Session # PS07
ID # 6165
March 4th at 11:30-12:00 pm EST

# Observations of Surface Gravity Wave Spectra from a Moving Platform

Luke Colosi
Luc Lenain, Nick Pizzo, and Laurent Grare
Scripps Institution of Oceanography, UCSD

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

*Photo: Nick Statom*

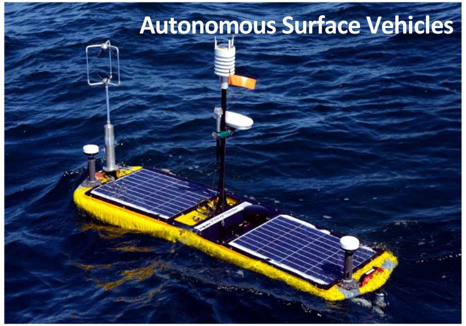
# Surface waves mediate momentum, mass, heat, and energy fluxes between the ocean and atmosphere

*Video: Laurent Grare*

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.


UAV Fixed-Wing


Autonomous Surface Vehicles


Research Vessels

# What observational platforms are available to measure surface waves?


UAV Multirotor


Satellites

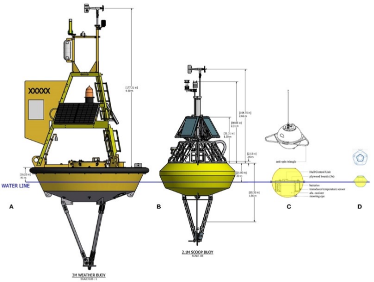
*https://scitechdaily.com/new-sentinel-6-sea-level-satellite-arrives-at-california-launch-site/*

Instrumented Aircraft

# Autonomous vehicles are well suited to study surface waves

## Historical

### Wave Buoys



### Satellites

### Research Platforms

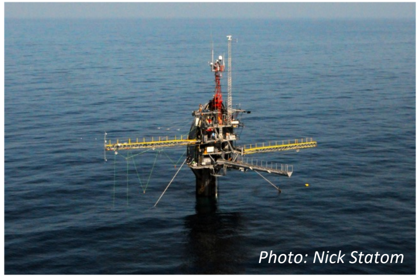


*Photo: Nick Statom*

## Autonomous surface vehicles

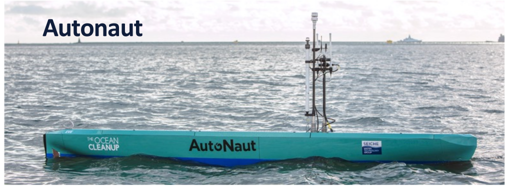
**Saildrones**

*Photo: Ted Pease*

*Photo: Nick Statom*

**Wave Glider**

**Autonaut**



*https://autonautusv.com/vessels-0*

**New generation of instrumented platforms** →

## Advantages:

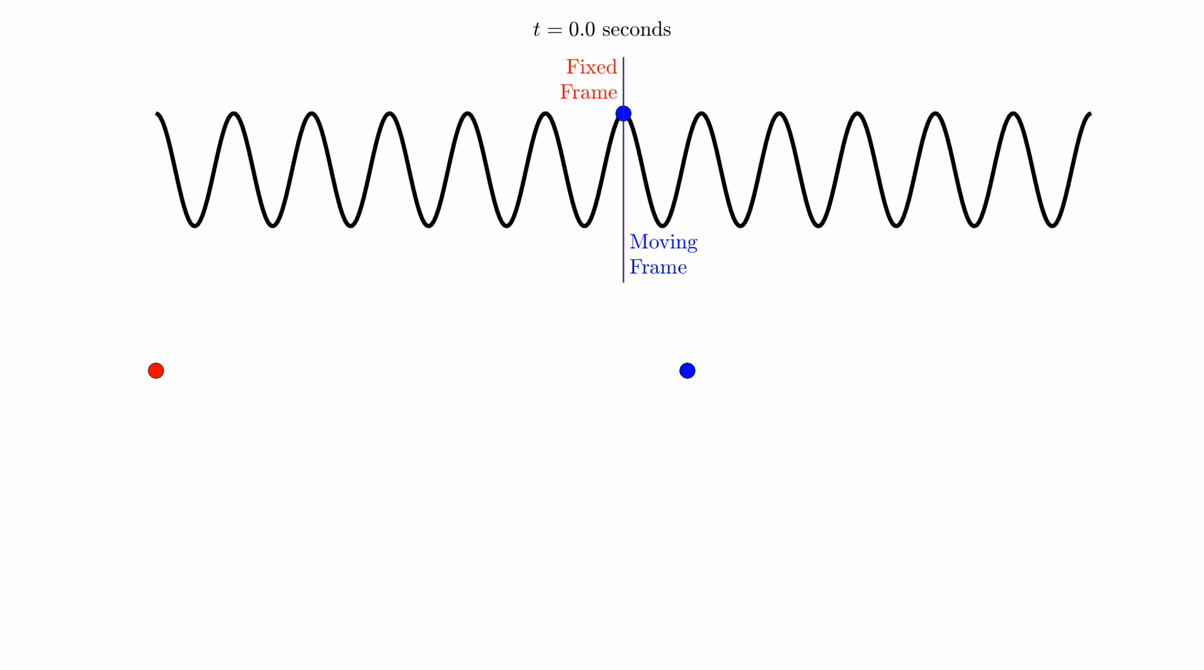
1. Uncrewed
2. Long duration deployments
3. Remote area data collection
4. Measurements taken over broad spatio-temporal scales

# Autonomous platforms measure the wave spectrum from the vehicle's motion (Lenain and Melville 2014, Thomson et al. 2018, Grare et al. 2021)

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

*Video: Nick Statom*

# 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

$$\omega_{ob}(k,\theta,U,\phi) = \omega_{in}(k) - \underbrace{kU\cos(\phi-\theta)}_{\text{Doppler Shift Term}}$$

