Current Retrieval from Remote Sensing Images of Ocean Waves

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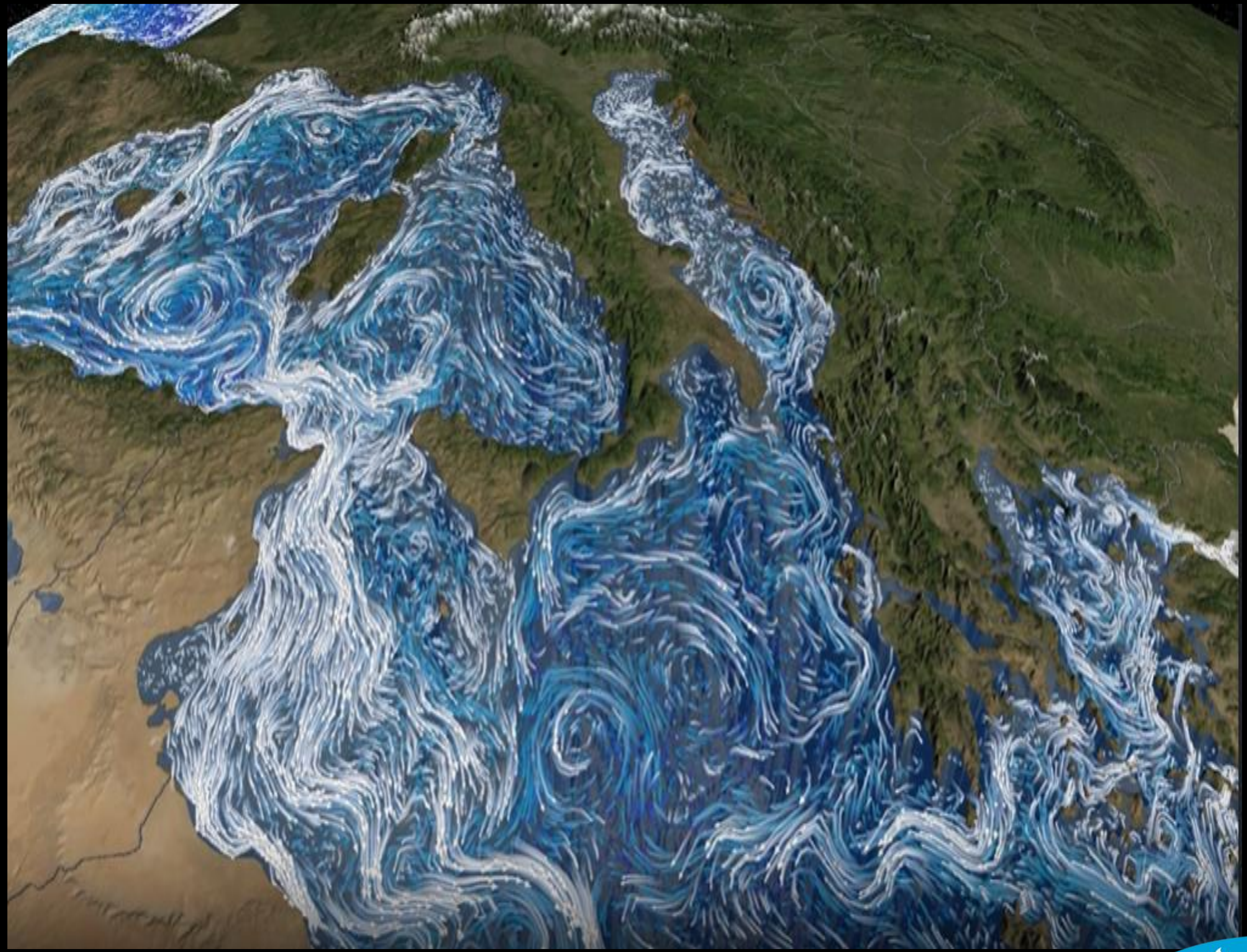


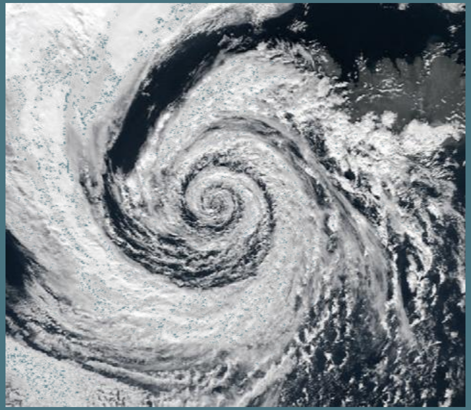
Motivation

Ocean current measurements have a wide range of practical applications.

