SMODE Scient Team Meeting
August 24th, 2022 12:35 – 12:50 pm

Observations of Surface Gravity Wave Spectra from a Moving Platform

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Colosi et al. in-prep for the Journal of Atmospheric and Oceanic Technology 2022.

Photo: Nick Statom

Surface waves mediate momentum, mass, heat, and energy fluxes between the ocean and atmosphere

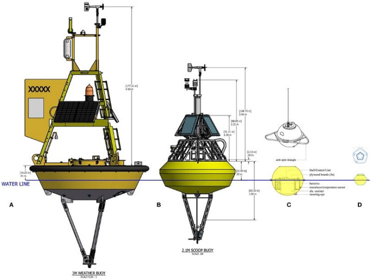
Quantifying the influence **surface waves** have on air-sea interactions will help **advance climate models** through **improved parameterization** of air-sea fluxes occurring at scales unresolved by models.

This **motivates** the need for **high quality measurements** of surface waves to improve our understanding of the **underlying physics** of the air-sea system.

Autonomous vehicles are well suited to study surface waves

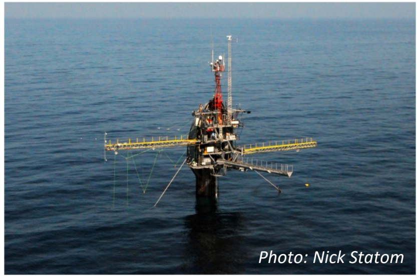
Historical

Wave Buoys



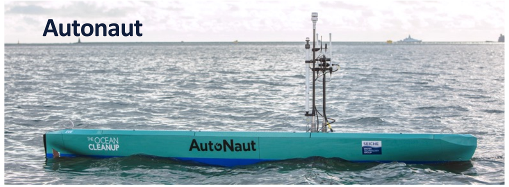
Satellites

Research Platforms



New generation of instrumented platforms →

Autonomous surface vehicles



https://autonautusv.com/vessels-0

Advantages:

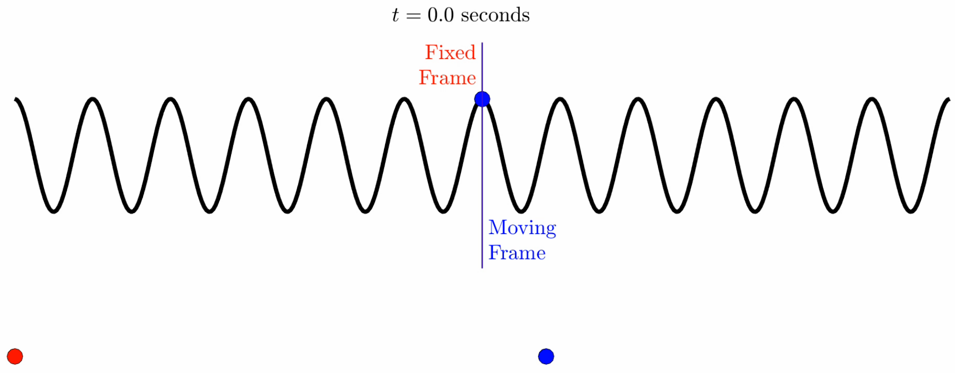
1. Uncrewed
2. Long duration deployments
3. Remote area data collection
4. Measurements taken over broad spatio-temporal scales

Autonomous platforms measure the wave spectrum from the vehicle's motion

How can we **interpret** wave measurements from these types of platforms and what are the **challenges**?

Note: See Lenain and Melville 2014, Thomson et al. 2018, and Grare et al. 2021 for more details.

The observed wave frequency differs due to the relative motion of the platform with respect to the waves



Fixed reference frame

Moving reference frame

Platforms motion relative to the incoming waves causes the observed frequency to be Doppler shifted

$$f_{ob}(k,\theta,U,\phi) = f_{in}(k) - \frac{kU\cos(\phi-\theta)}{2\pi}$$

Observed frequency: Frequency measured in the moving reference frame of the platform

Intrinsic frequency: Frequency measured in the absence of platform motion

Wavenumber magnitude

Platform speed

Angle between the direction of wave and platform propagation

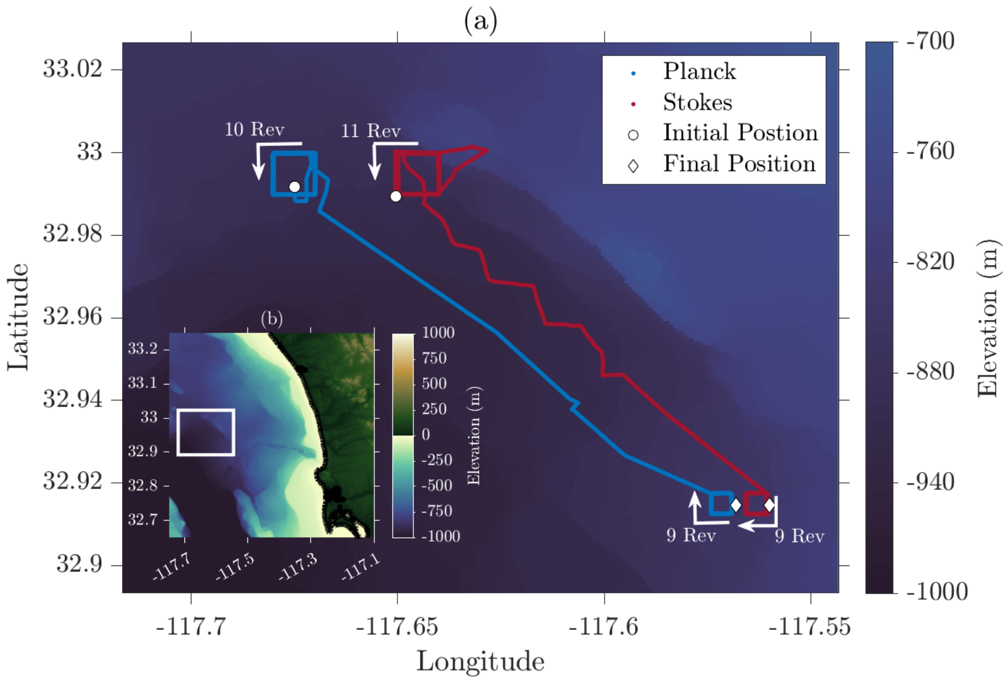
Doppler Shift Term

Observations of wave spectra in a reference frame free from Doppler effects requires a **mapping** from observed to intrinsic frequency.

Goals

- Develop a **general approach** to account for platform motion artifacts in the directional wave spectrum from Doppler effects, building upon the work of Longuet-Higgins (1986), and Collins et al. (2017).
- **Validate** this method using a **unique dataset** collected from a fleet of Wave Gliders off the coast of Southern California in September 2020.
- **Apply** this method to the SMODE pilot dataset collected from the WHOI Wave Glider.

