Mitigating Wind Turbine Interference in the US HF Radar Network

Dale Trockel[1], Anthony Kirincich[2], Brian Emery[3], Hugh Roarty[4], Josh Trockel[1], Chad Whelan[1]

1 CODAR OCEAN SENSORS

2 WOODS HOLE OCEANOGRAPHIC INSTITUTION

3 UC SANTA BARBARA

4 RUTGERS

Talk Outline

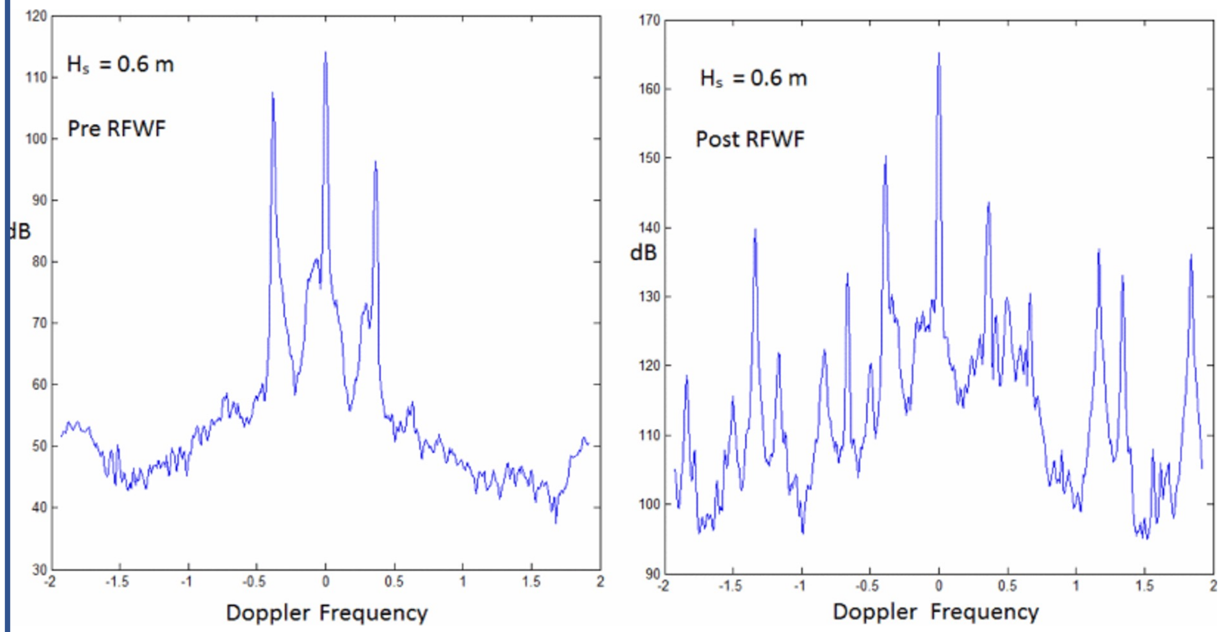
- Background
- Mitigation Methods
- Status / Next Steps
- Summary

Talk Outline

- Background
- Mitigation Methods
- Status / Next Steps
- Summary

Cause Of WTI in HF Radar

2011



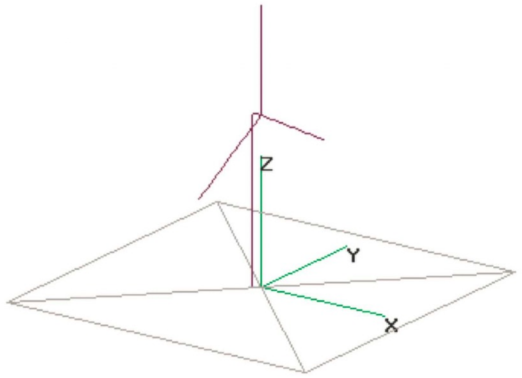
L. R. Wyatt, A. M. Robinson and M. J. Howarth, "Wind farm impacts on HF radar current and wave measurements in Liverpool Bay," *OCEANS 2011 IEEE - Spain*, Santander, 2011, pp. 1-3.

2012

Estimation of Wind Turbine Radar Signature at 13.5 MHz

Calvin C. Teague and Donald E. Barrick
CODAR Ocean Sensors, Ltd.
1914 Plymouth Street, Mountain View, CA 94303
Email: cal@codar.com, don@codar.com

***Abstract*—The radar cross sections (RCS) and frequency spectra of a wind turbine consisting of three conducting blades of 42.0 m radius, with a vertical mast of 65 m over a perfect ground plane, was estimated using the Numerical Electromagnetics Code (NEC). The NEC input deck, parsing the NEC output to select the RCS numbers, plotting the time series, and calculating and plotting the frequency spectra were all done by bash shell scripts. The shell scripts generally set up several environment variables and then called Ruby, Octave or Gnuplot programs to perform the text manipulations, data calculations and plot generation. Calibrated plots of time series and frequency spectra for several cases are included.**



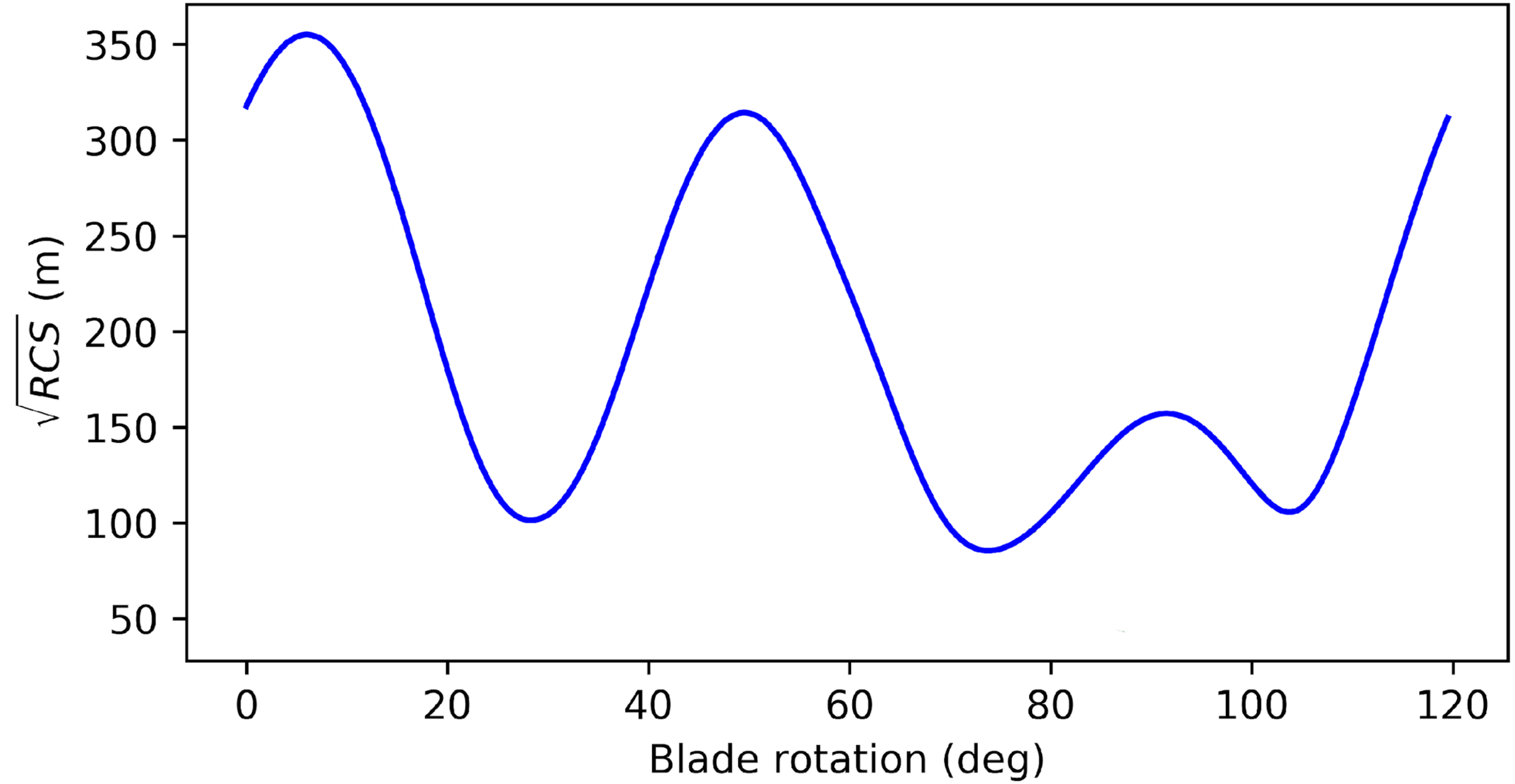
I. Introduction

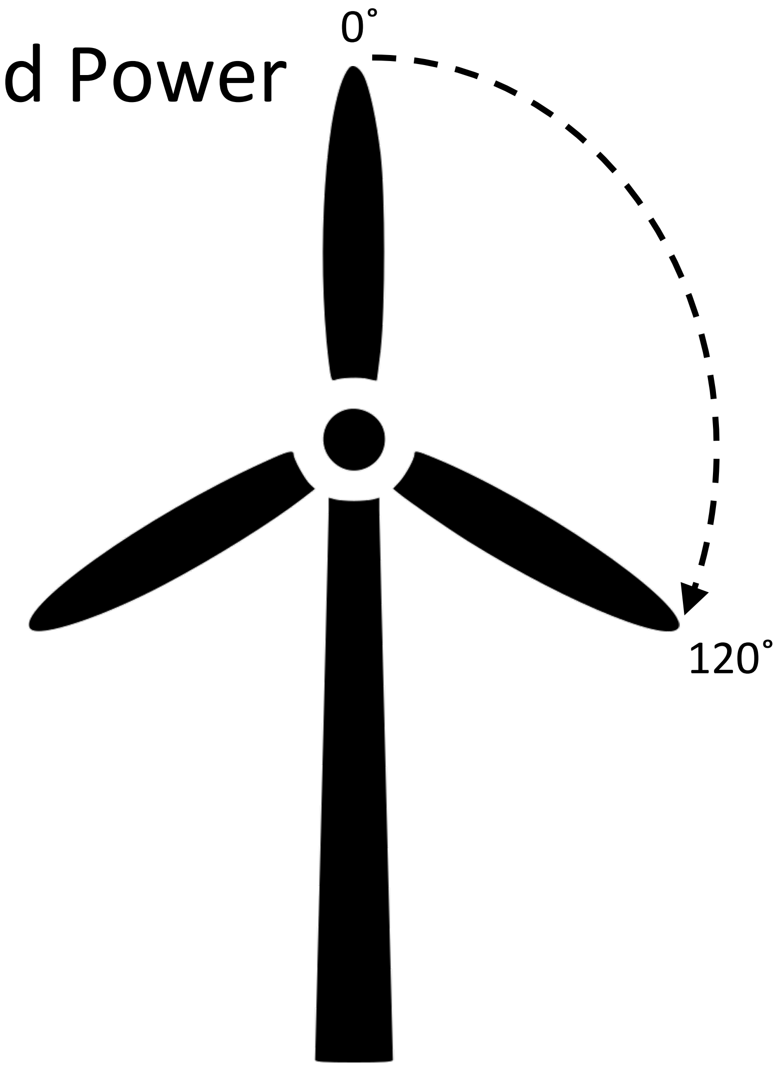
As offshore wind turbines are developed and deployed, high-frequency (HF) radar networks are being installed to aid in planning and operating large wind farms. In addition,