**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

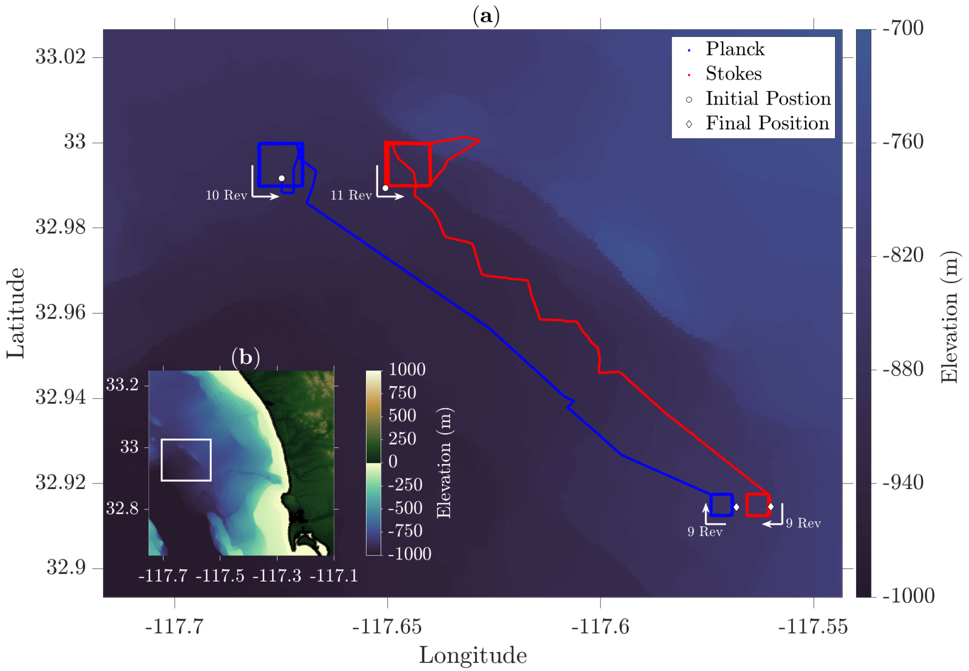
Doppler Shift Term

**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 modulations 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.

# Del Mar Experiment 2020

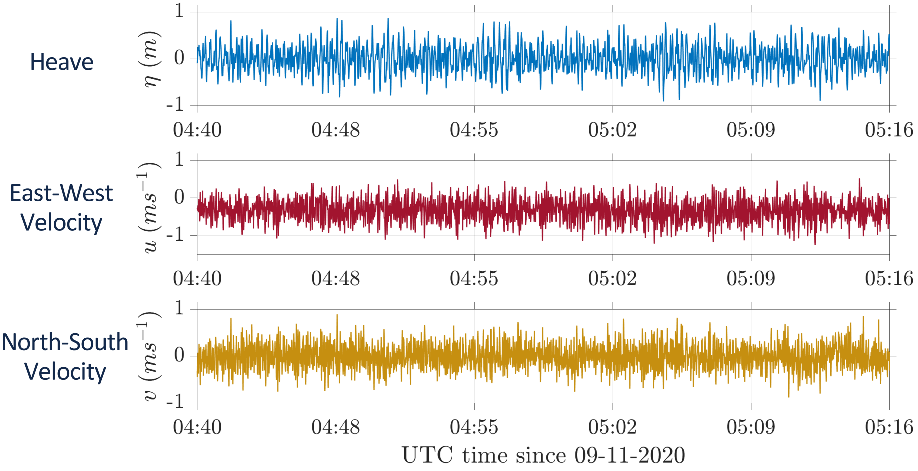


*Colosi et al. in-prep for JTECH*

- 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 ($\sim 200°$).

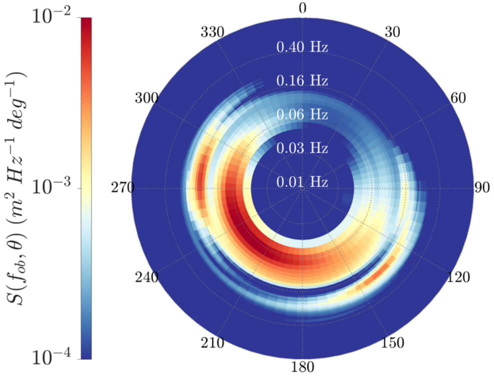
# Directional and omni-directional wave spectrum computed from the motion of the platform