Del Mar Experiment 2020



- September 9th - 11th, 2020.
- 1000 m and 500 m edge length squares
- Environmental Conditions:
  - Wind: $2 - 8\,ms^{-1}$ coming from the Northwest ($\sim 300°$).
  - Sea State: $0.8 - 1.2\,m$ significant wave height with wind-waves coming from the Northwest ($\sim 280°$) and swell coming from the Southwest ($\sim 200°$).

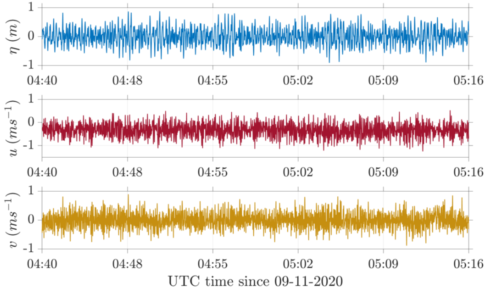
Directional and omni-directional wave spectrum computed from the motion of the platform

Input Data

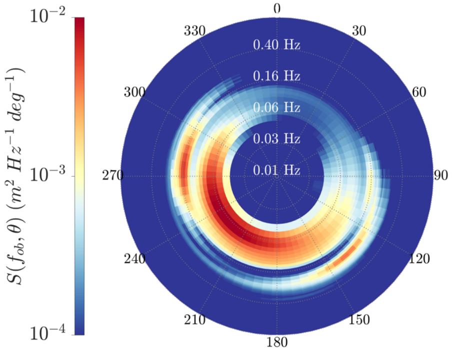
Heave

East-West Velocity

North-South Velocity



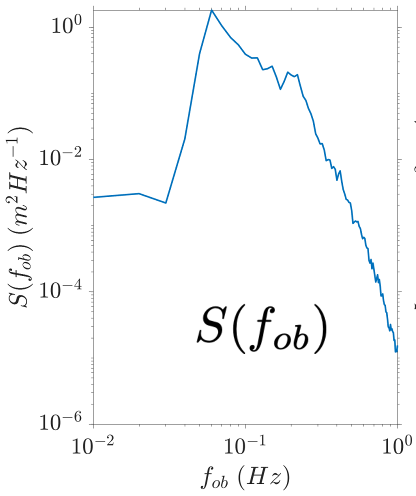
Directional Spectrum $S(f_{ob}, \theta)$



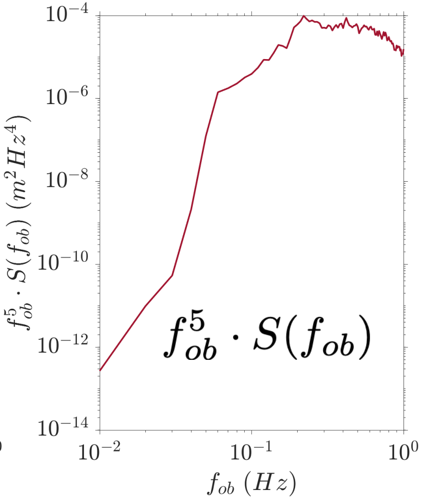
- Derived using maximum entropy method
- Directions coming from