WTRIM - HF

Cause Of WTI in HF Radar

Periodic Radar Cross Section = Periodic Reflected Power

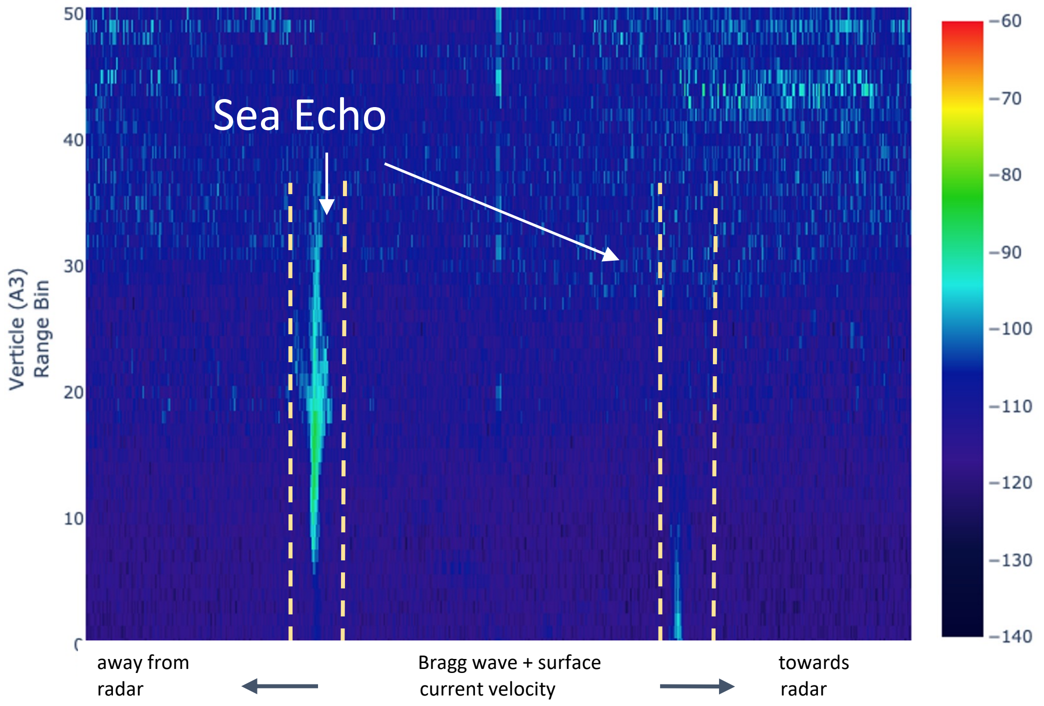


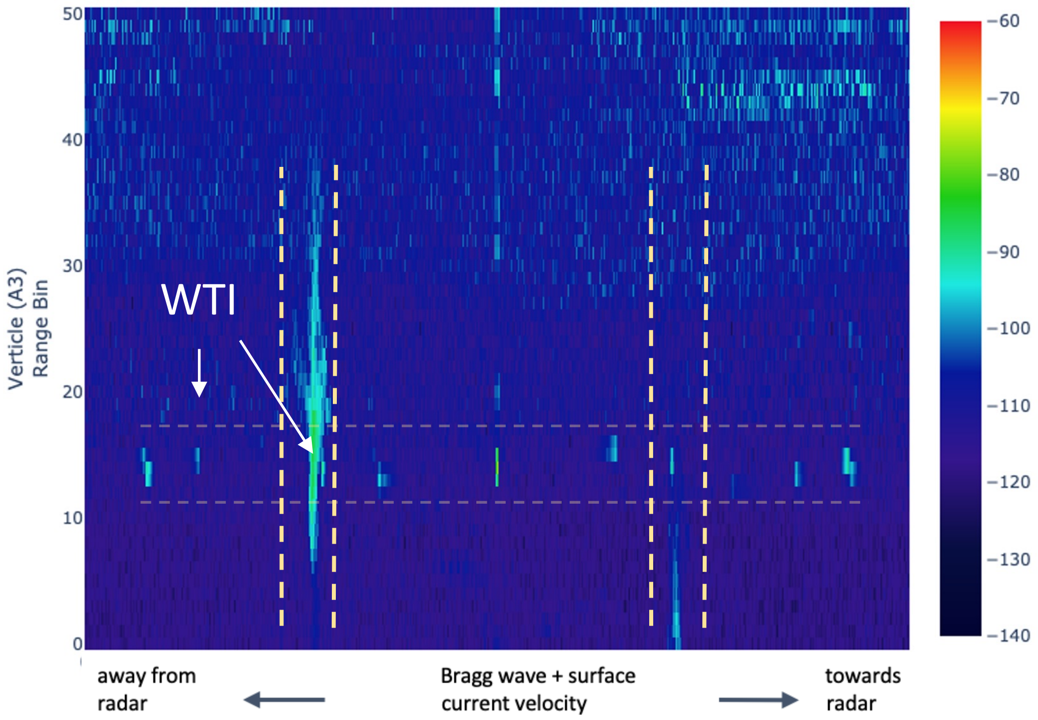


WTRIM - HF

Interference mechanism for HF is different from air traffic control or weather radars

WTI Appearance in HF Radar (4.5 MHz)

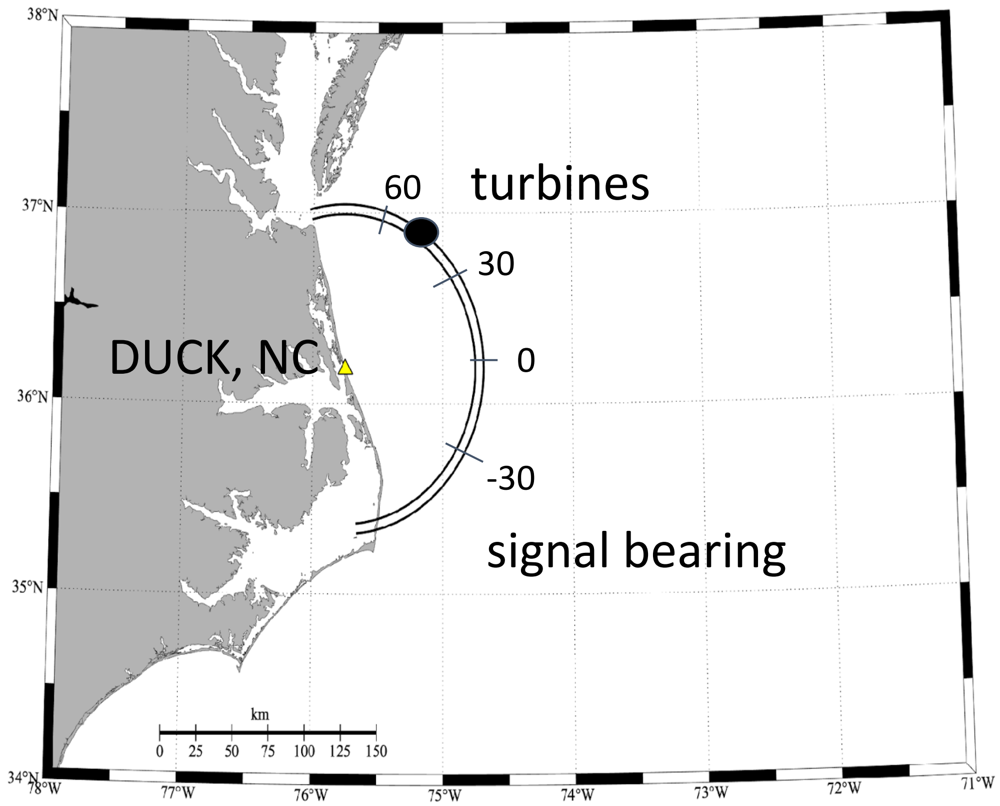


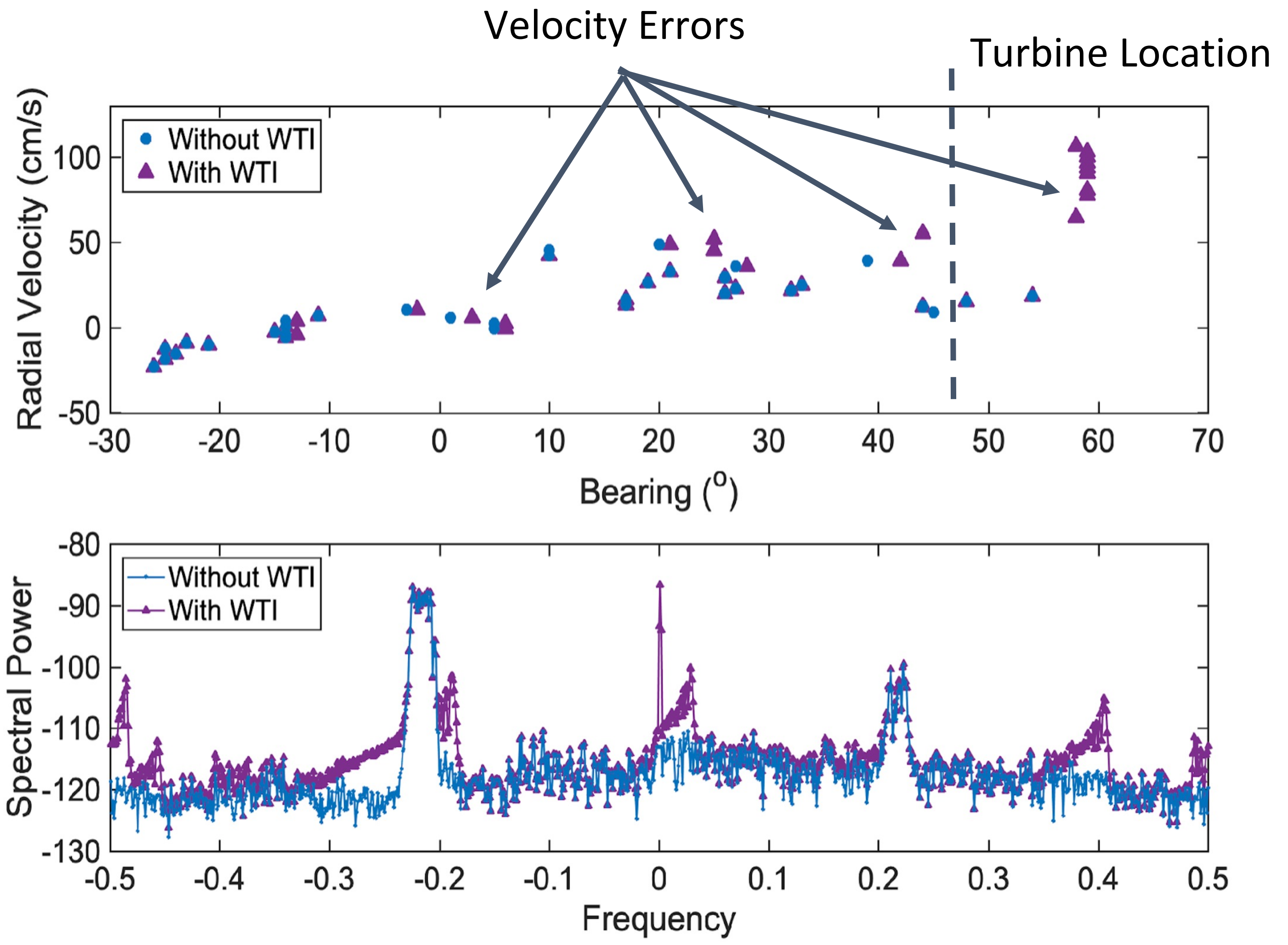


Periodic RCS can produce harmonic peaks (WTI) in HFR Doppler spectra that can contaminate sea echo