**Input Data**



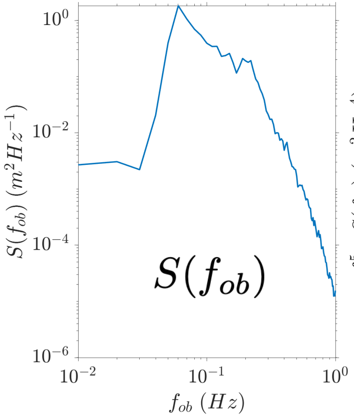
Derive Spectral Wave Parameters

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

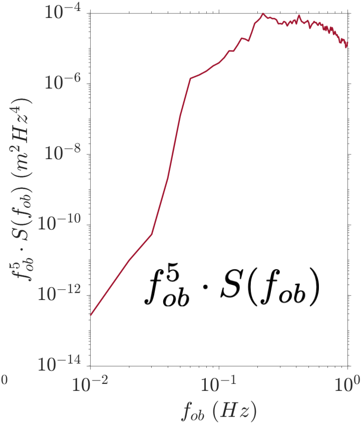


- Derived using maximum entropy method
- Directions coming from

**Omni-directional Spectrum**

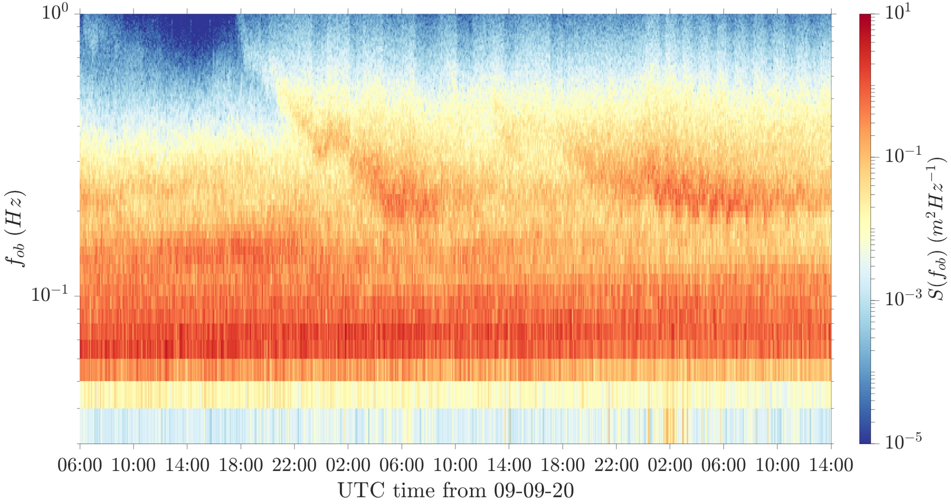


**Saturation Spectrum**

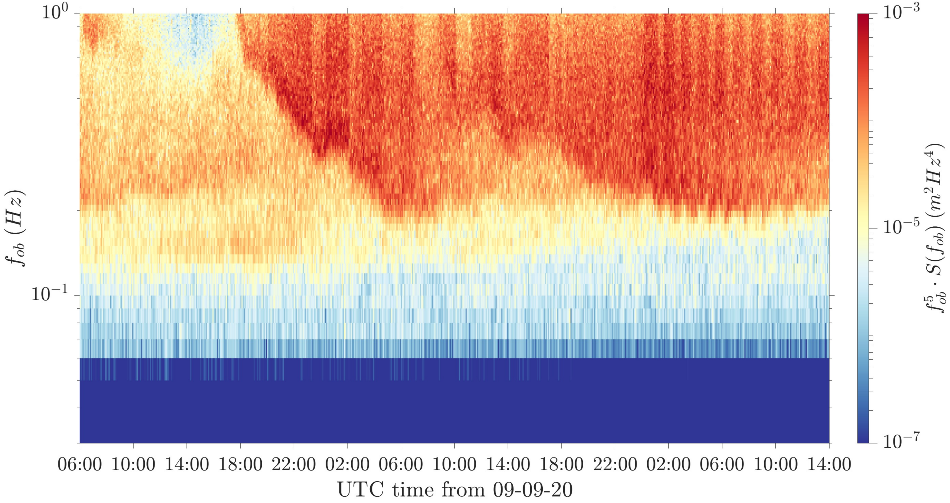


# Spectrogram of surface waves observed by a wave glider

### Omni-directional Spectrogram



### Saturation Spectrogram



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

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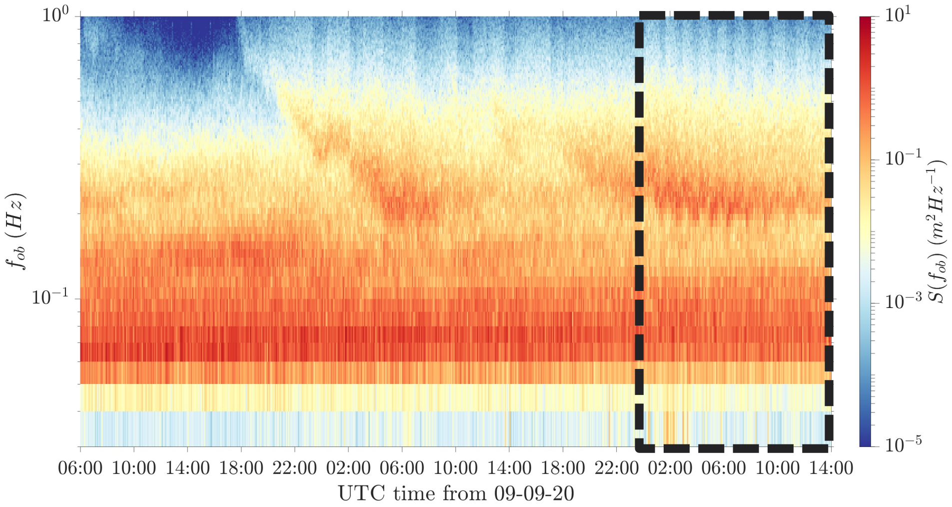
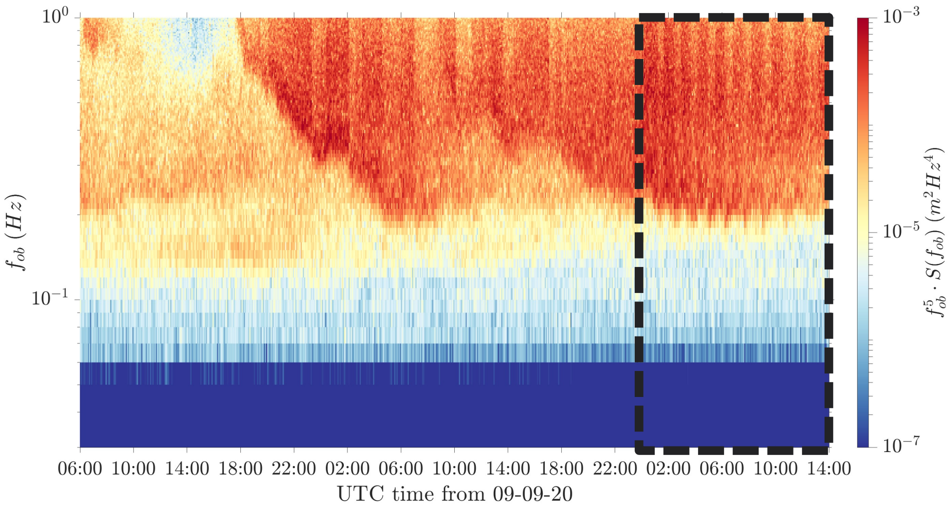
## Omni-directional Spectrogram