Measure the impact of oil spills. [1]

Choose more efficient shiping routes. [2]

Track the movement of microplastics. [3]



Predict climate events. [4]

Background

There are many ways to measure ocean current using in situ methods such as:

Eulerian:
- Moorings on surface
- Submerged moorings

Lagrangian:
- Surface-following drogues
- Underwater drogues

Disadvantages:

- ✕ Instrument Error
- ✕ Limited Data Area
- ✕ Time Consuming to Deploy
- ✕ Expensive

Hence

- There has been growing interest in using radar images instead.
- They can map large areas with a single radar image.

Location of Mediterranean Sea radar image

X-band marine radar antenna

Project Aims

This project will study first simulated waves and then waves from the Eastern Mediterranean Sea:

Simulated Data Waves:

- Compare existing methods to find the wavenumber dependent effective current.
- Understand the factors that influence accuracy in the current inversion method.

Eastern Mediterranean Waves:

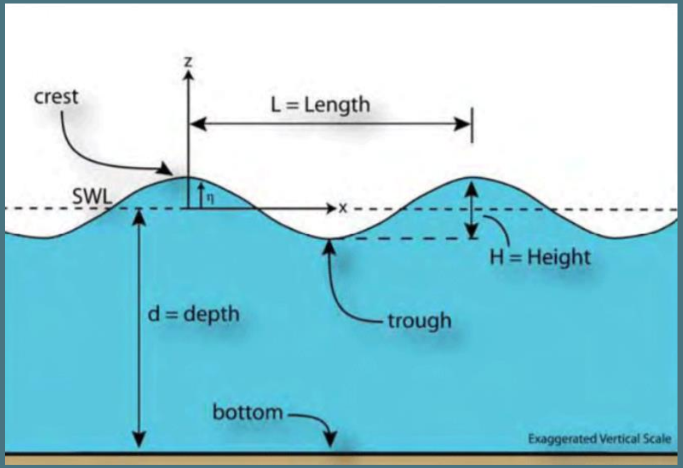
- Use previous methods to find the current profile which can be compared to in situ methods in the field.
- Study the impact of shear on the current inversion.

Research Question:
What factors influence the accuracy of current retrieval using radar images?

Theoretical Techniques Basics

Waves

Waves are a disturbance in a medium. For ocean water, they can be caused by winds, boats or other forces.



Basic Properties:

- Wavelength - L
- Wavenumber - $\frac{2\pi}{L}$
- Wave Period - T
- Angular frequency - $\omega = \frac{2\pi}{T}$

Dispersion Relation

The dispersion relation gives the relationship between angular frequency & wavenumber. It is different if there is or isn't a current beneath the waves.

No Current

For ocean waves the dispersion relation is:

$$\omega_0(\vec{k}) = \sqrt{gk\tanh(kh)}$$

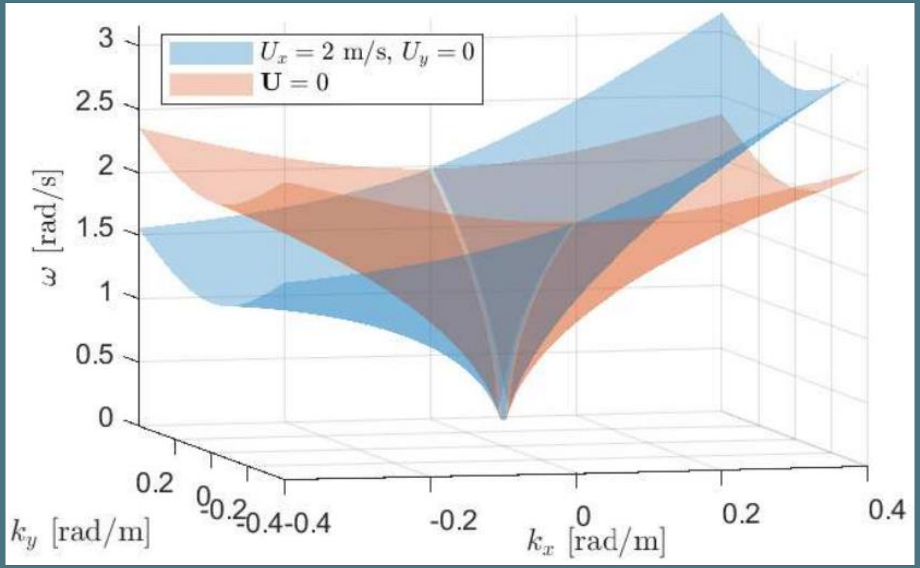
Plotted by the red surface.