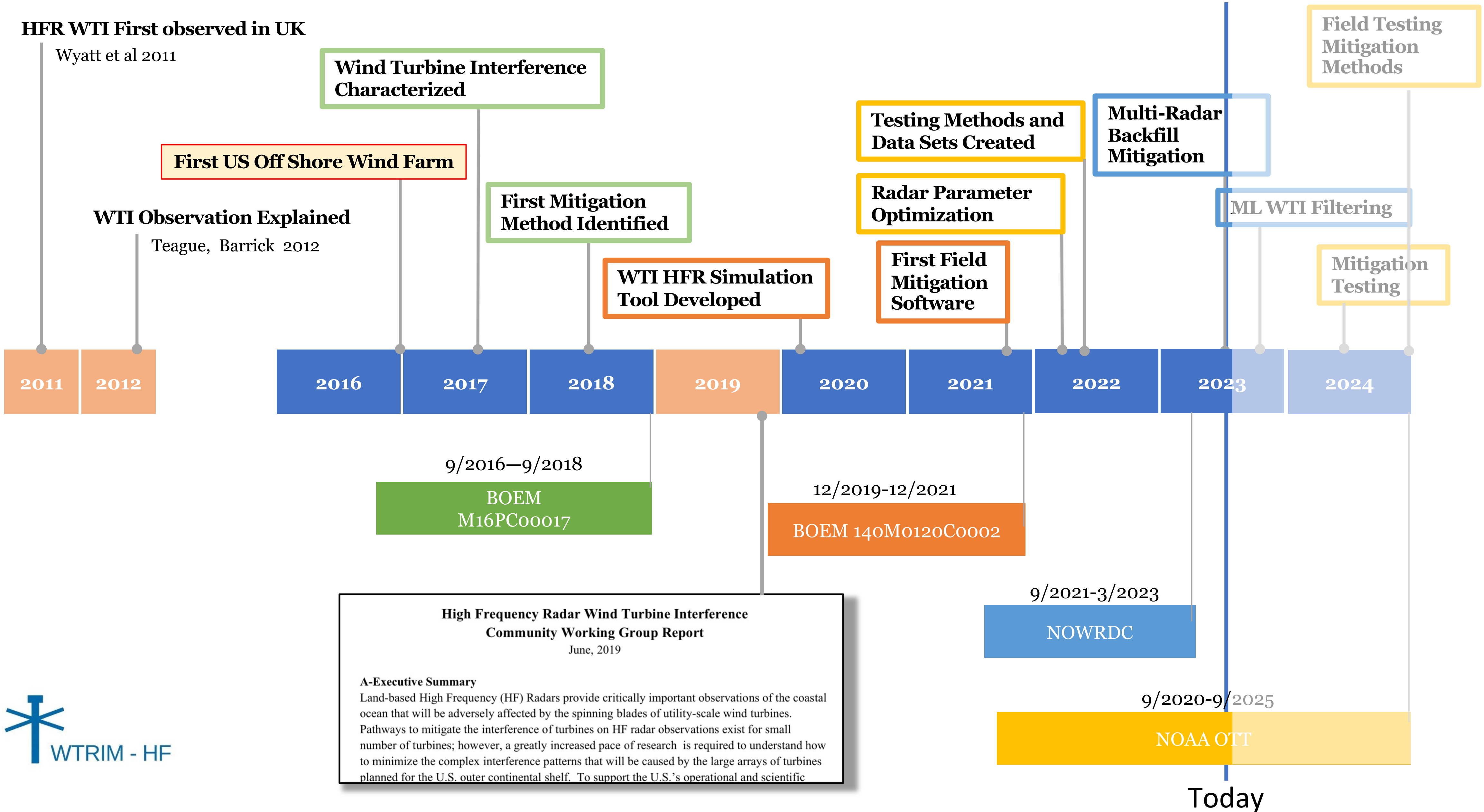
WTI: Example Impact on Radial Velocities

Shown with OTT-supported simulations, variable rotation rates cause challenging WTI.





Timeline of HFR WTI Mitigation Efforts

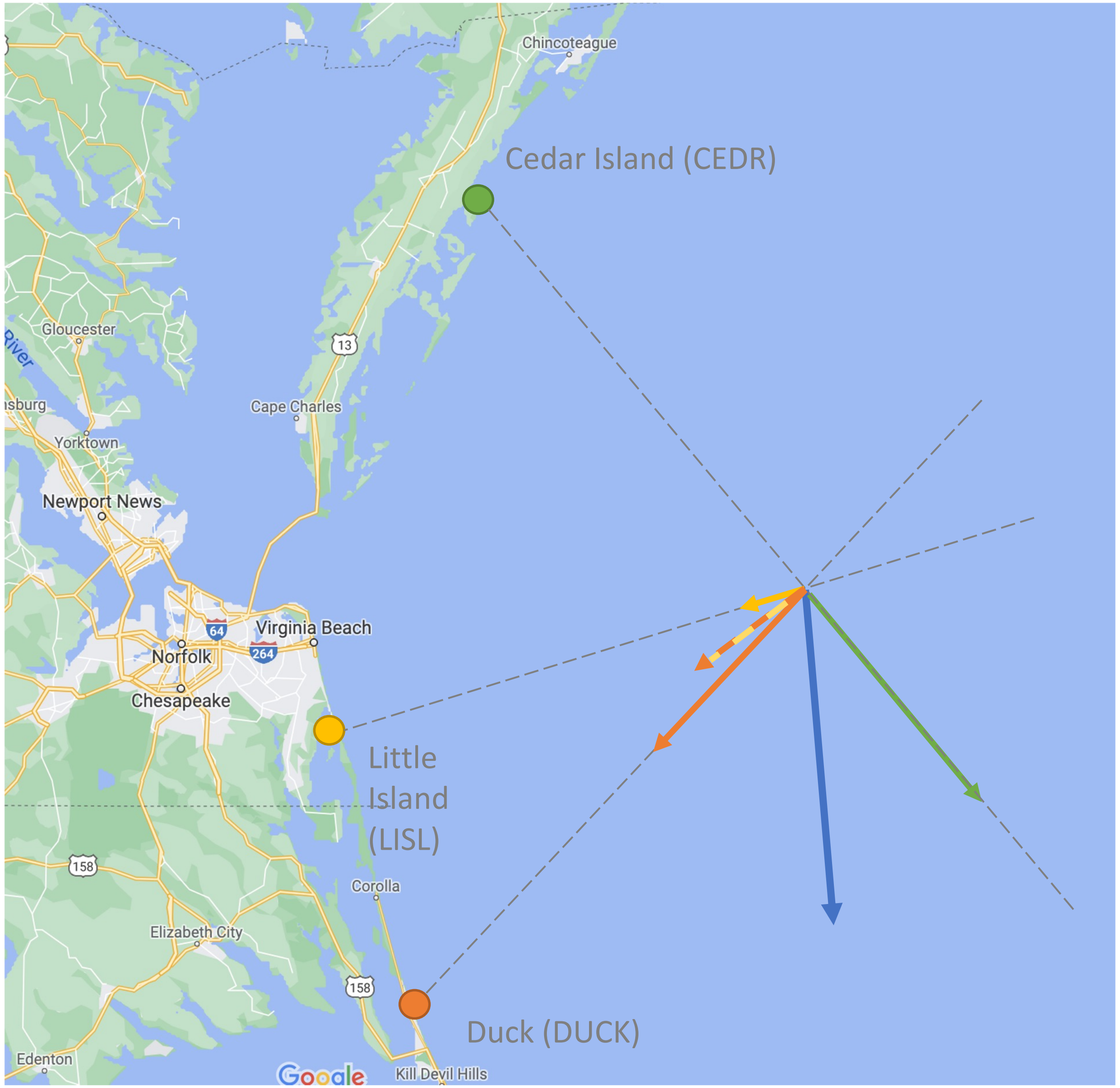


WTRIM - HF

NOWRDC

DELIVERABLES

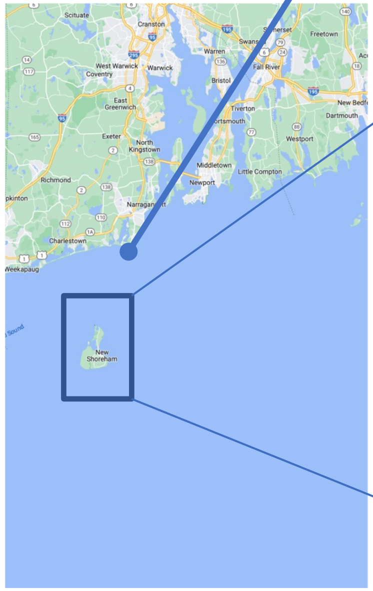
- **<u>Software to simulate WTI</u>** in HF radar data with the ability to capture the effects of **variable rotation rates**
- **<u>Machine Learning models</u>** that accurately estimate turbine rotation rates, rotation rate variability, and yaw angle from HF radar Doppler spectra
- **<u>Bistatic currents</u>** to reduce the impacts of WTI and WTI mitigation

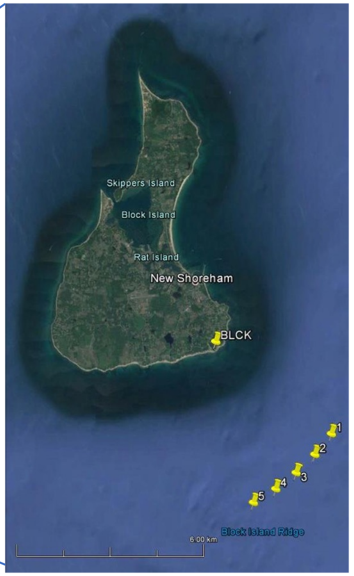


WTRIM - HF

DELIVERABLES

- <u>**software to simulate WTI**</u> and assess the impact of an offshore wind farm on HFR measurements
- <u>**validation data sets and test procedures**</u> that can be used to develop mitigation tools
- assessment of the <u>**best practices for HF radar**</u> operation within potential WTI areas
- <u>**software to detect and remove, or mitigate, WTI impact**</u> on ocean surface current measurements