## Saturation Spectrogram



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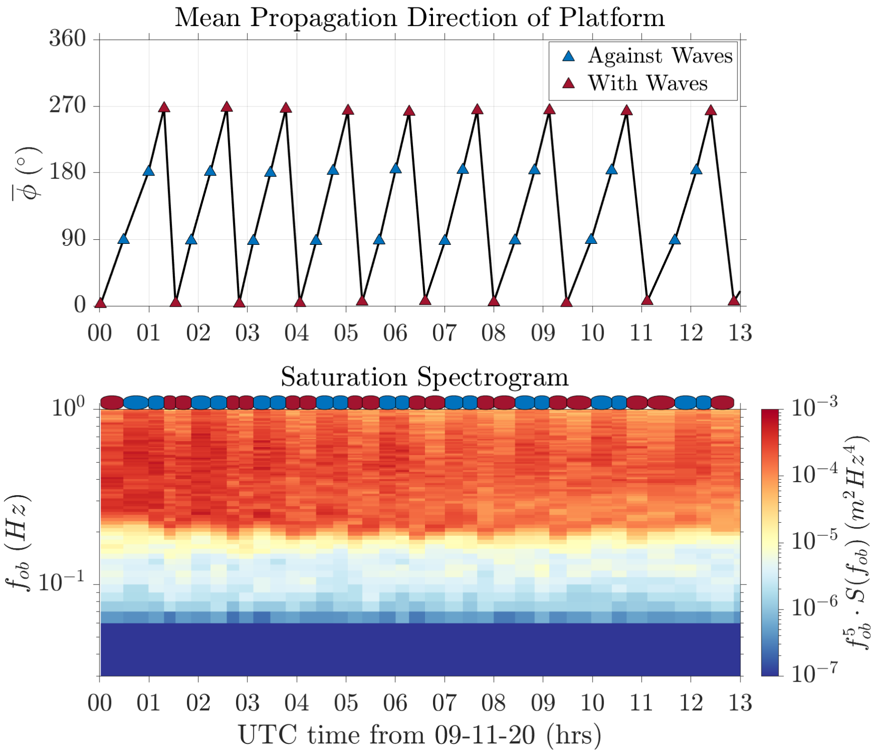
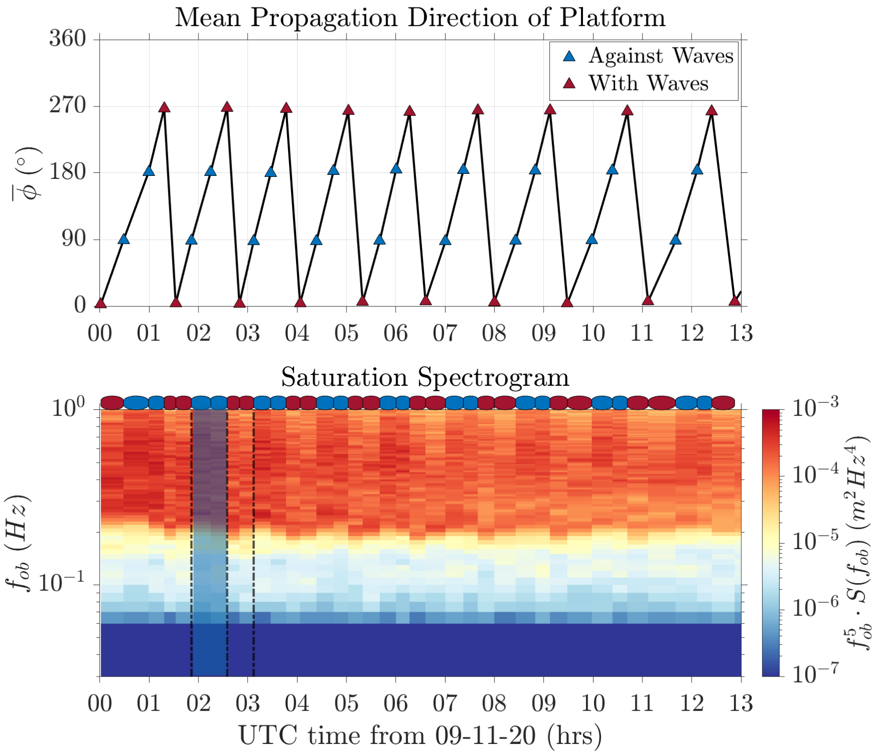
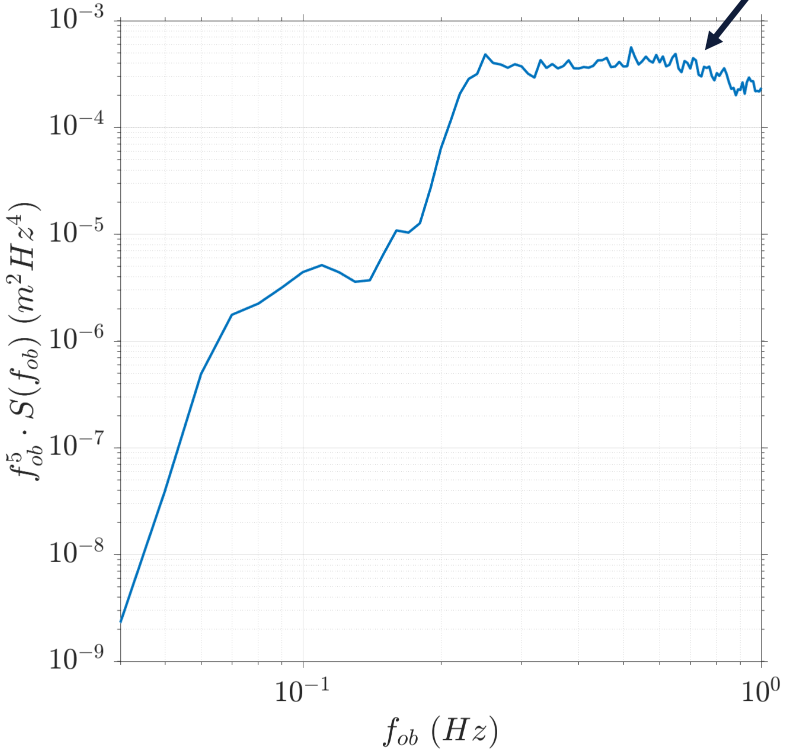


The platform’s motion is impacting the observed wave spectra.

# Spectrogram of surface waves observed by a wave glider





**Against Waves**

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

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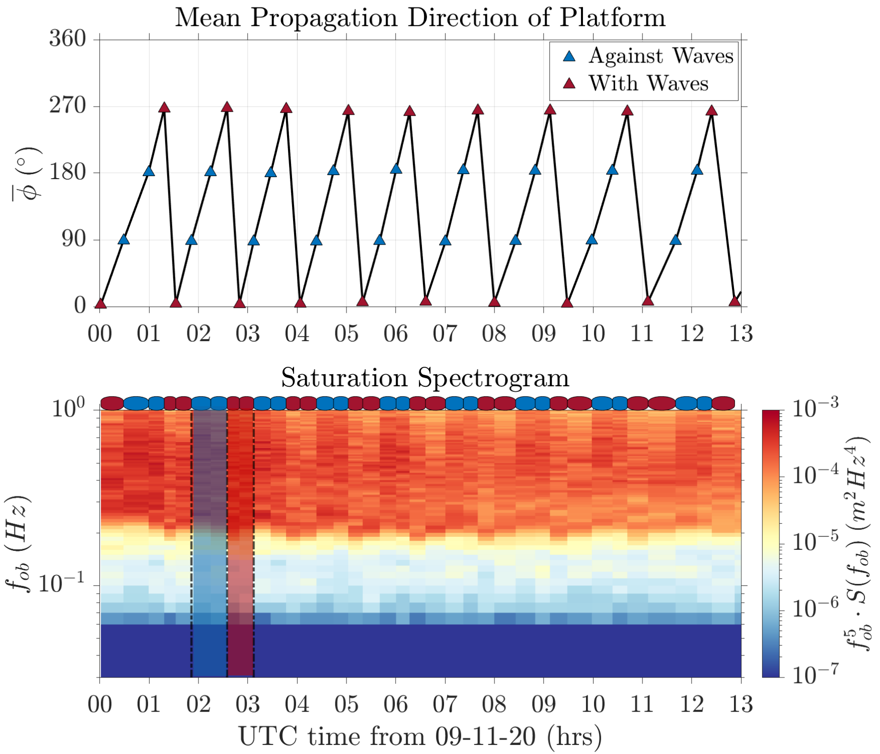