Current Present

Add a current parallel to waves. Dispersion relation becomes:

$$\omega_0(\vec{k}) = \sqrt{gk\tanh(kh)} + \vec{k}\cdot\vec{U}$$

Plotted by the blue surface.

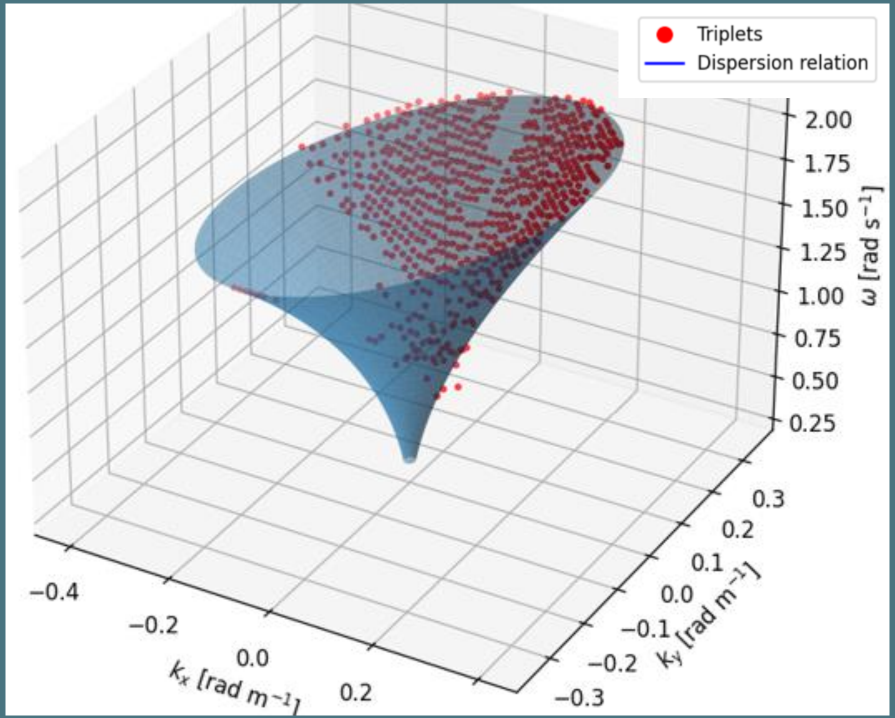


Theoretical Techniques Step 1

1a) Measure Dispersion Relation

We can use an FFT to find the energy spectrum depending on wavenumbers and frequencies.

- The maximum values of this energy spectrum correspond to the dispersion relation in triplets $(k_x, k_y, \omega_{trip})$.



1b) Find Effective Current

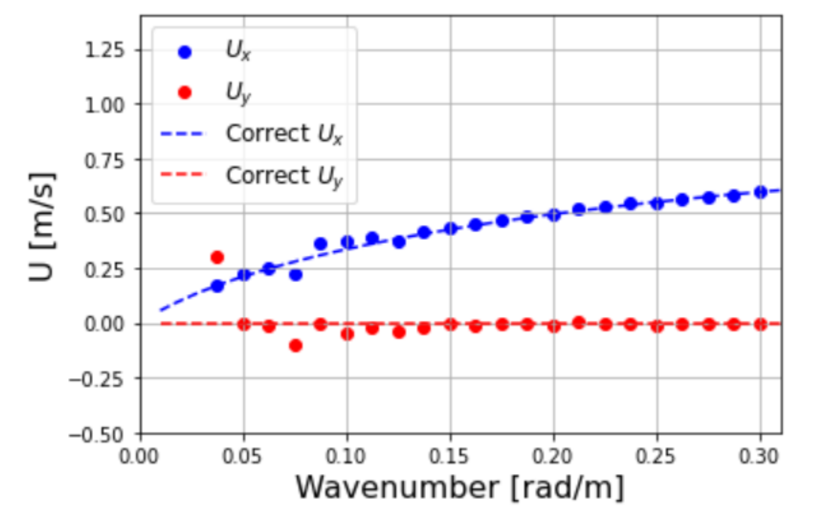
From previous slide we have:

$$\omega_{trip} = \sqrt{gk\tanh(kh)} + \vec{k} \cdot \vec{U}$$

We just need to find $\vec{U}$ through one of 3 existing algorithms:

1. Least Squares Method [5]
2. Normalized Scalar Product Method (NSP) [6]
3. Polar Current Shell Method (PCS) [7]

We assumed the current was constant at all depths which is not true.