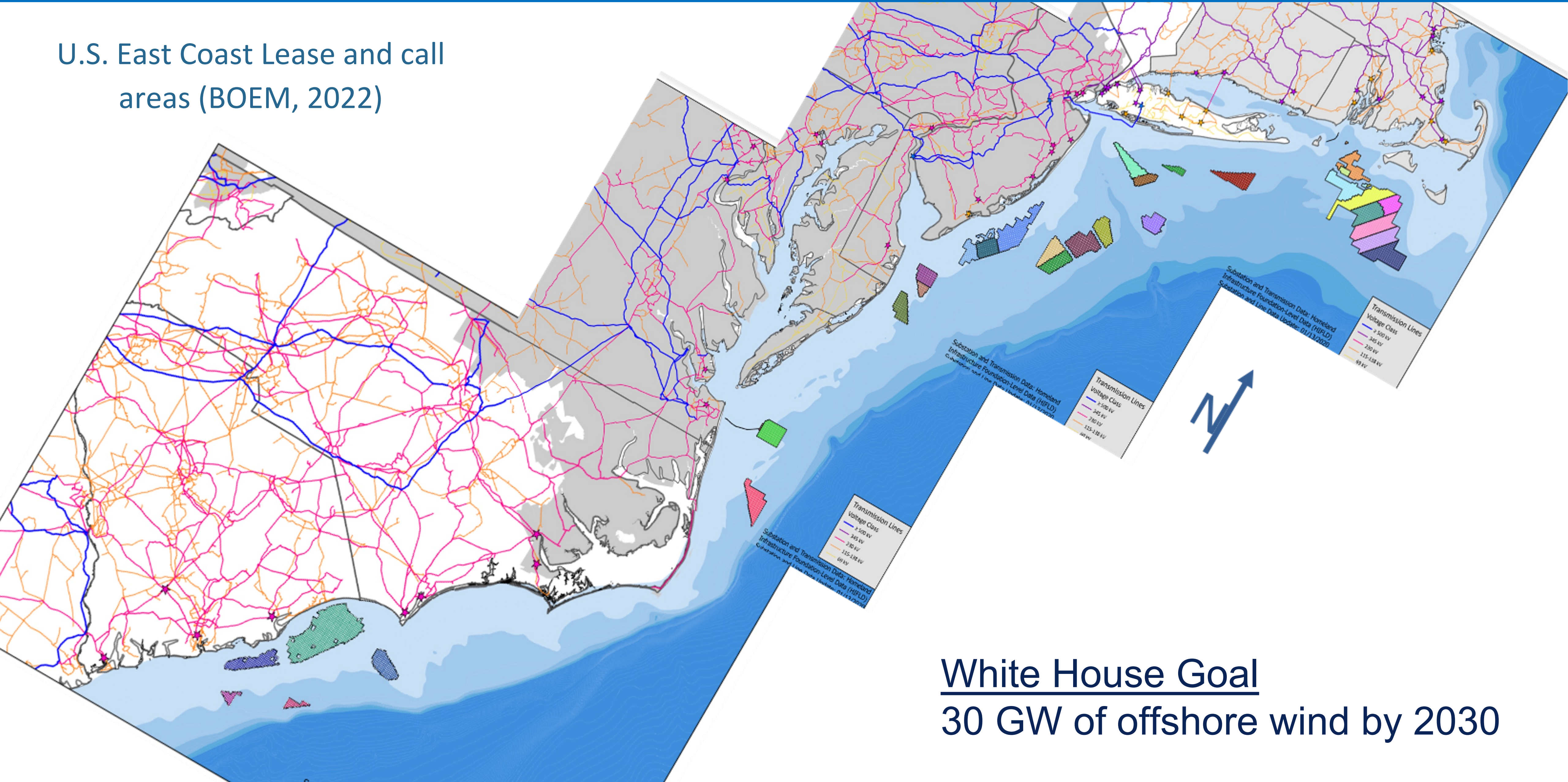


Year 1-2 efforts have focused on Block Island data and simulations.

WTRIM - HF

Need for HFR WTI Mitigation Efforts

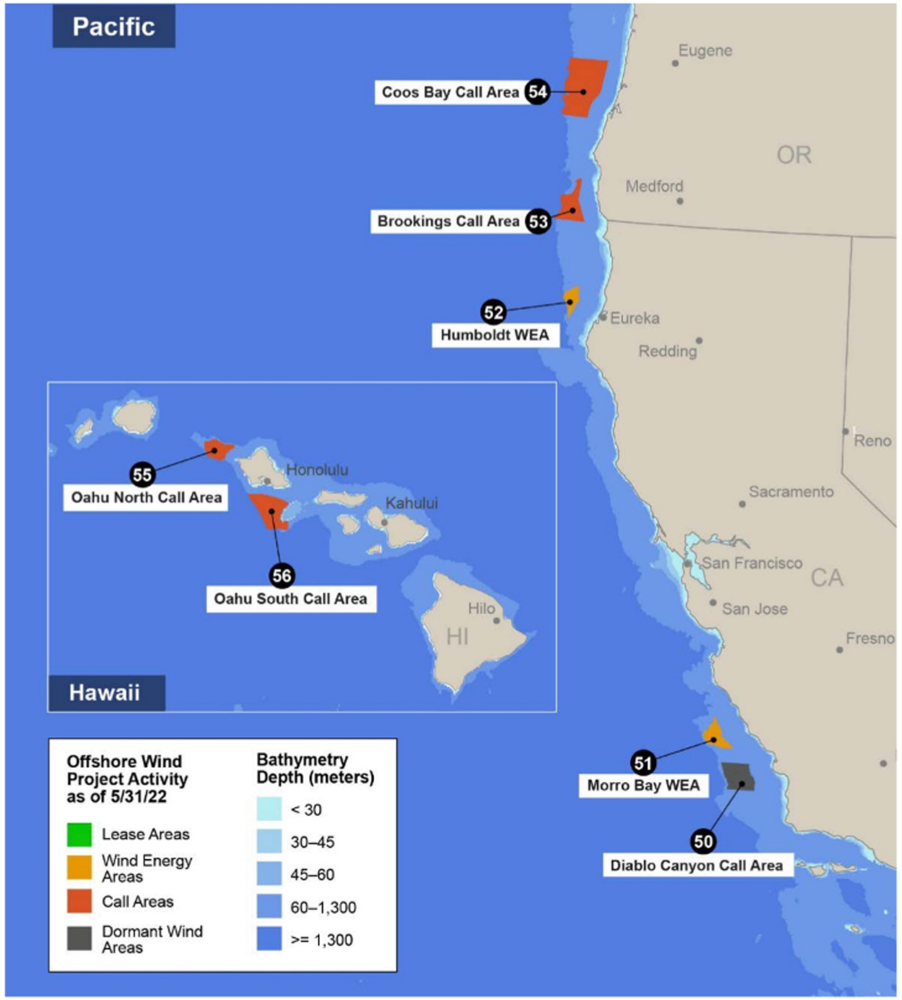
U.S. East Coast Lease and call areas (BOEM, 2022)

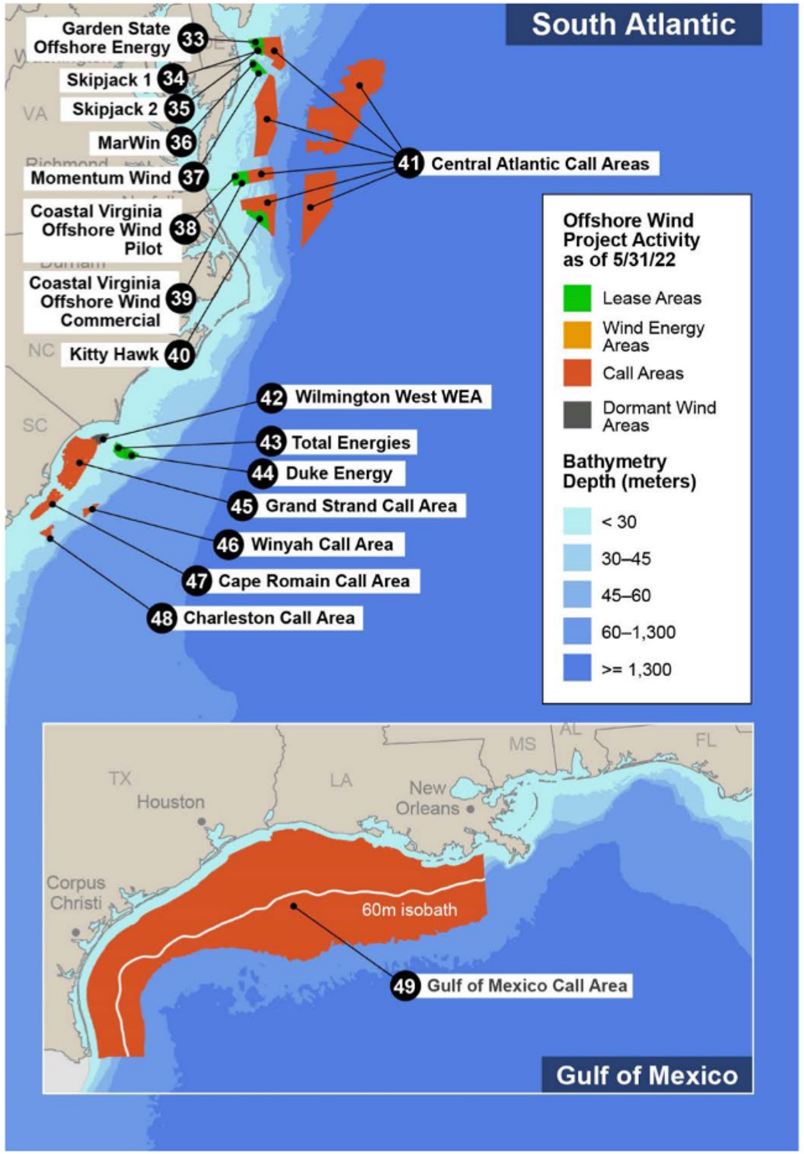


White House Goal

30 GW of offshore wind by 2030

Need for HFR WTI Mitigation Efforts





Offshore wind is not just an East Coast issue.

<u>White House Goal</u>

300 GW of offshore wind by 2050

CONUS lease and call areas (BOEM, 2022)

Talk Outline

- Background
- Mitigation Methods
- Status / Next Steps
- Summary

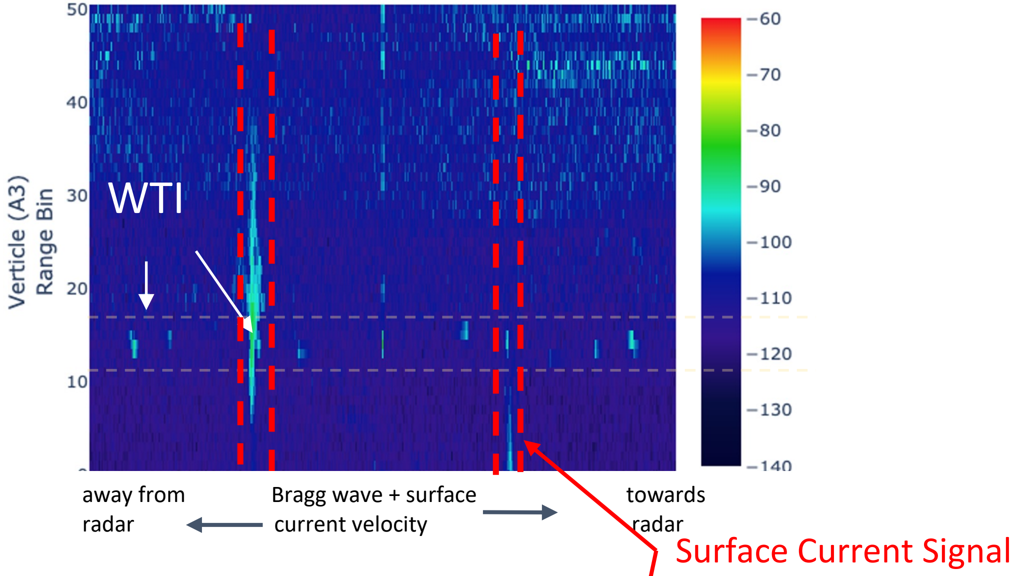
Radar Optimization

Changing the sweep rate of the radar will reduce the number of potential impacts.