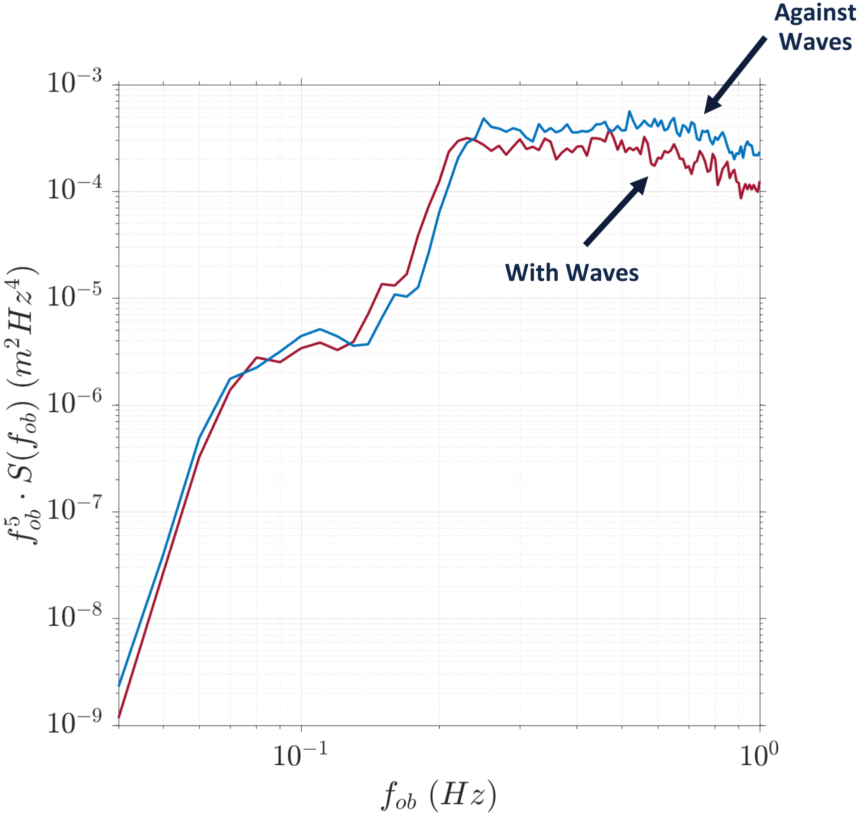

**Against Waves**

**With Waves**

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

# Methods to account for Doppler shift in wave spectra

## 1D Method

**Observe 1D Spectrum**

**Map from observed to intrinsic frequency**

**Map 1D Spectrum into intrinsic frequency space**

$$S_{ob}(f_{ob}) \longrightarrow f_{ob}(k, \overline{\theta}, U, \phi) \mapsto f_{in}(k) \longrightarrow S_{in}(f_{in}) \cdot \frac{\partial f_{ob}}{\partial f_{in}}$$

(Collins et al. 2017)

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(Collins et al. 2017)

## 2D Method

(our approach)

**Observe 2D Spectrum**

**Map from observed to intrinsic frequency**

**Map 2D Spectrum into intrinsic frequency space**

**Compute 1D spectrum from 2D Spectrum**

$$S_{ob}(f_{ob}, \theta) \longrightarrow f_{ob}(k, \theta, U, \phi) \mapsto f_{in}(k) \longrightarrow S_{in}(f_{in}, \theta) \cdot \frac{\partial f_{ob}}{\partial f_{in}} \longrightarrow S_{in}(f_{in}) = \int_0^{2\pi} S_{in}(f_{in}, \theta) \cdot \frac{\partial f_{ob}}{f_{in}} d\theta$$

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**Map 2D Spectrum into intrinsic frequency space**

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

**Compute 1D spectrum from 2D Spectrum**

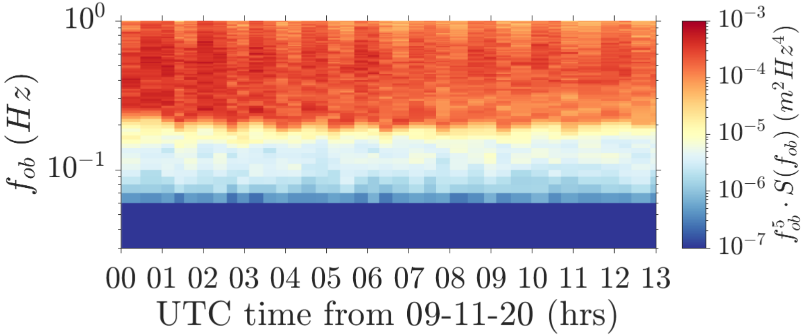
$$S_{in}(f_{in}) = \int_0^{2\pi} S_{in}(f_{in}, \theta) \cdot \frac{\partial f_{ob}}{\partial f_{in}} d\theta$$

If only 1D spectra are used, this leads to an over modification due to the mapping.

**We need to use a full 2D spectrum.**

# Comparison between 1D and 2D methods

**OBSERVED**



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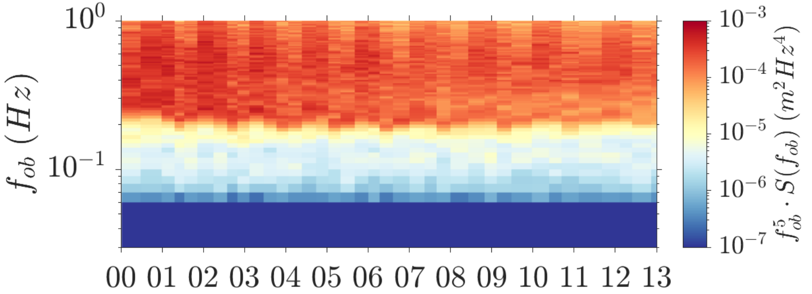
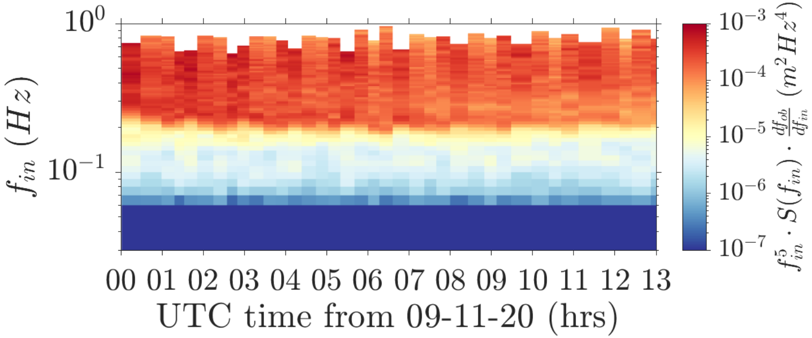