Azimuthal Integration

Omni-directional Spectrum

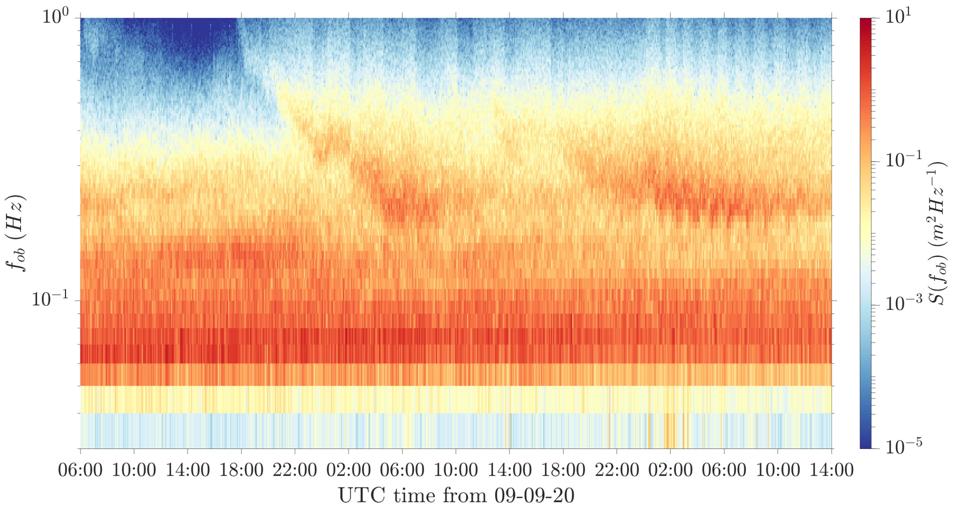


Saturation Spectrum

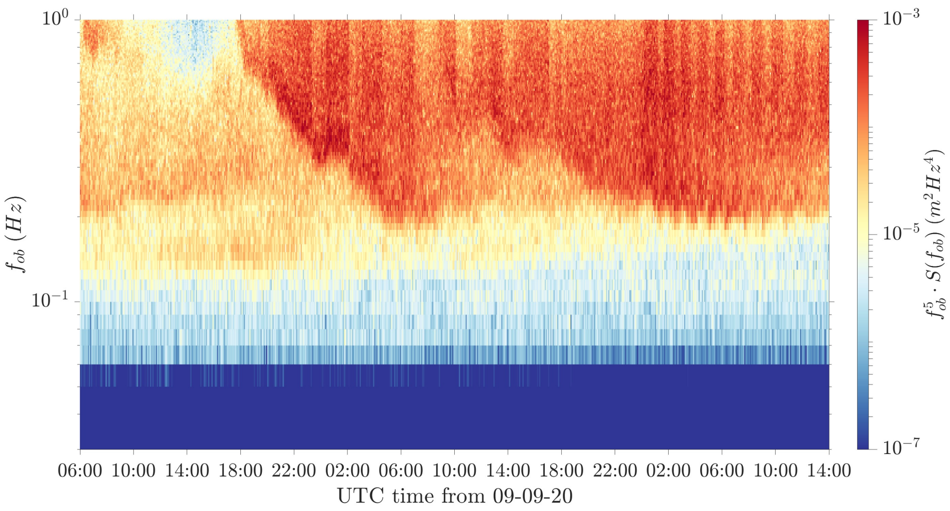


Spectrogram of surface waves observed by a wave glider

<u>Omni-directional Spectrogram</u> $S(f_{ob}, t)$



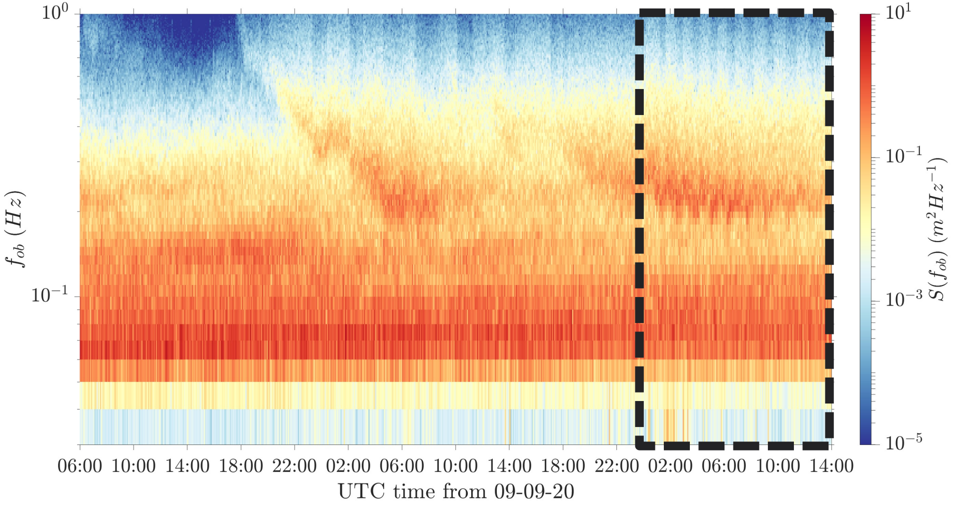
<u>Saturation Spectrogram</u> $f_{ob}^5 \cdot S(f_{ob}, t)$



Modulations of spectra are particularly **visible** at high frequencies.

Spectrogram of surface waves observed by a wave glider

Omni-directional Spectrogram $S(f_{ob}, t)$



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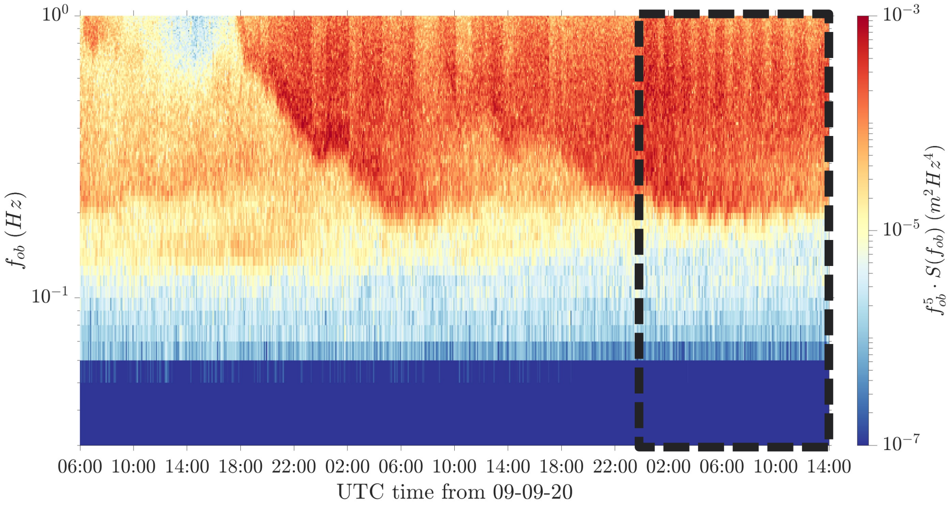

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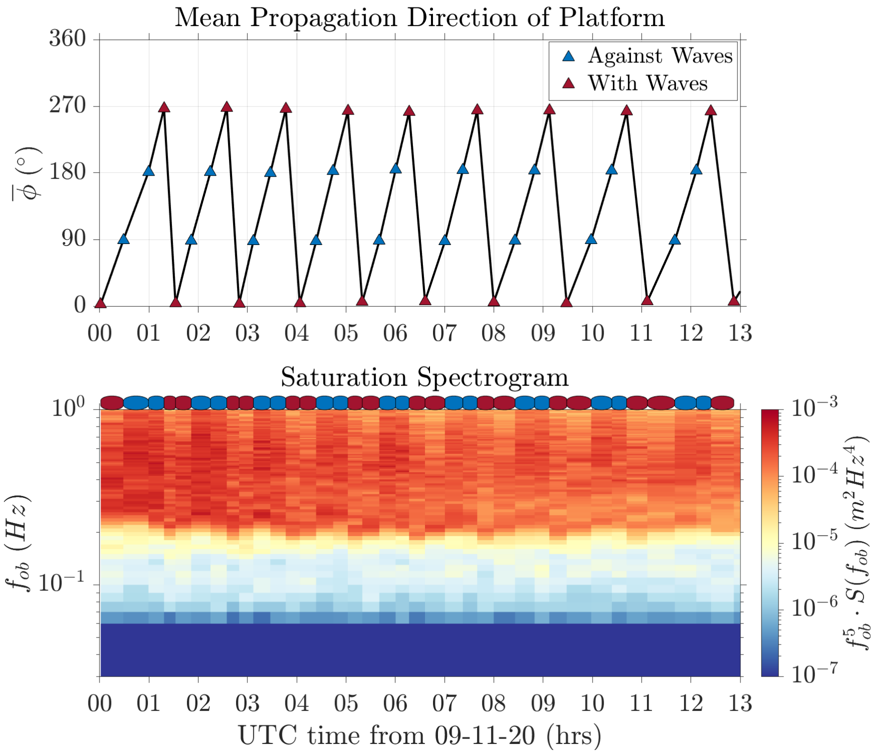
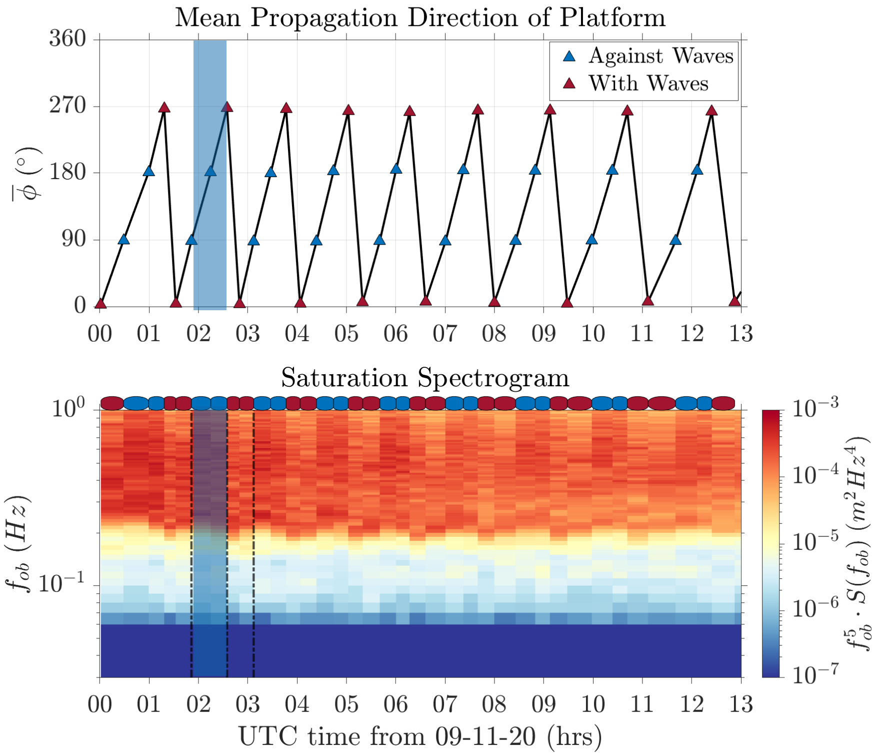
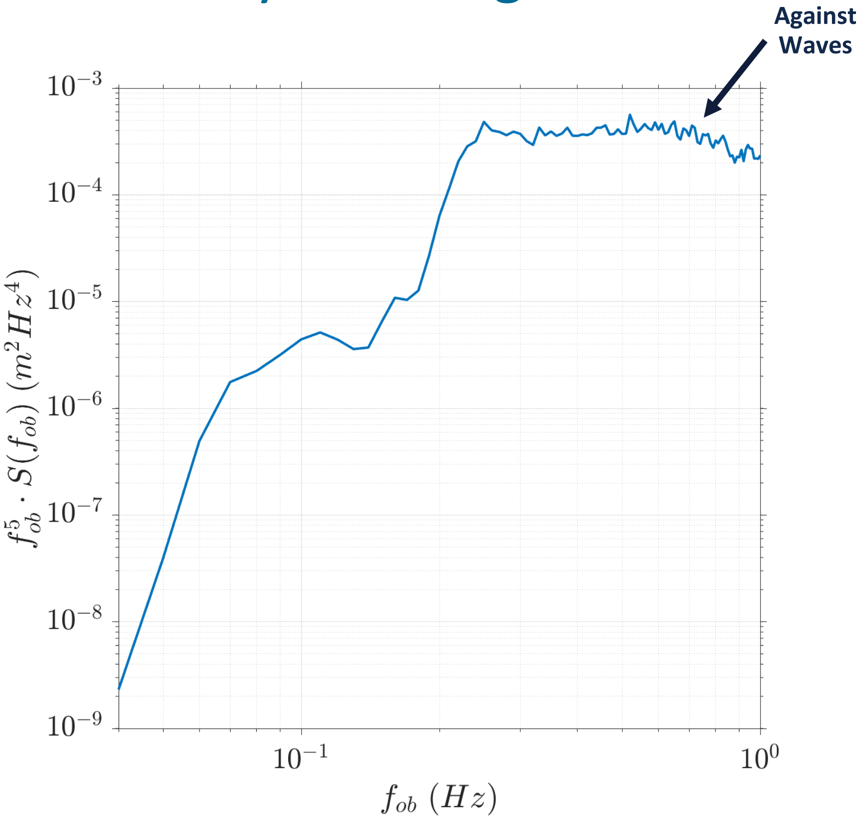