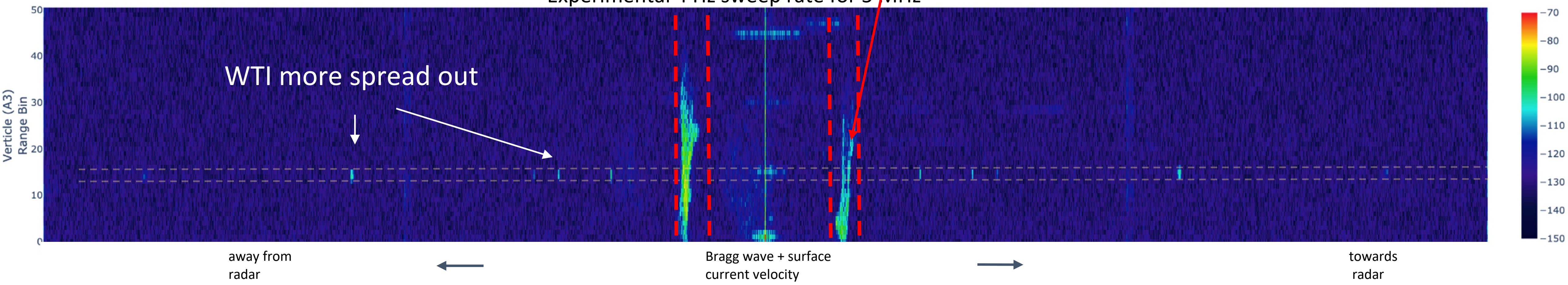
Example of two turbines simulated in HFR spectra with different sweep rates.

Both examples have the same turbine characteristics

Typical 1 Hz sweep rate for 5 MHz



Experimental 4 Hz sweep rate for 5 MHz



work based on BOEM funded efforts

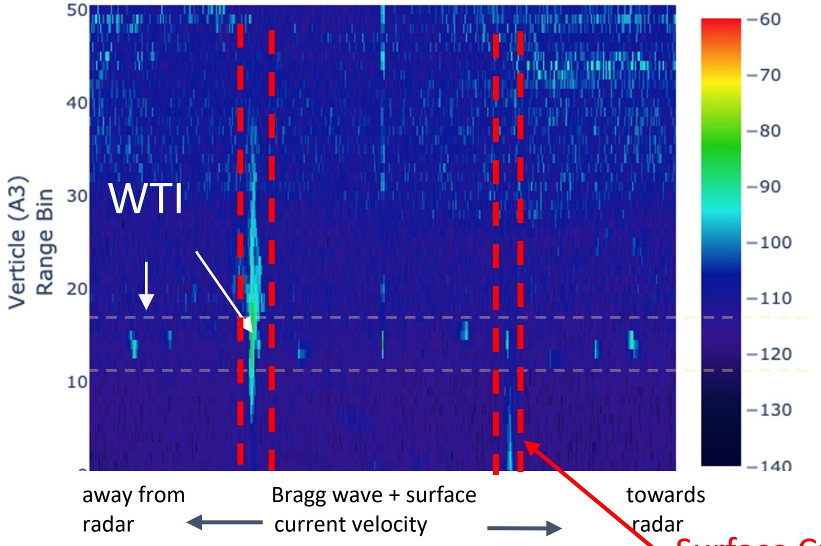
Radar Optimization

Changing the sweep rate of the radar will reduce the number of potential impacts.

Example of two turbines simulated in HFR spectra with different sweep rates.

Both examples have the same turbine characteristics

Typical 1 Hz sweep rate for 5 MHz

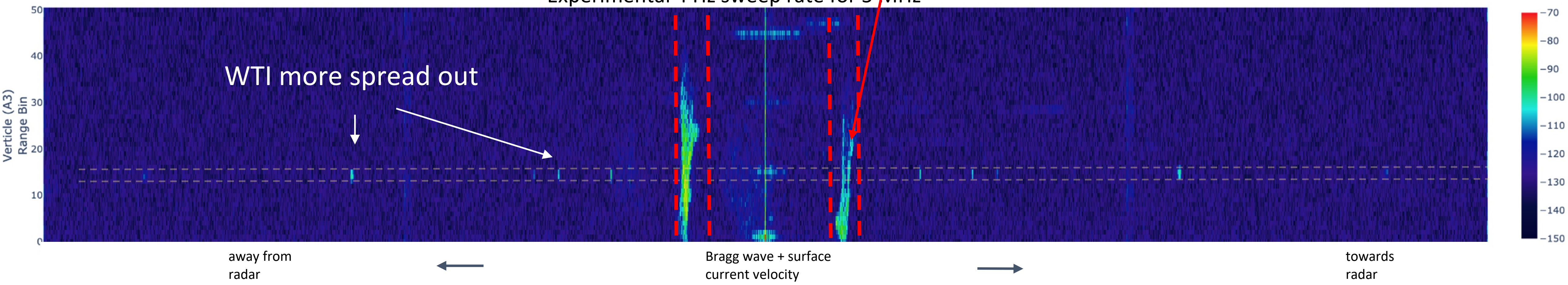


Optimization is limited by bandwidth…

FCC HFR Bands

Region 2		
Low (MHz)	High (MHz)	BW* (kHz)
4.438	4.488	50
5.250	5.275	25
13.450	13.550	100
16.100	16.200	100
24.450	24.650	200
26.200	26.420	220
41.015	*41.665*	*650*
43.350	*44.000*	*650*

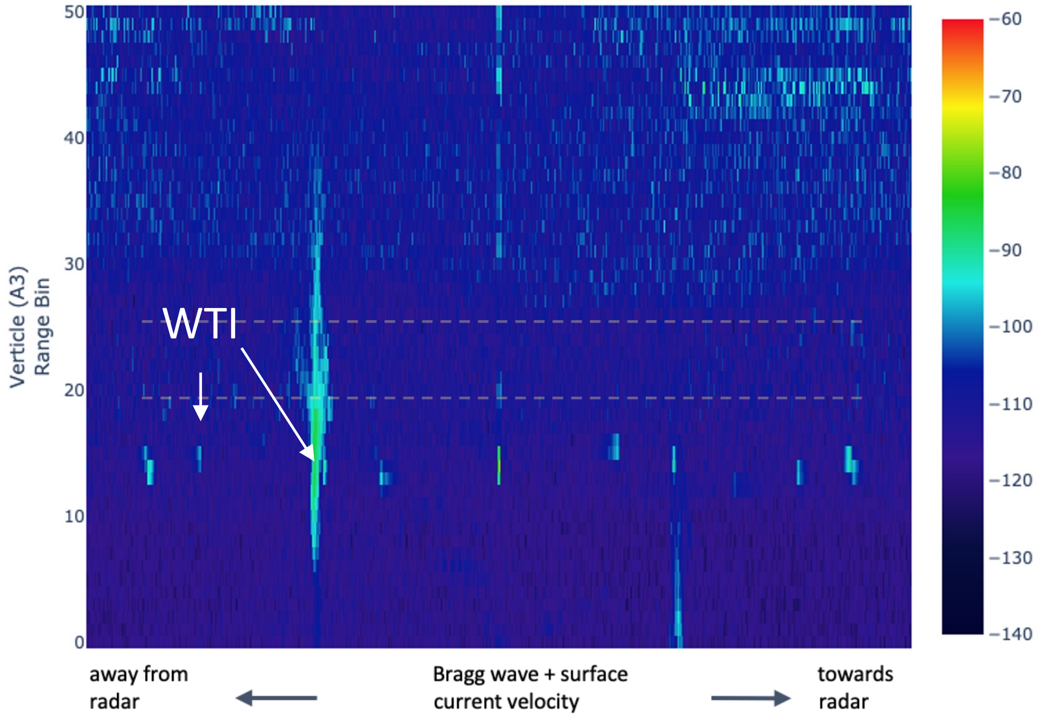
Experimental 4 Hz sweep rate for 5 MHz

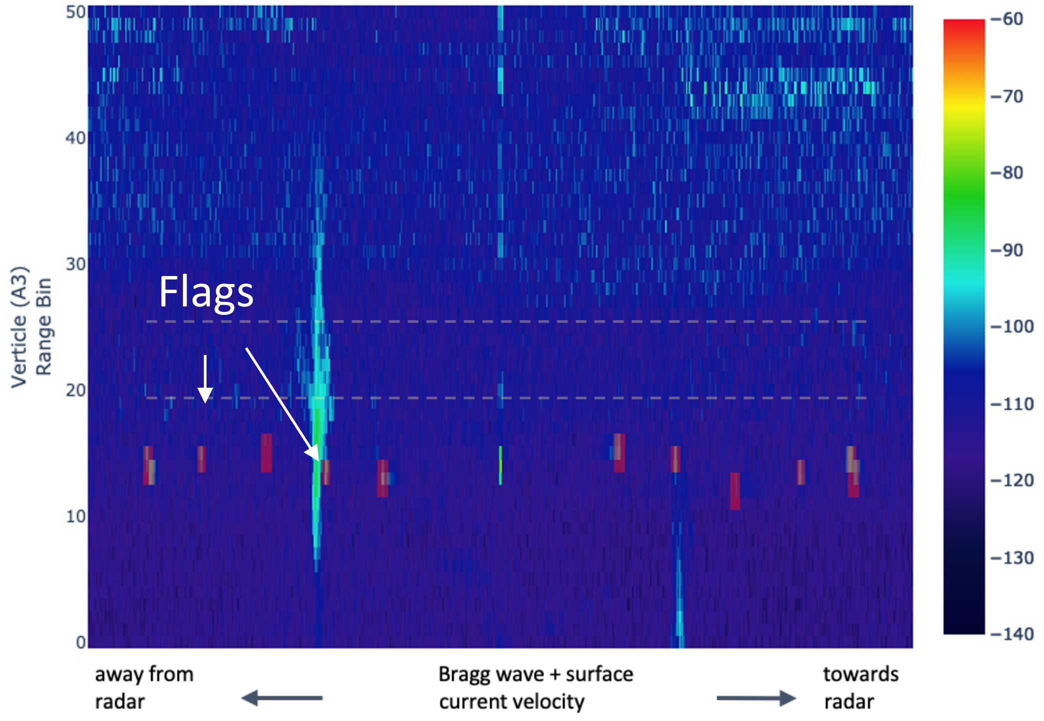


work based on BOEM funded efforts

Software Tools

Real-time software has been developed that can identify, flag, and remove WTI peaks from processing.

