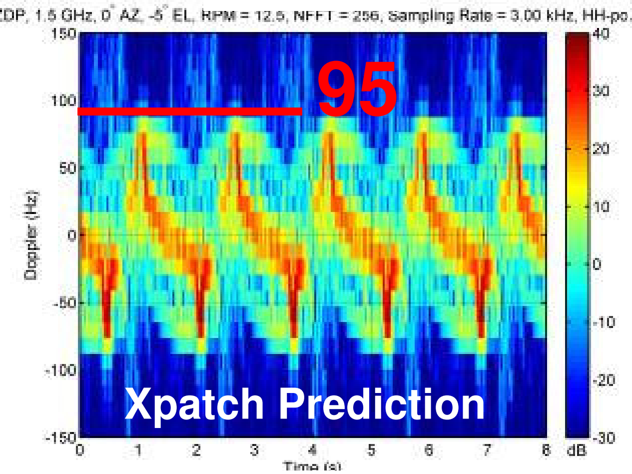
Maximum Doppler Estimation

L-band, 0° AZ, RPM = 12.5, HH-pol

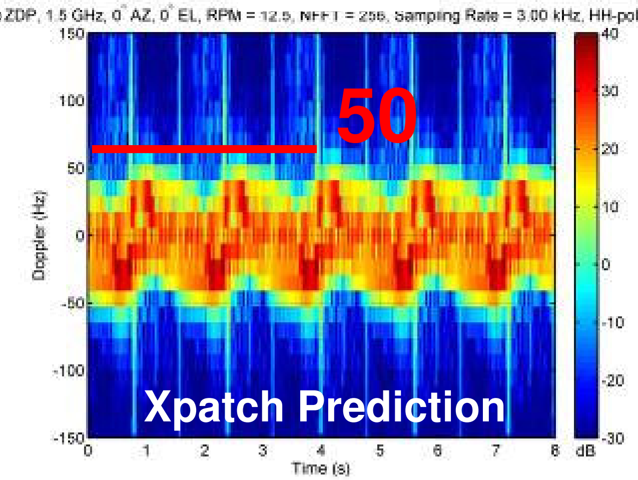
EL = -10°



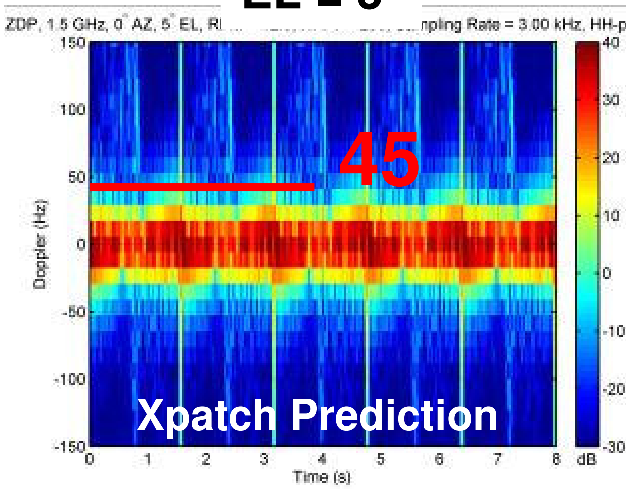
EL = -5°



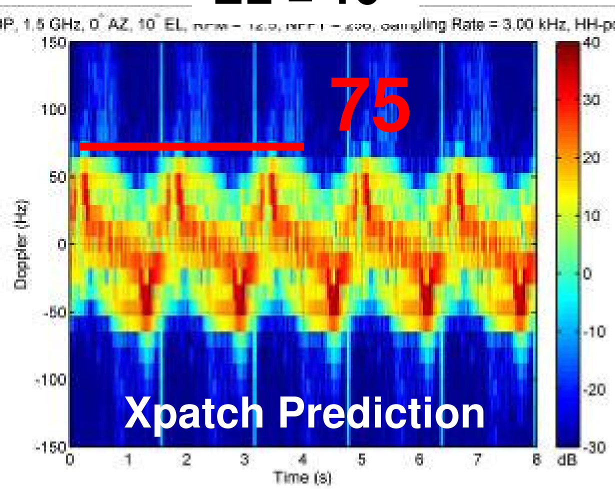
EL = 0°

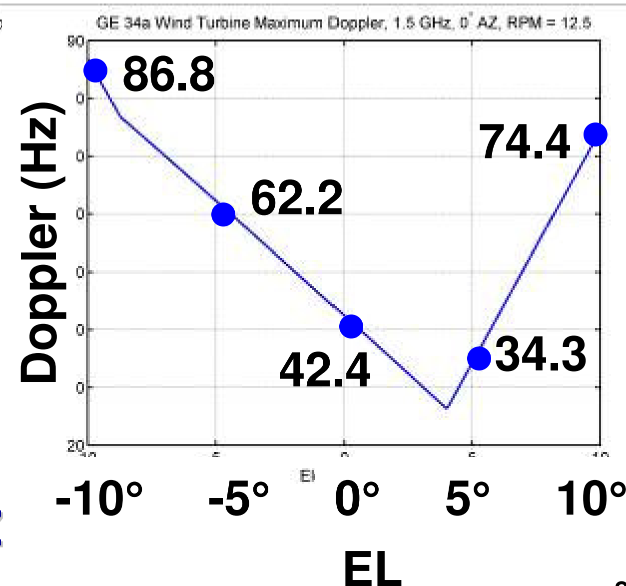


EL = 5°



EL = 10°





Maximum Doppler estimate NOT accurate near 0° AZ

Summary (1)

- **Geometry preparation is tedious and time consuming**
- **Spectrogram captures major Doppler effects with only**
  - Using a very coarse geometry mesh
  - Sampling at Nyquist rate
  - Simplifying hub/nacelle/tower geometry
  - Including only rotating parts
- **Prediction can produce accurate RCS, but can be improved with**
  - a more precise geometry
  - finer mesh
  - known pitch angle
  - higher rotational angle sampling rate
  - actual material and internal structure
- **Knowledge of radar systems crucial in determining prediction accuracy requirements**

Summary (2)

Measurement vs. Prediction

- **Measurement**
  - Can measure "as built" configuration
  - Include all RF effects
  - Includes dynamic effects of bending and twisting of composite blades
- **Prediction**
  - Is not limited to certain azimuth and elevation angles
  - Is not limited by weather and measurement equipment availability
  - Can predict systems before they are built