The platform's motion is impacting the observed wave spectra.

Spectrogram of surface waves observed by a wave glider





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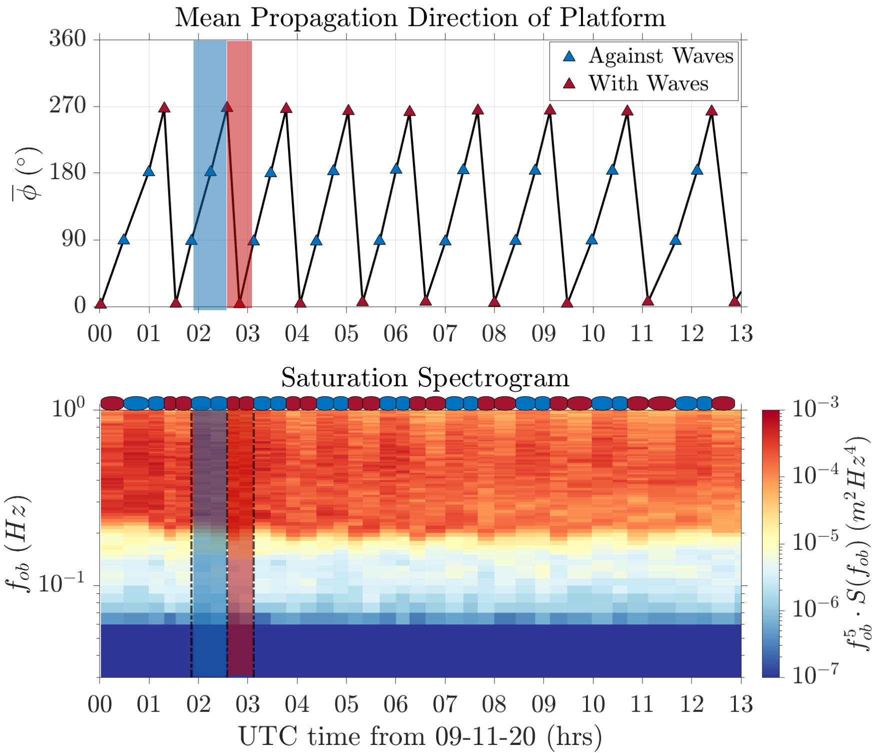
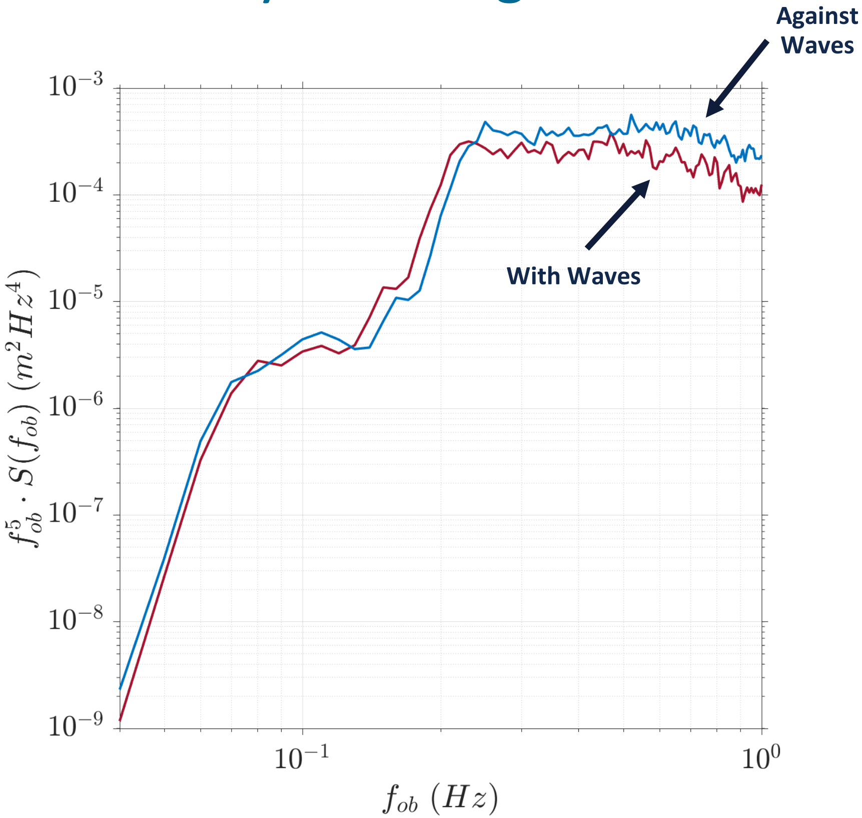
Spectrogram of surface waves observed by a wave glider





The platform’s motion is impacting the observed wave spectra.