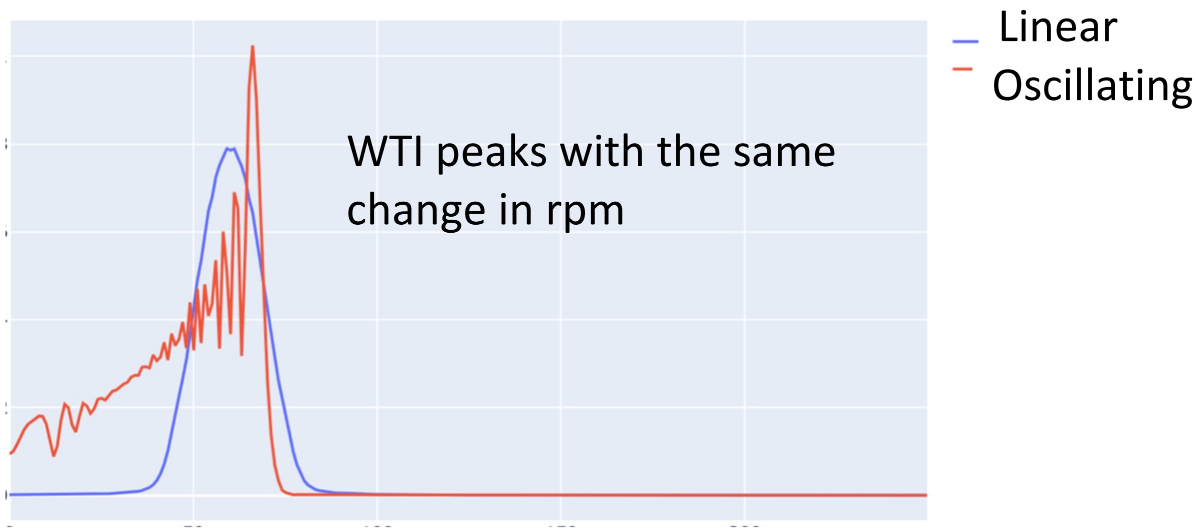


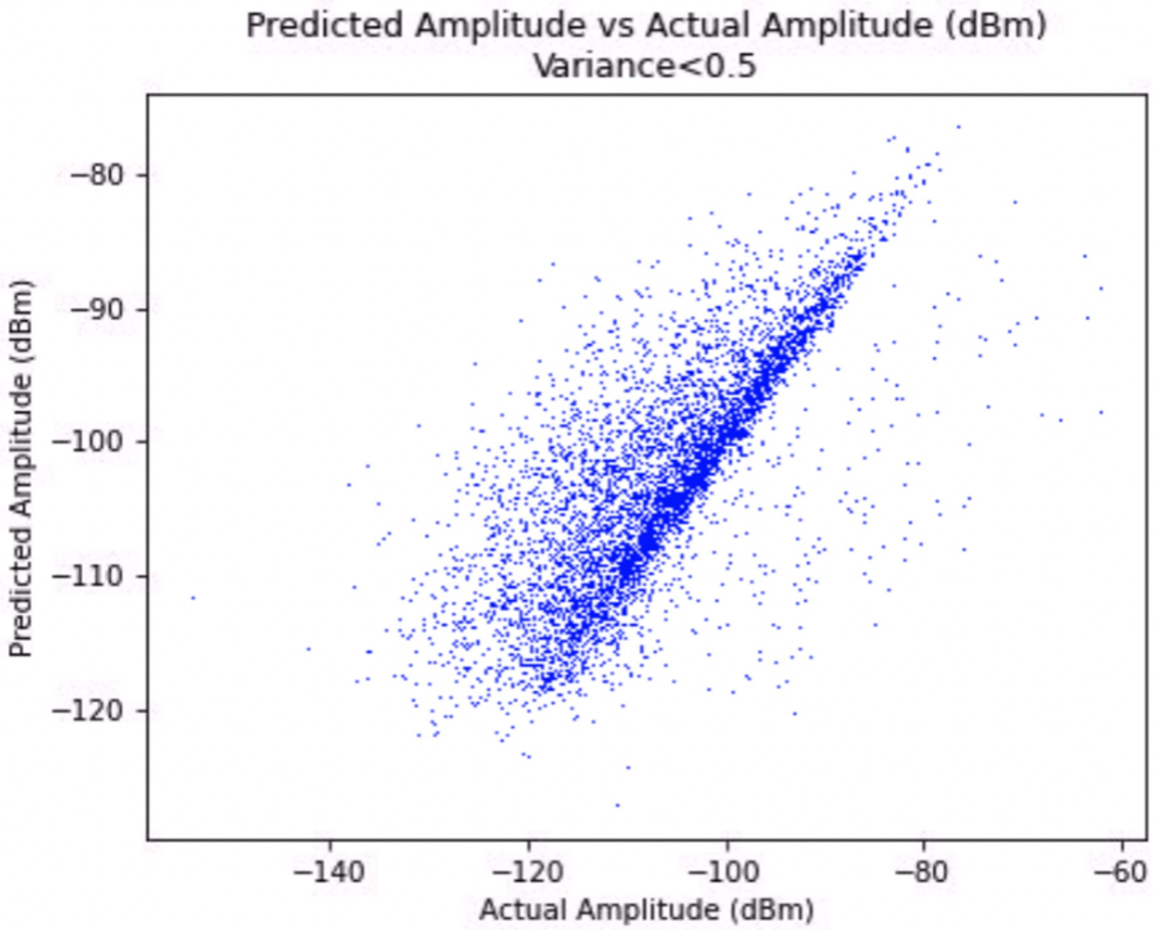


WTI Removal

WTI is highly sensitive to rotation rate variations.

Variations in WTI within the sample period are difficult to separate from the sea echo.

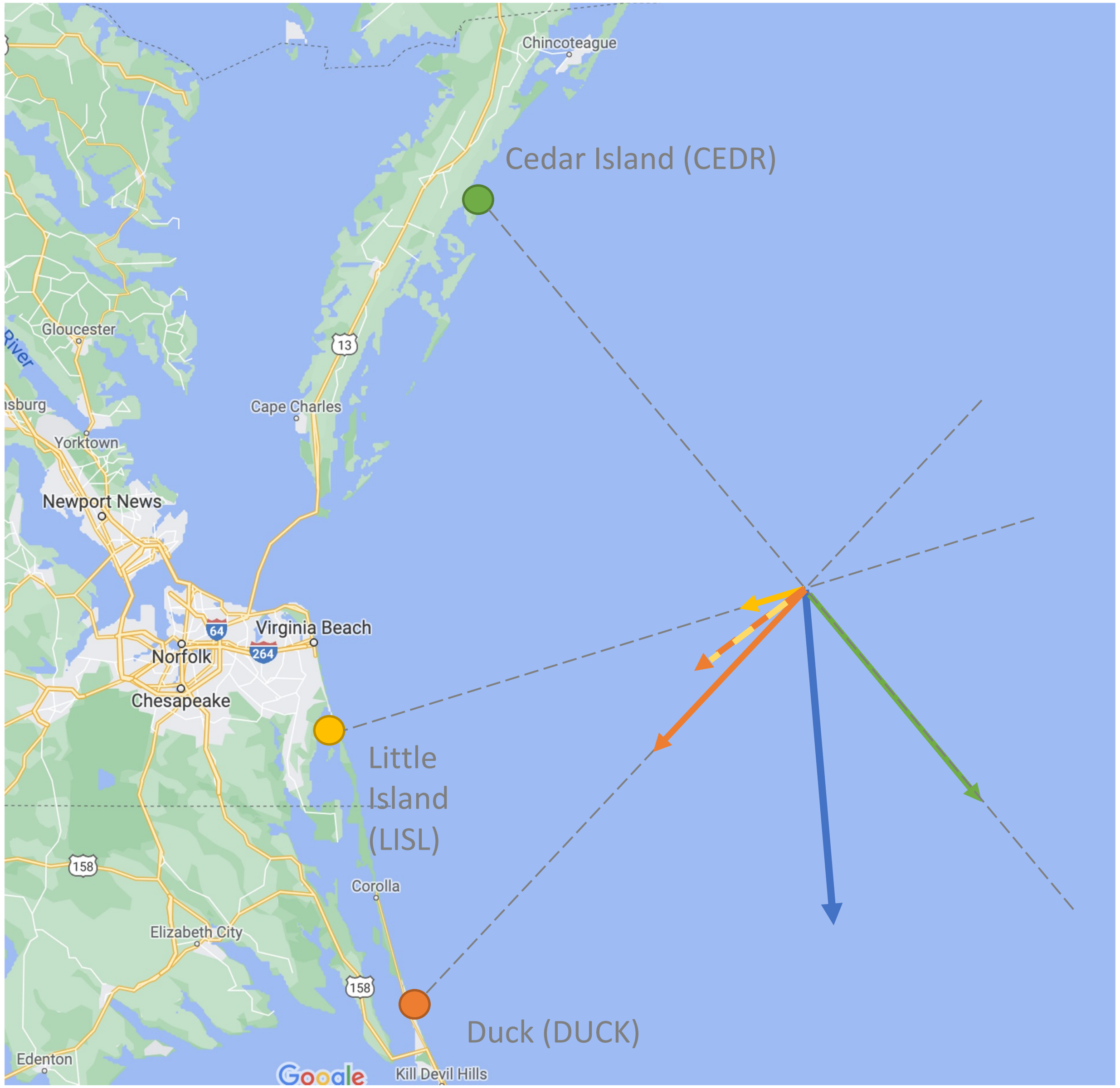




Observation Redundancy

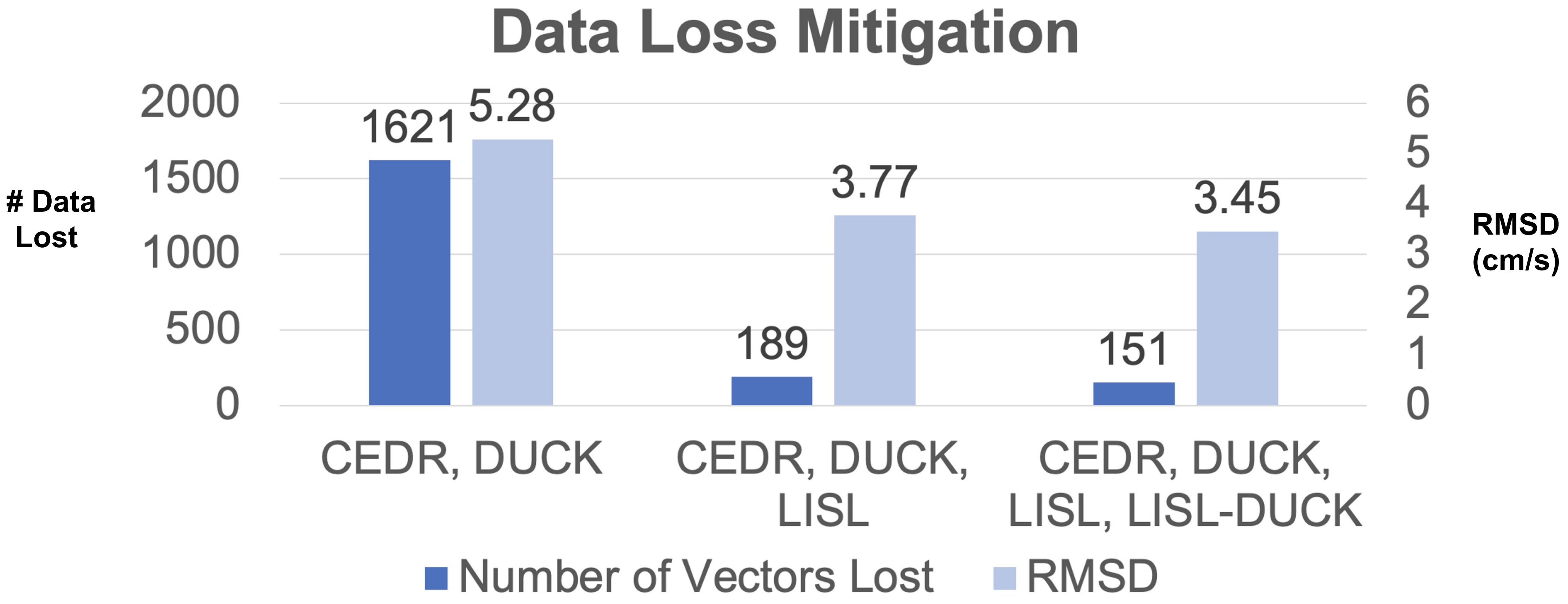
Testing gap reduction with bistatic processing:

- Most of U.S. network optimized for coverage with minimal sites
- WTI can affect radials anywhere in range cell
- If WTI found in 1 radial, the total current vector is lost
- Additional observations provide redundancy (e.g. through more sites or use of bistatic processing)



WTRIM - HF

Observation Redundancy Results

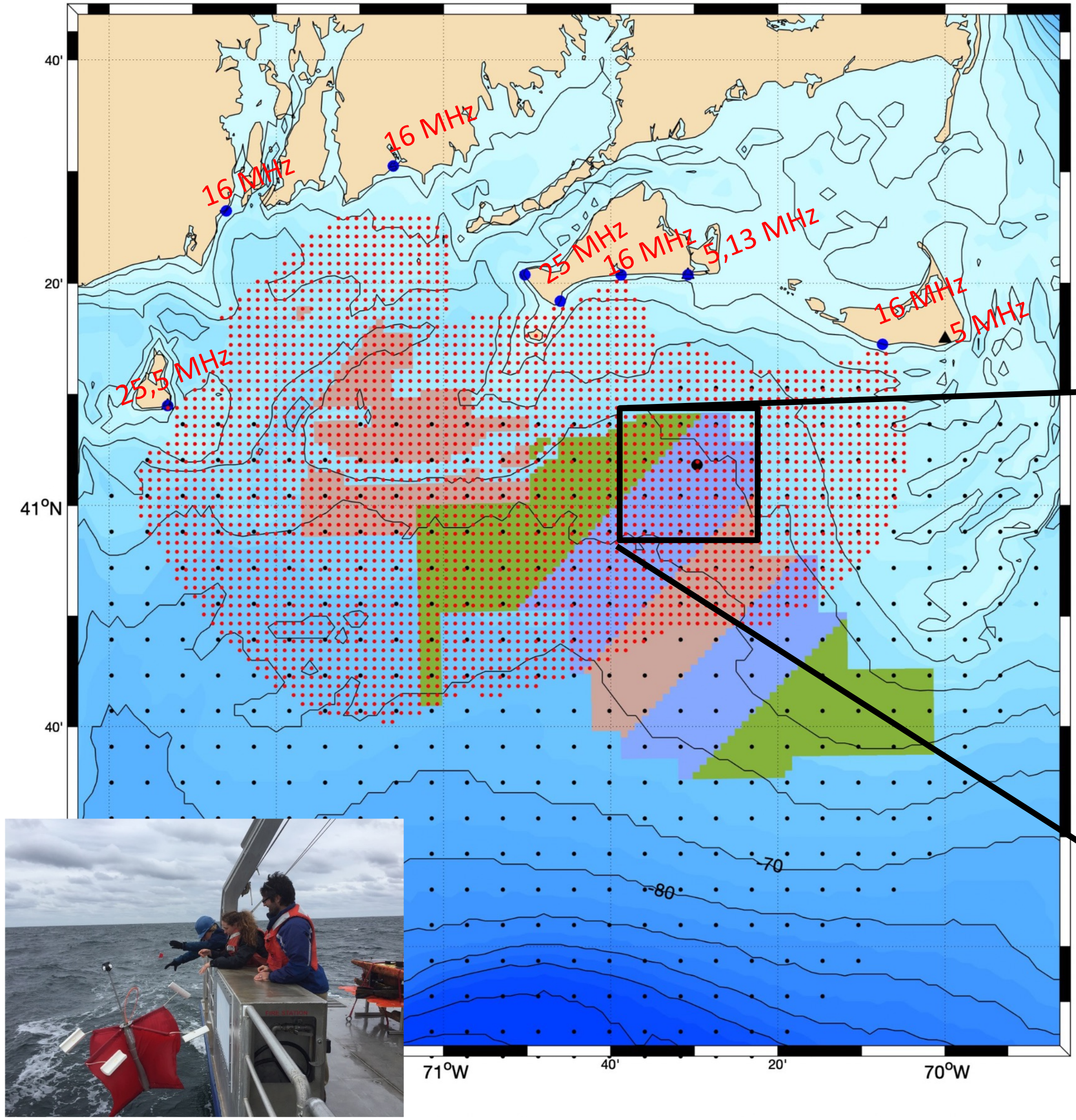


WTRIM - HF

Talk Outline

- Background
- Mitigation Methods
- Status / Next Steps
- Summary

Next Steps: IOOS OTT 2023 field work



Wind Turbine Radar Interference Mitigation (WTRIM) 2023 field work within Vineyard Wind 1 (OCS-A 0501)

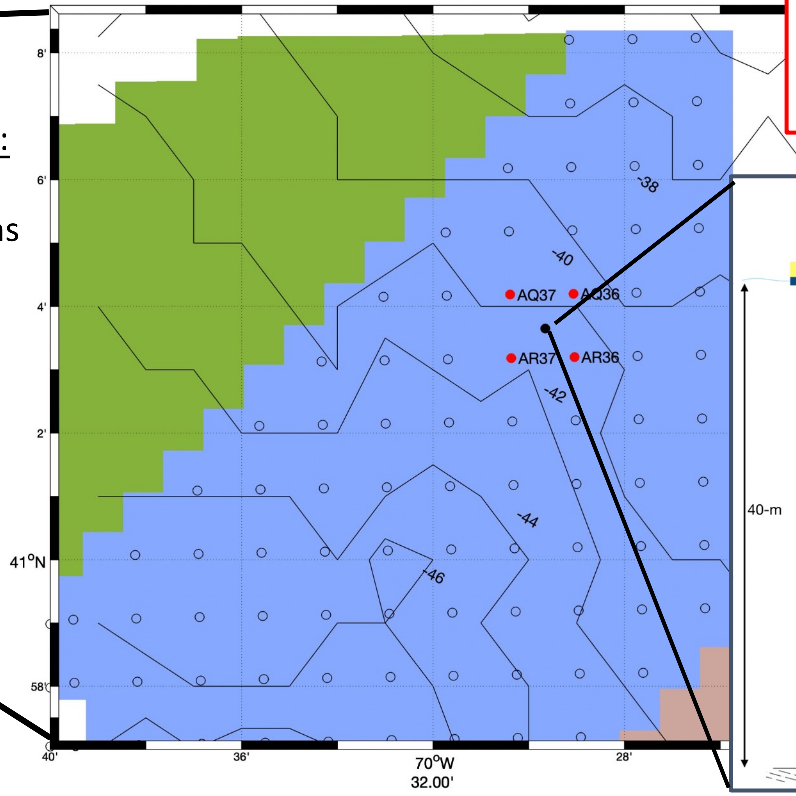
Goals:

- Test software with large numbers of turbines
- Constrain WTI amplitude variations with range and frequency
- Test network design mitigations

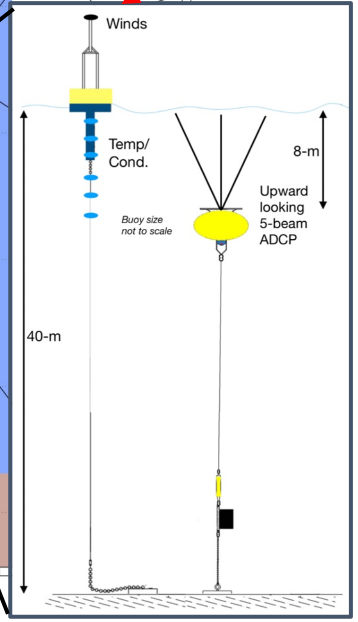
<u>In situ validation via:</u>

moored observations

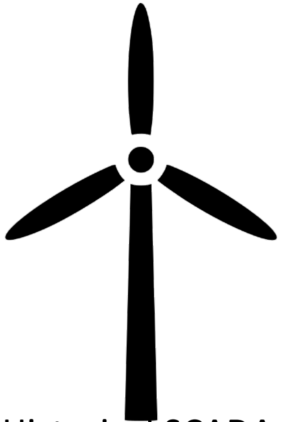
large area drifter deployments



buoy-based camera system for rotation rates



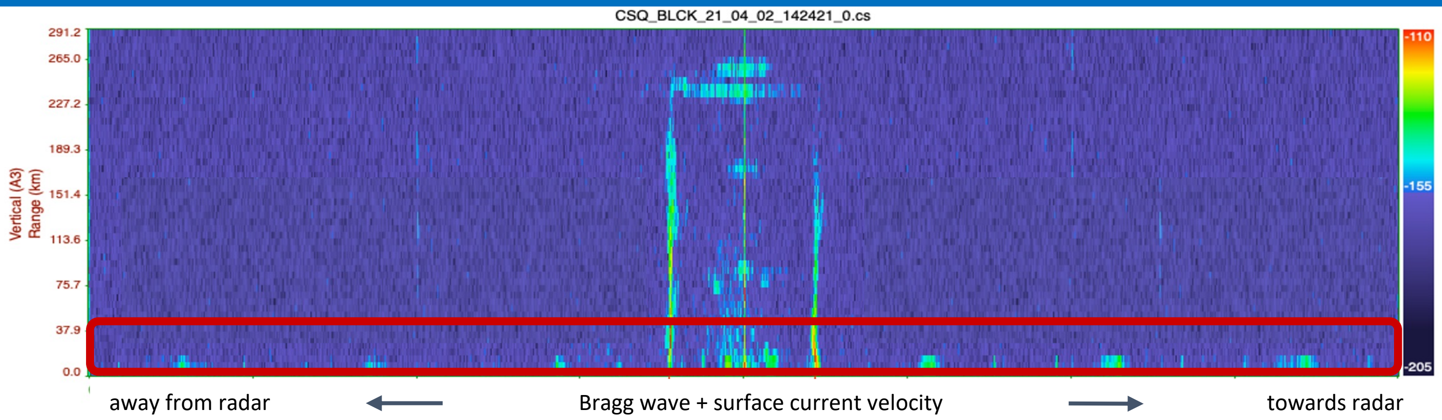
Validation and Calibration With SCADA Data



Historical SCADA

```
simTh = bear*pi/180;

%//Default wind relative direction
simTw = 270.0; % Deg CWN, the 'from' direction
simWStd = 1.0; % units?

simOpt(3) = 1;

if simOpt(3) ~= 2 % 'Wind noise? (No/Yes/Off)',...

    %// Bearing of wind direction in radians
    tw = simTw*pi/180;

    %// For Positive Bragg Peak: wind-wave stnd dev.
    simWpB = sqrt((cos((simTh-tw)/2).^4 + 0.01)/1.01);

    %// For Negative Bragg Peak: wind-wave stnd dev.
    simWnB = sqrt((sin((simTh-tw)/2).^4 + 0.01)/1.01);

else

    % wind noise off?
    simWpB = ones(length(simTh),1);
    simWnB = ones(length(simTh),1);
end
```