**1D METHOD**



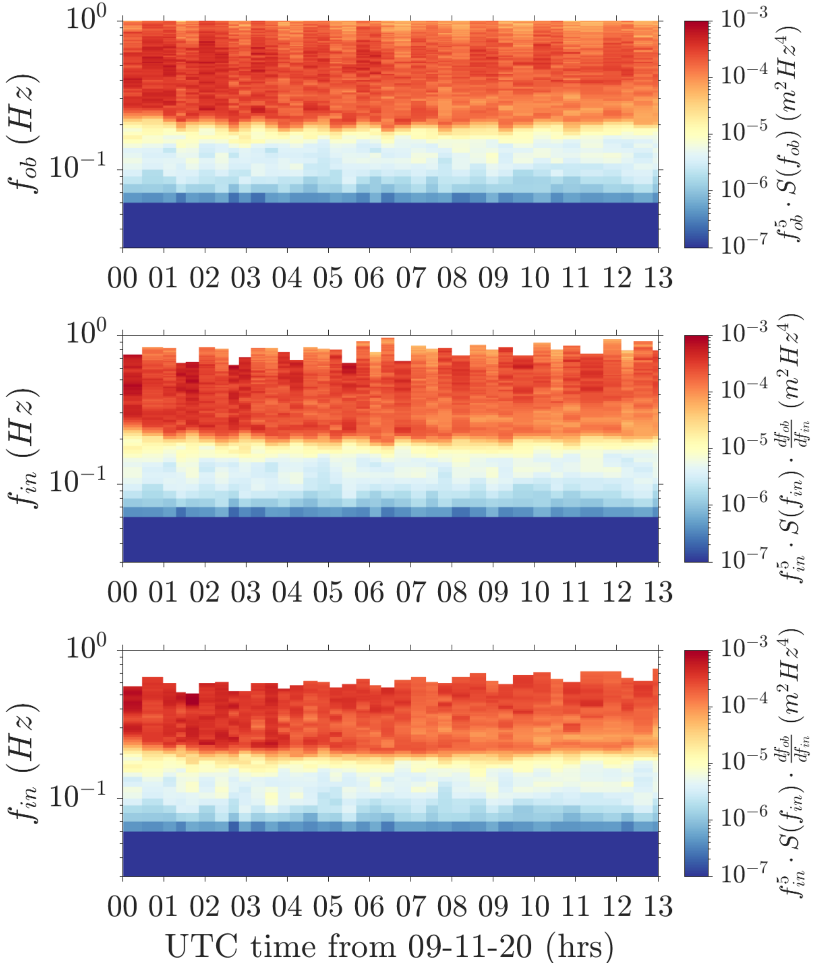
# Comparison between 1D and 2D methods

**OBSERVED**

**1D METHOD**

**2D METHOD**

(our approach)



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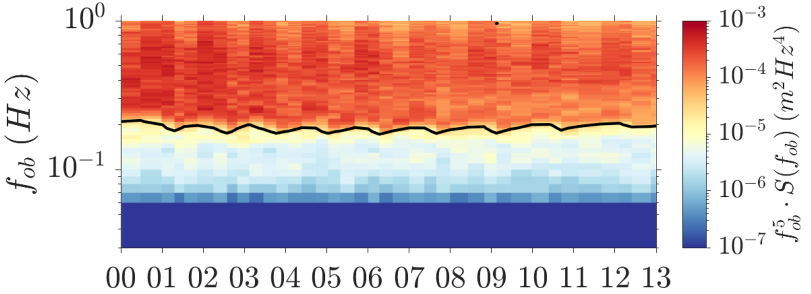
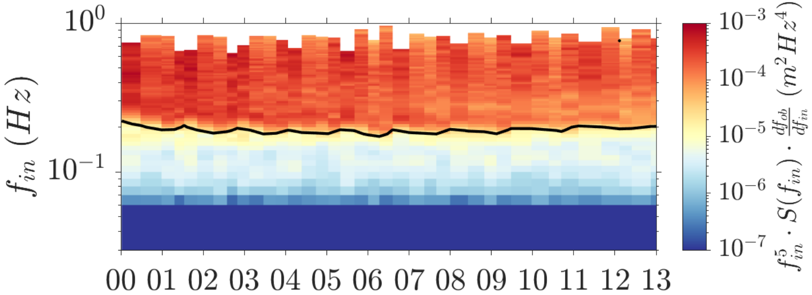
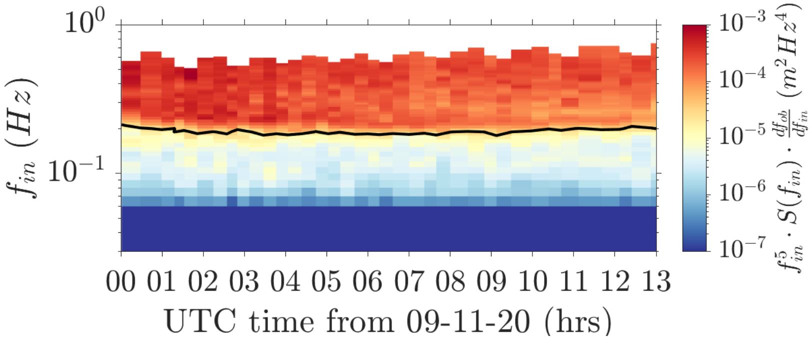