Methods to account for Doppler shift in wave spectra

1D Method

Assume all waves come from the same direction

Observe 1D Spectrum

$$S_{ob}(f_{ob})$$

→

Map from observed to intrinsic frequency

$$f_{ob}(k, \overline{\theta}, U, \phi) \mapsto f_{in}(k)$$

→

Map 1D Spectrum into intrinsic frequency space

$$S_{in}(f_{in}) \cdot \frac{\partial f_{ob}}{\partial f_{in}}$$

(Collins et al. 2017)

Methods to account for Doppler shift in wave spectra

1D Method

Assume all waves come from the same direction

Observe 1D Spectrum		Map from observed to intrinsic frequency		Map 1D Spectrum into intrinsic frequency space	
$S_{ob}(f_{ob})$	$\longrightarrow$	$f_{ob}(k, \bar{\theta}, U, \phi) \mapsto f_{in}(k)$	$\longrightarrow$	$S_{in}(f_{in}) \cdot \frac{\partial f_{ob}}{\partial f_{in}}$	(Collins et al. 2017)

2D Method (our approach)

Uses directional distribution of wave field

Observe 2D Spectrum		Map from observed to intrinsic frequency		Map 2D Spectrum into intrinsic frequency space		Compute 1D spectrum from 2D Spectrum
$S_{ob}(f_{ob}, \theta)$	$\longrightarrow$	$f_{ob}(k, \theta, U, \phi) \mapsto f_{in}(k)$	$\longrightarrow$	$S_{in}(f_{in}, \theta) \cdot \frac{\partial f_{ob}}{\partial f_{in}}$	$\longrightarrow$	$S_{in}(f_{in}) = \int_0^{2\pi} S_{in}(f_{in}, \theta) \cdot \frac{\partial f_{ob}}{\partial f_{in}} d\theta$

We need to use a full 2D spectrum.

Less high-frequency waves can be resolved the faster a platform moves with the waves

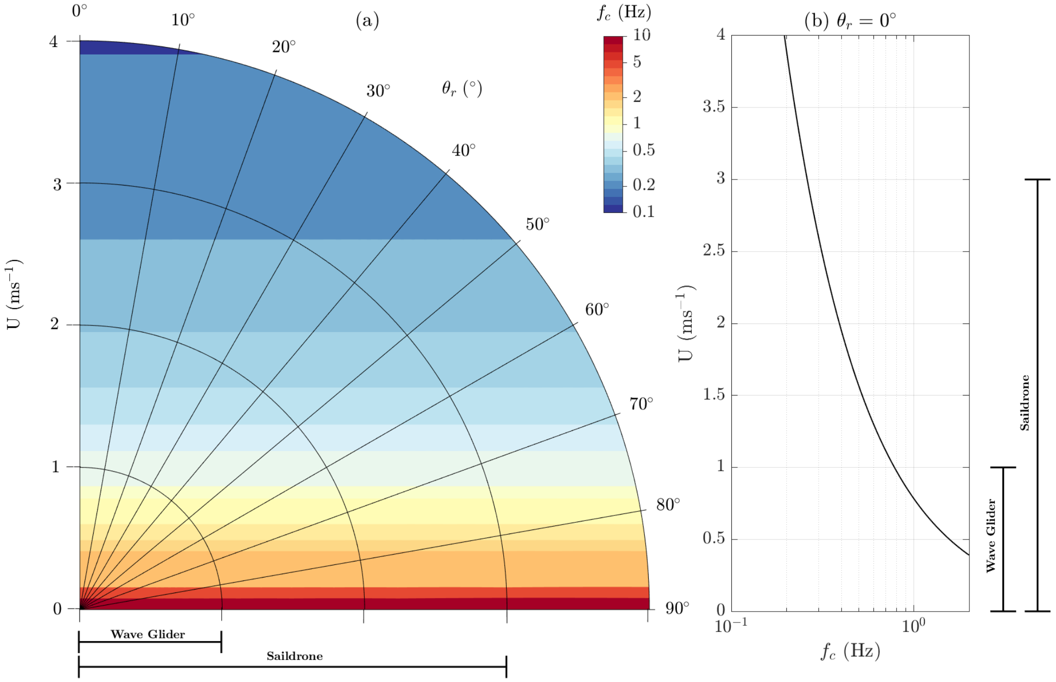
When the platform **moves in the direction of wave propagation**, we cannot resolve frequencies above:

$$f_c = \frac{g}{4\pi U \cos(\theta_r)}$$

Platform speed

Angle between the direction of wave and platform propagation

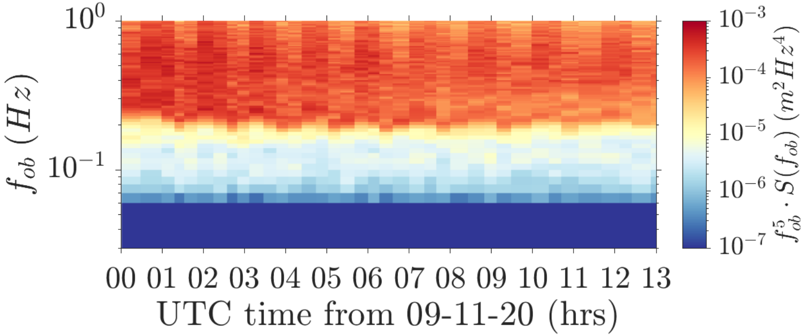
Cutoff Frequency $f_c(U, \theta_r)$



Less frequencies resolved as U increases or $\theta_r \to 0$.