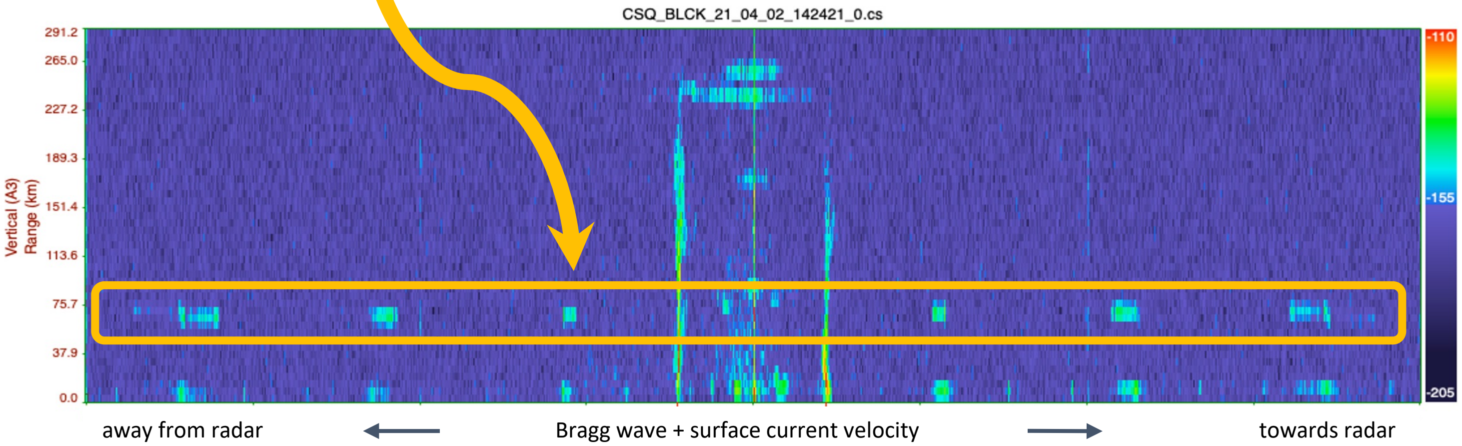
Simulate WTI



Historical HFR Doppler Spectra

Historical SCADA Data is need to:

- calibrate simulations
- augment ML training data sets
- validate mitigation flagging



Buoy based camera systems will provide redundancy to SCADA data.

WTRIM - HF

Talk Outline

- Background
- Mitigation Methods
- Status / Next Steps
- Summary

Summary 1

Funded WTRIM R&D projects have:

- Observed WTI in HFR data and **documented impacts** on ocean current observations
- **Provided a clear theoretical understanding** of WTI in HFR data
- **Enabled robust simulations** of real world situations
- **Developed mitigation methods**, including:
  - radar optimization strategies
  - software that can detect, flag & remove WTI from current processing
  - network design strategies

Block Island 5-turbine array, installed 2016

WTRIM - HF

Summary 2

Current status:

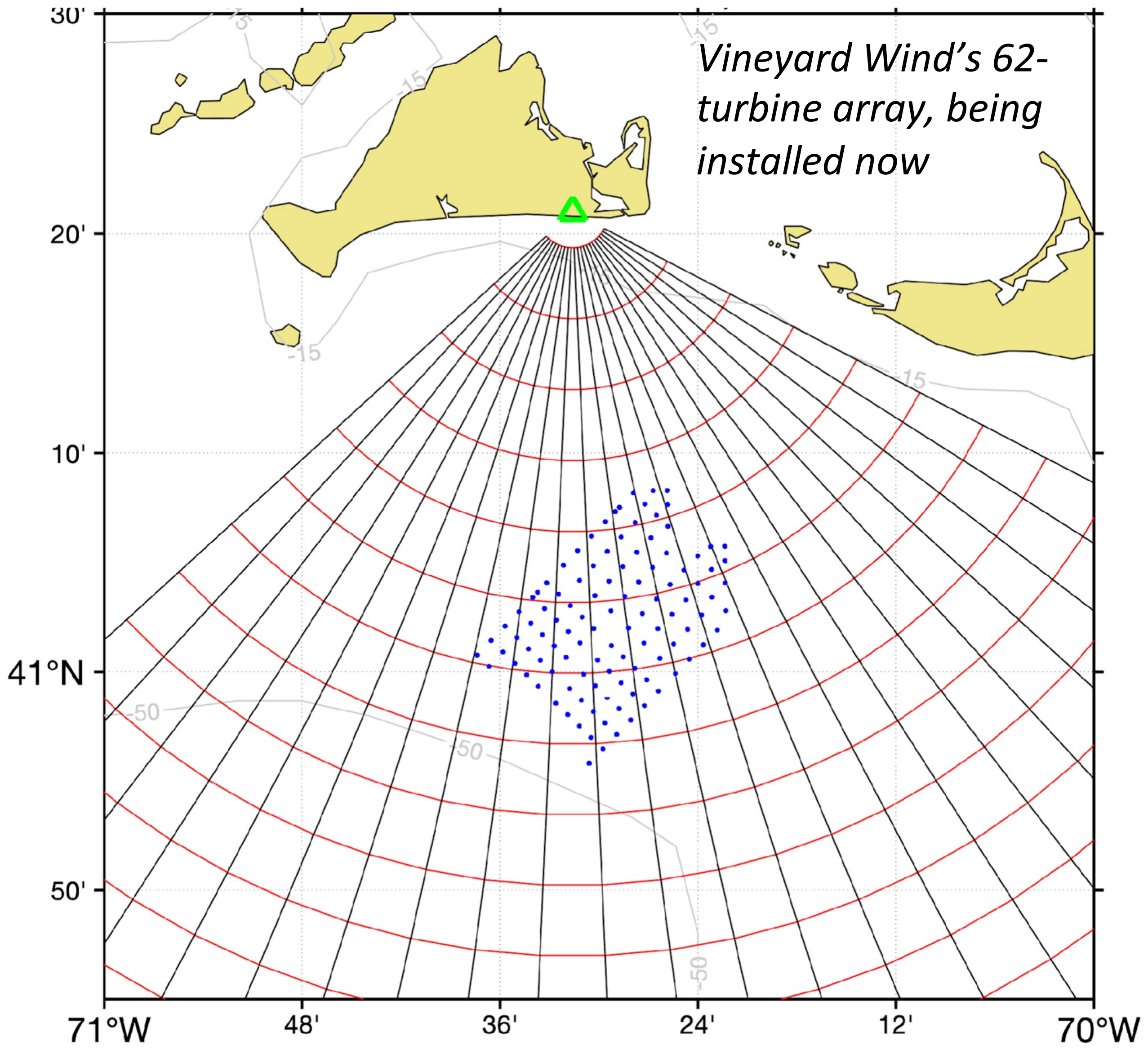
Software effectively estimates the Doppler location of the WTI based on yaw angle, rotation rate and variation.

The sensitivity of WTI characteristics to rotation rate variability has blocked efforts to **separate** WTI from the sea echo.

2023-2024 efforts will:

- constrain WTI amplitude estimates
- validate software for large numbers of turbines and impact on currents
- investigate/validate network mitigation methods

WTRIM - HF



Summary 3

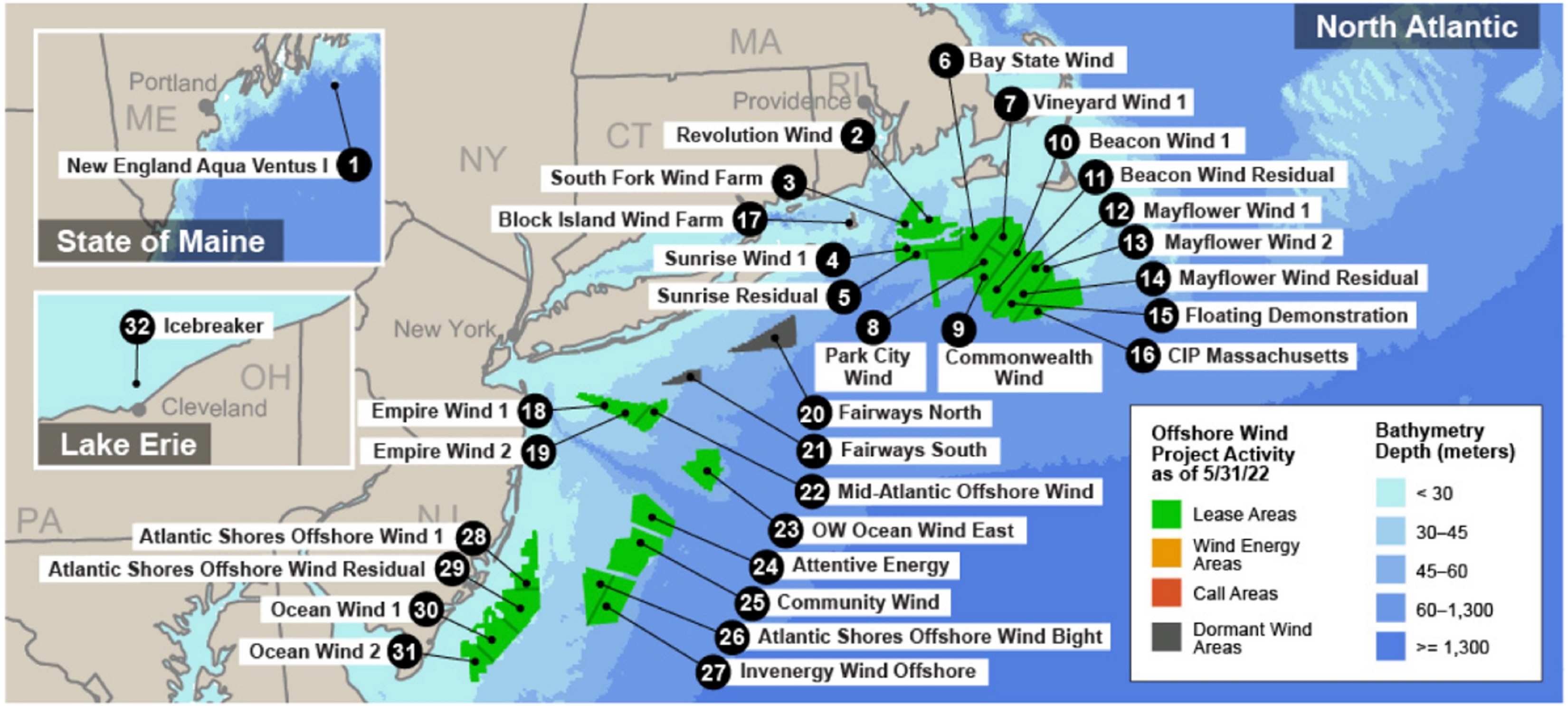
Takeaways:

Additional experience with large arrays - and historical turbine data - is required to characterize turbine variability and test mitigation methods.

Effective mitigation will likely require a combination of WTI software, radar hardware optimization, and holistic network design.

Efforts to date have focused on mitigating impacts to ocean currents – impacts to waves or other HFR uses not yet been considered.

BOEM (2022) Atlantic areas in development/consideration



WTRIM - HF