**1D METHOD**



**2D METHOD**
(our approach)

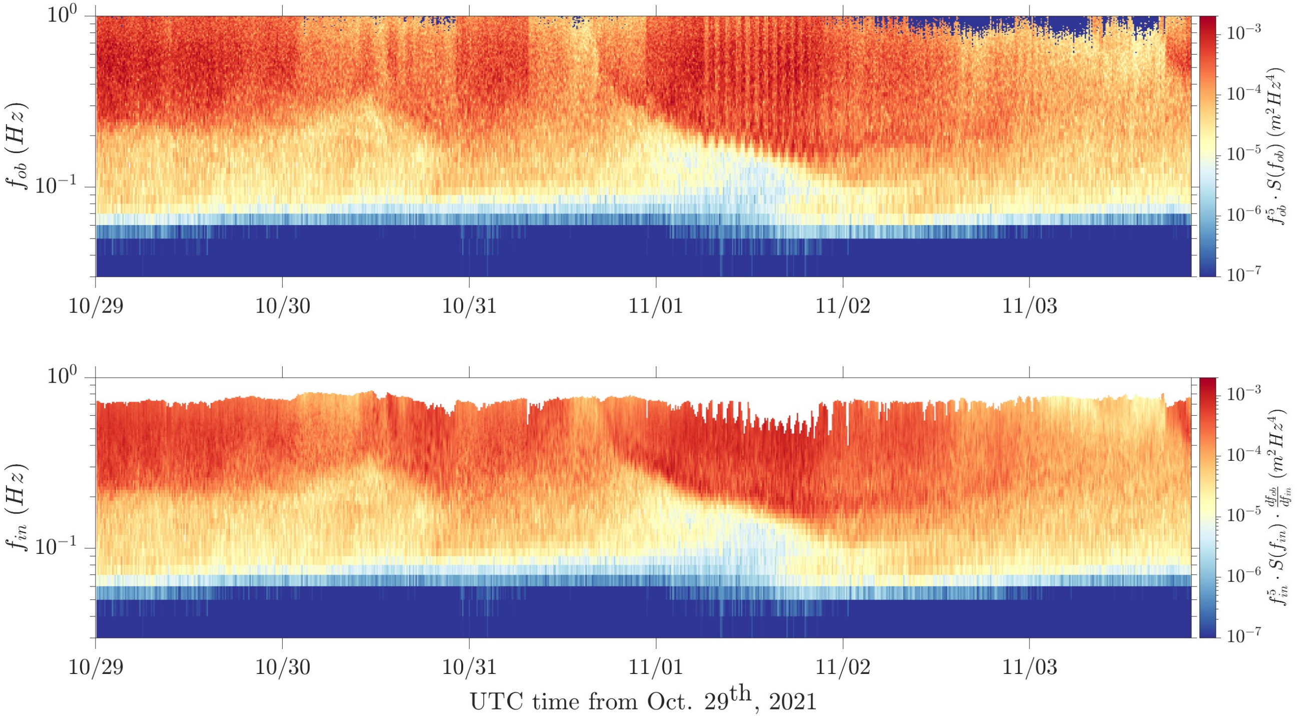


# SMODE Pilot Experiment 2021

**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)).

*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

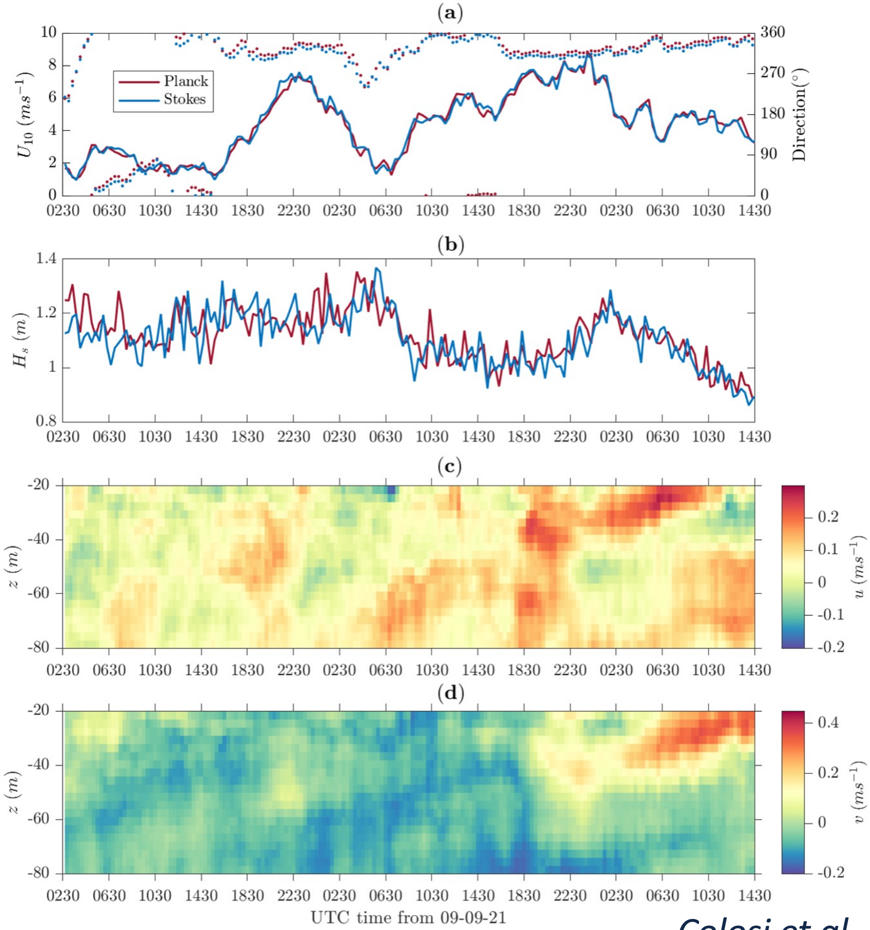
Github Repository: https://github.com/lcolosi/WaveGlider.

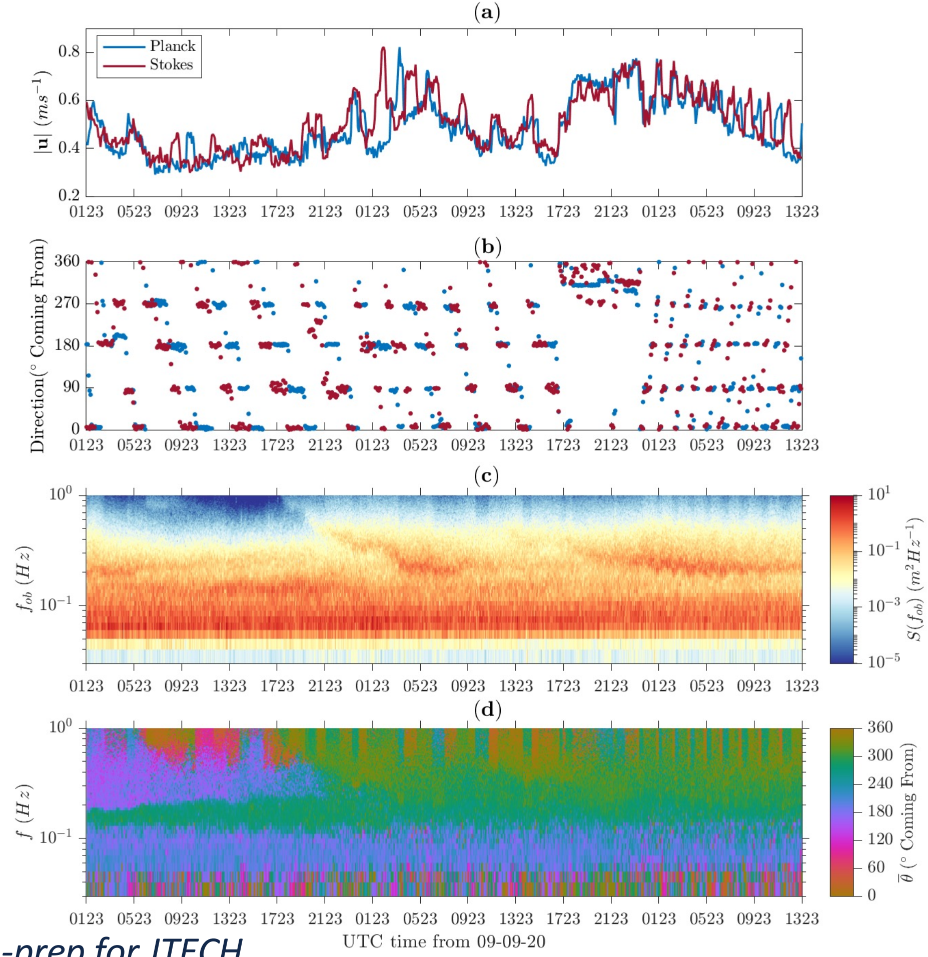
Contact information: Luke Colosi; lcolosi@ucsd.edu; (831) 840-1612; lcolosi.github.io,