Comparison between 1D and 2D methods

OBSERVED



Comparison between 1D and 2D methods

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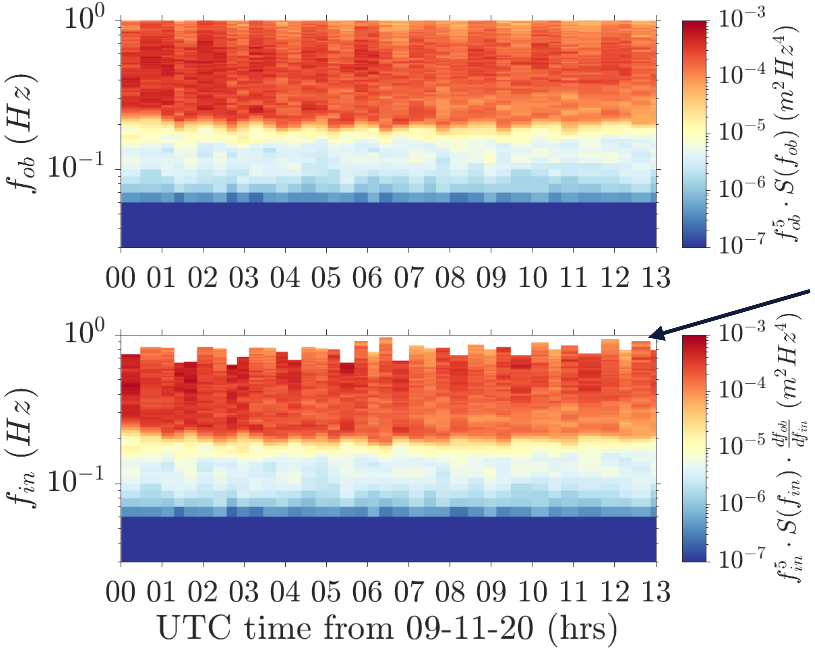
1D METHOD



Unresolved high-frequency waves

Comparison between 1D and 2D methods

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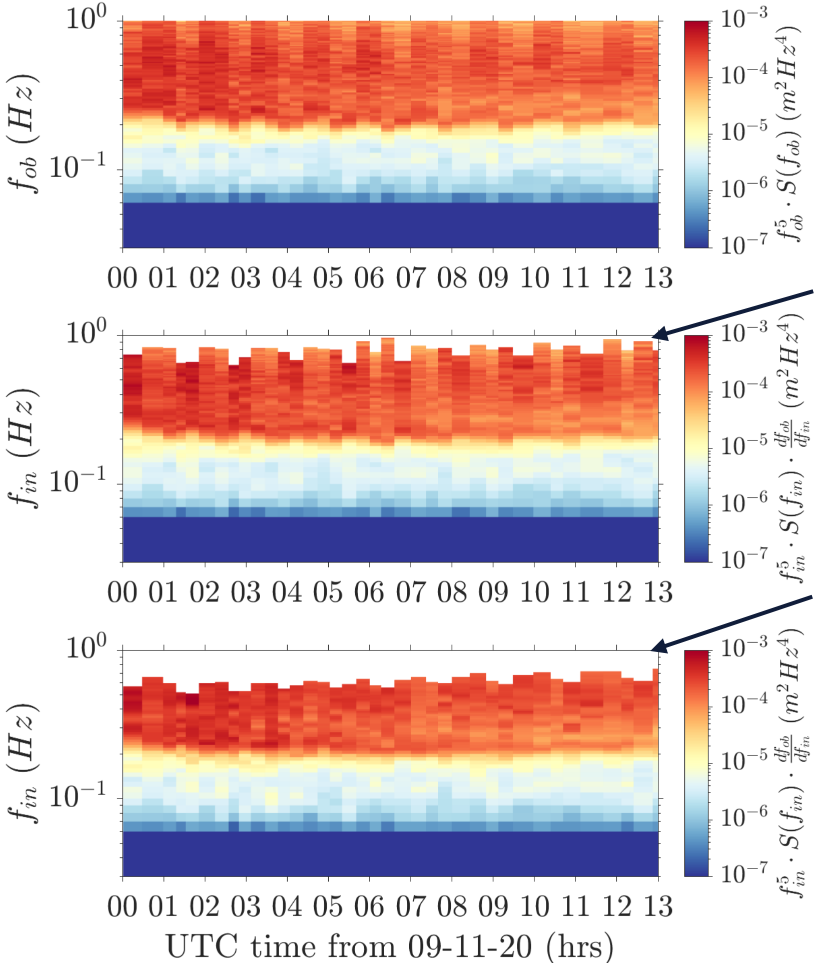
1D METHOD

2D METHOD
(our approach)



Unresolved high-frequency waves

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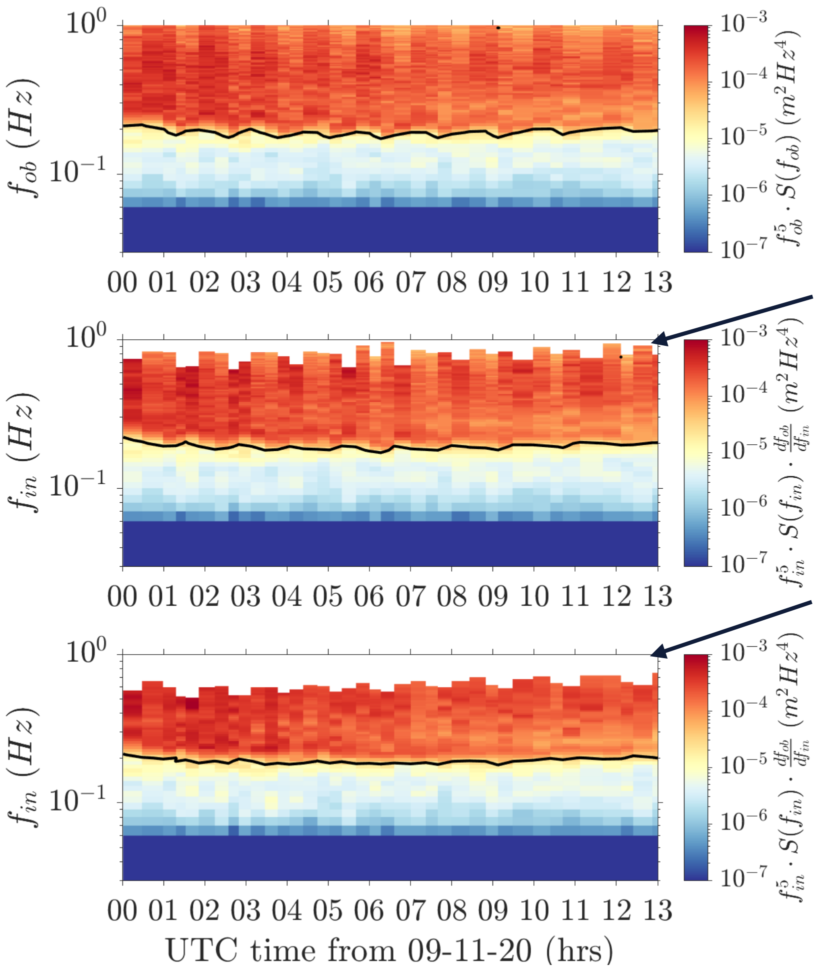
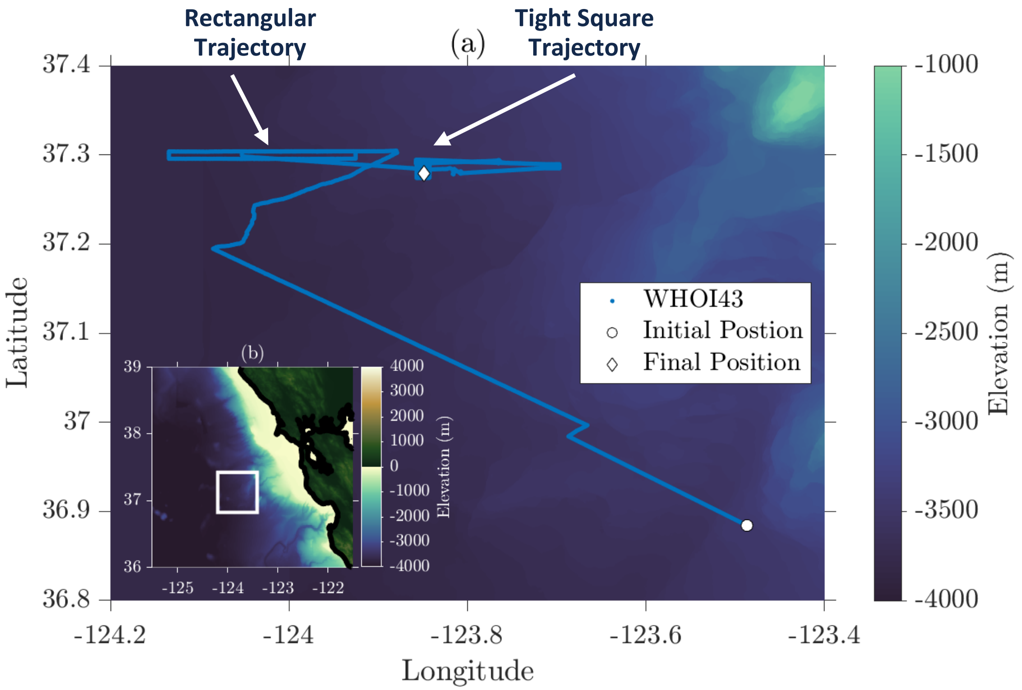