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

# Supplemental Slides

# Environmental Conditions for Del Mar 2020





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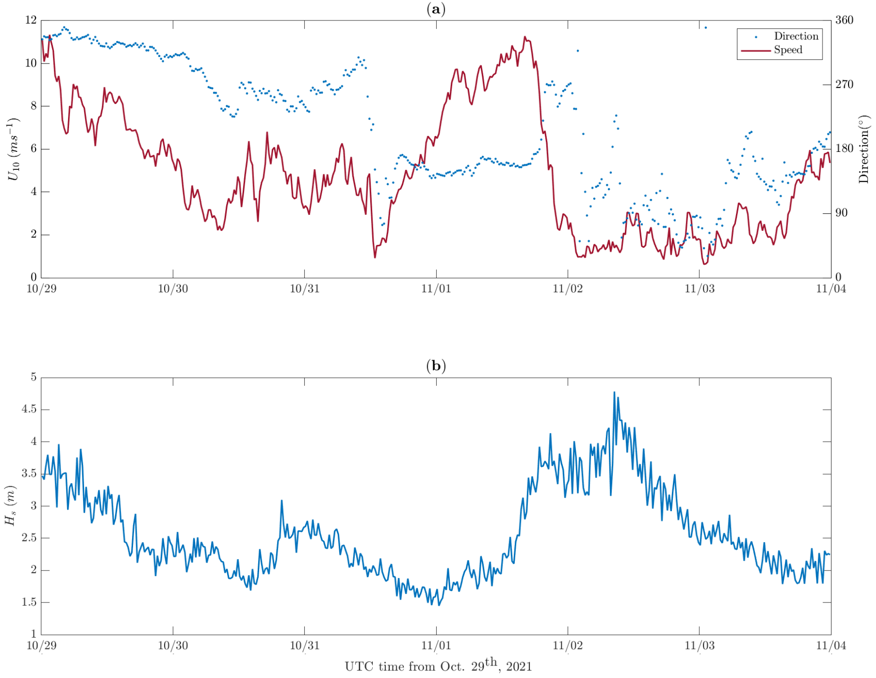
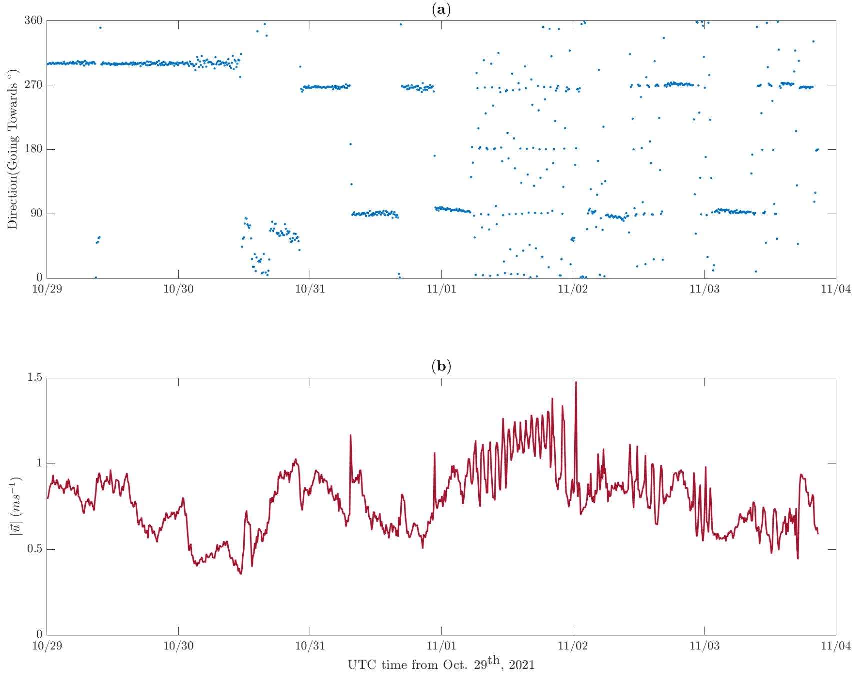
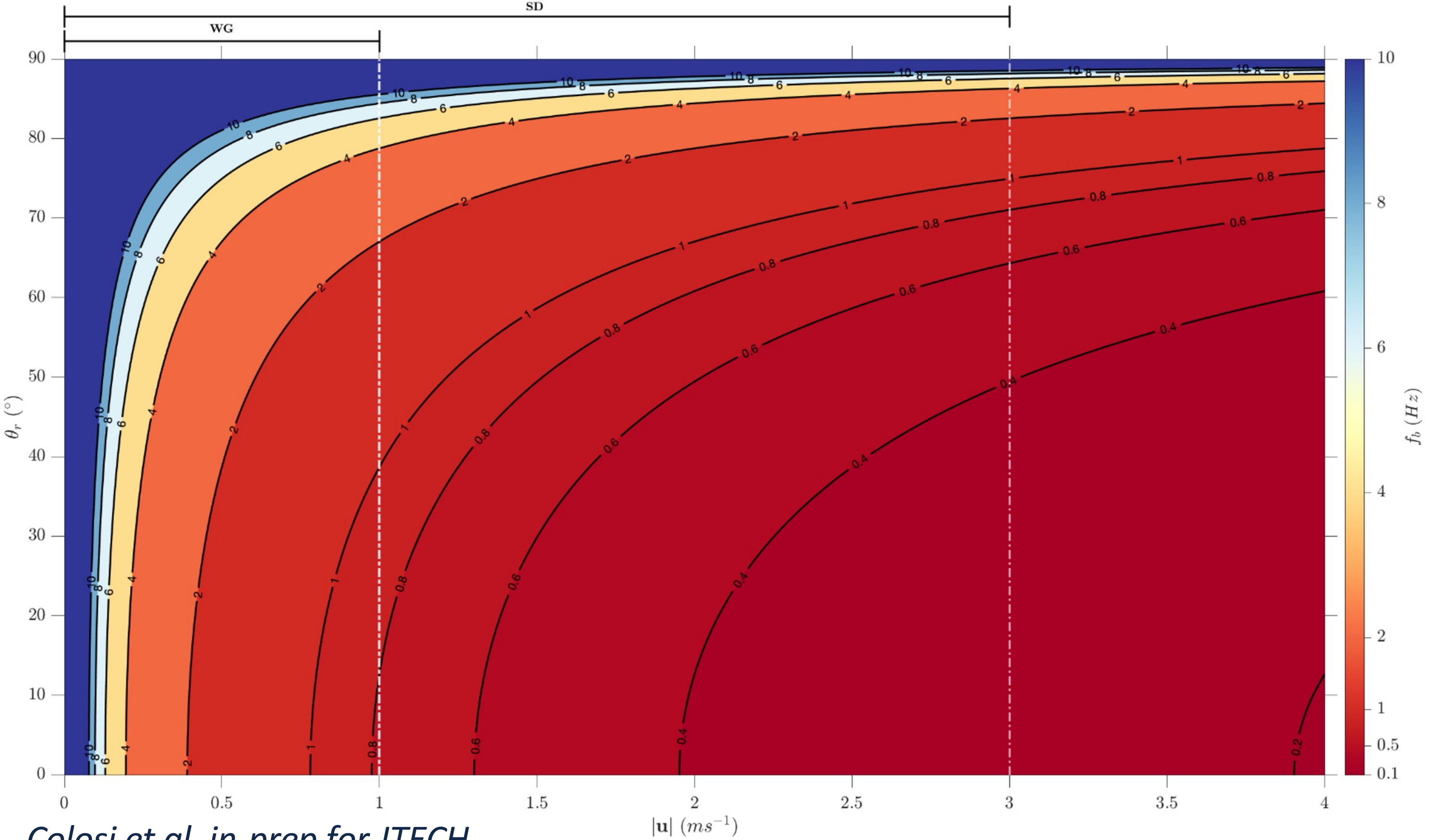
# Environmental Conditions for SMODE 2021





# Frequency Ambiguity Implications



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When the platform is moving with the waves, then:

$$0 \leq \theta_r < 90$$

and

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

Bifurcation Frequency

Conclusion:

$$U \uparrow \text{ and } \theta_r \downarrow \Rightarrow f_b \uparrow$$