Unresolved high-frequency waves

Unresolved high-frequency waves

SMODE Pilot Experiment 2021



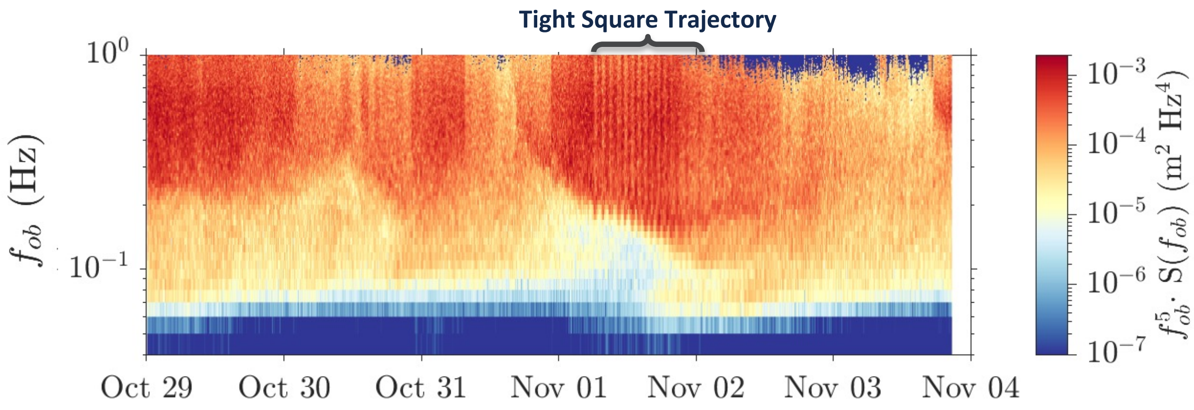
Environmental Conditions

- Wind: $2 - 12\ ms^{-1}$ coming from the Southeast ($\sim 130°$).
- Sea State: $2 - 5\ m$ significant wave height with wind-waves coming from the Northwest ($\sim 330°$) and Southeast ($\sim 100°$)and swell coming from the Northwest ($\sim 300°$).

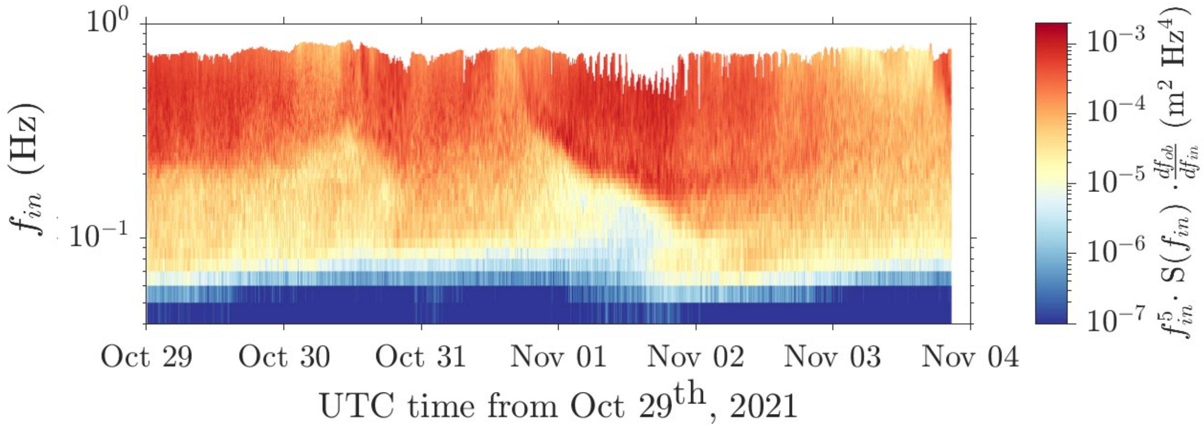
SMODE expands the range of environmental conditions.

Comparison between observed and intrinsic frequency spectrograms

OBSERVED



2D METHOD
(our approach)



Conclusions

- An **autonomous platform's motion** impacts the spectral measurements of waves.

- **Modulations** in wave spectra **depend upon** the wave frequency, the platform speed, and the angle between the direction of wave and platform propagation.

- The intrinsic frequency frame provides a **coherent** way to compare wave measurements from moving platforms and provide **accurate measurements** of directional surface waves down to short scales (O(1m)).

- Speed and direction of the platform should be **considered carefully in experimental planning.**

Colosi et al. in-prep for the Journal of Atmospheric and Oceanic Technology 2022.

References

Cavaleri, L., Fox-Kemper, B., & Hemer, M. (2012). Wind waves in the coupled climate system. *Bulletin of the American Meteorological Society*, *93*(11), 1651-1661.

Lenain, L., & Melville, W. K. (2014). Autonomous surface vehicle measurements of the ocean's response to Tropical Cyclone Freda. *Journal of Atmospheric and Oceanic Technology*, *31*(10), 2169-2190.

Thomson, J., Girton, J. B., Jha, R., & Trapani, A. (2018). Measurements of directional wave spectra and wind stress from a wave glider autonomous surface vehicle. *Journal of Atmospheric and Oceanic Technology*, *35*(2), 347-363.

Grare L, Statom NM, Pizzo N and Lenain L (2021) Instrumented Wave Gliders for Air-Sea Interaction and Upper Ocean Research. *Front. Mar. Sci.* 8:664728. doi: 10.3389/fmars.2021.664728

Longuet-Higgins, M. S. (1986). Eulerian and Lagrangian aspects of surface waves. *Journal of Fluid Mechanics*, *173*, 683-707.

Collins III, C. O., Blomquist, B., Persson, O., Lund, B., Rogers, W. E., Thomson, J., ... & Graber, H. C. (2017). Doppler correction of wave frequency spectra measured by underway vessels. *Journal of Atmospheric and Oceanic Technology*, *34*(2), 429-436.

Resources

Github Repository: https://github.com/lcolosi/WaveGlider.

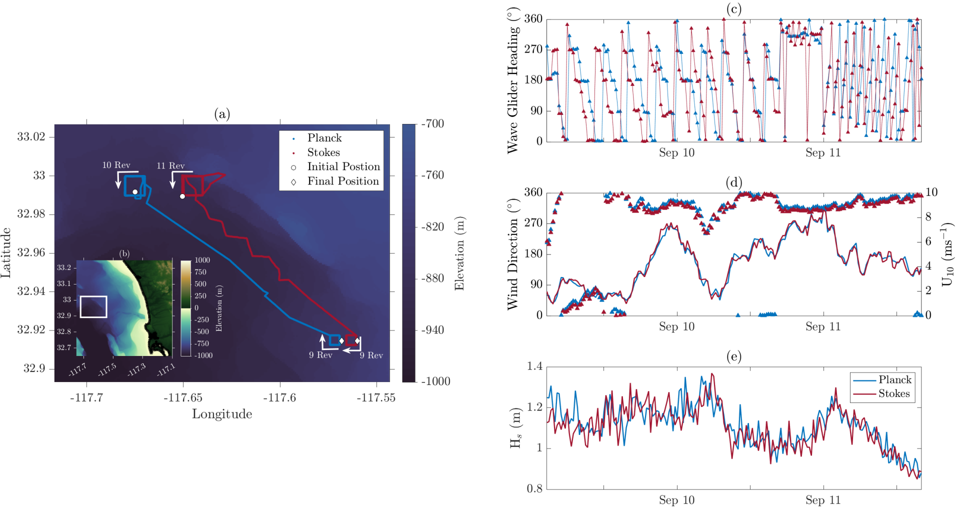
Contact information: Luke Colosi; lcolosi@ucsd.edu; (831) 840-1612; lcolosi.github.io,

SIO Air-Sea Interaction Laboratory Website: https://airsea.ucsd.edu/

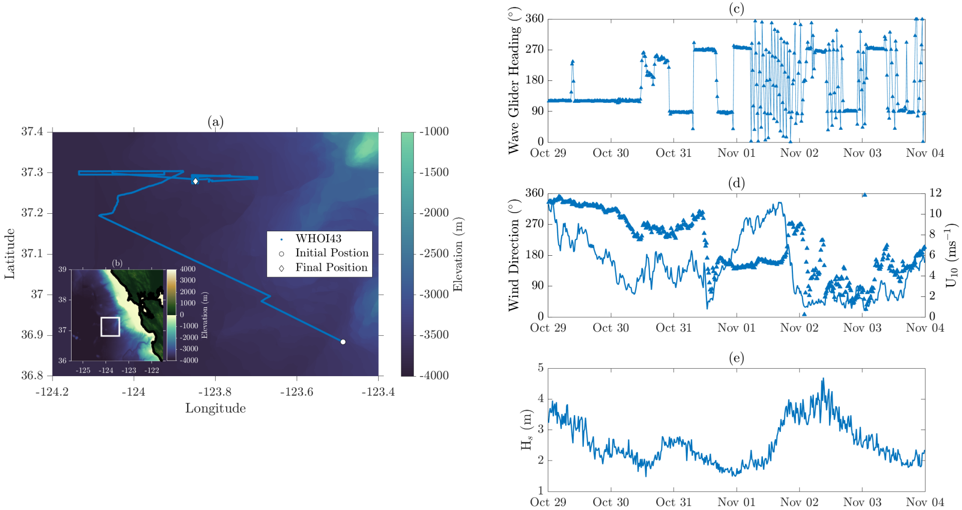
Supplemental Slides

Experimental Assets and Environmental Conditions

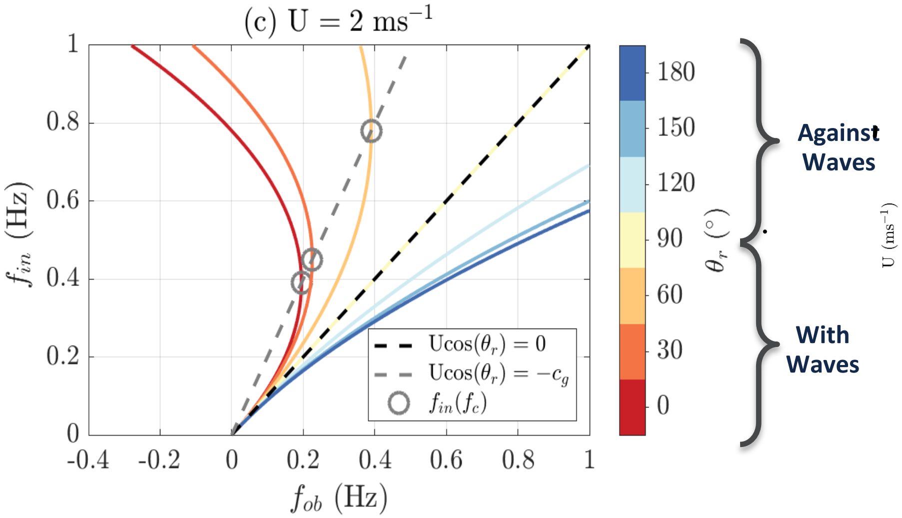
DELMAR2020



SMODE2021



Less high-frequency waves can be resolved the faster a platform moves with the waves



Cutoff Frequency $f_c(U, \theta_r)$