This does not give us the true velocity of the current instead it represents a wavenumber dependent Doppler-shift, $c(\vec{k})$.

Theoretical Techniques Step 2

2a) Inversion Problem

This Doppler shift velocity is a weighted average of current as a function of depth which was derived by Stewart and Joy [8]:

$$\vec{c}(k) = 2k \int_{-\infty}^{0} \vec{U}(z) e^{2kz} dz$$

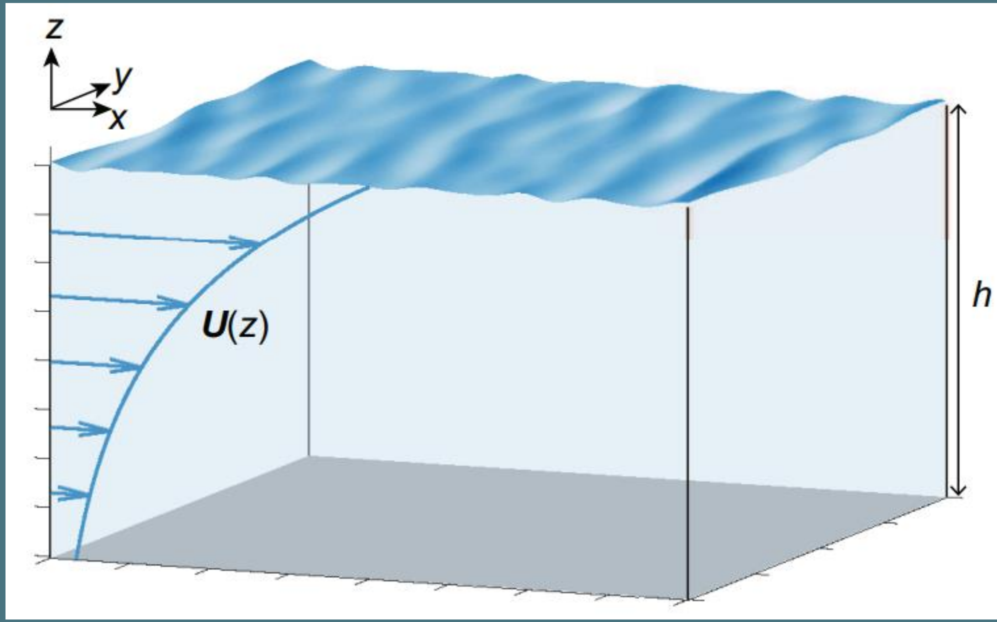
We need to use an algorithm to invert this integral using the values of $\vec{c}(k)$ to find the depth-dependent velocity $\vec{U}(z)$.

2b) Invert Integral

Invert integral using one of the following algorithms:

1. Effective Depth Method (EDM) [8]
2. Polynomial Effective Depth Method (PEDM) [10]

EDM requires an assumption of the functional form of the current profile which is why the PEDM was developed in 2019 to avoid this assumption.

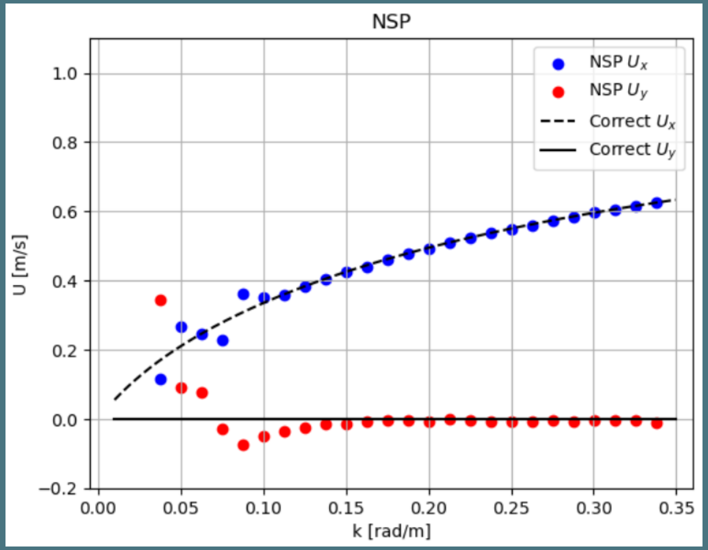


Simulated Results Doppler Shifts

We studied 2 separate wave fields one having a current direction of **0°** and the other having a current direction of **30°.** For this presentation we will focus on **0°** case.

1) Use NSP Method

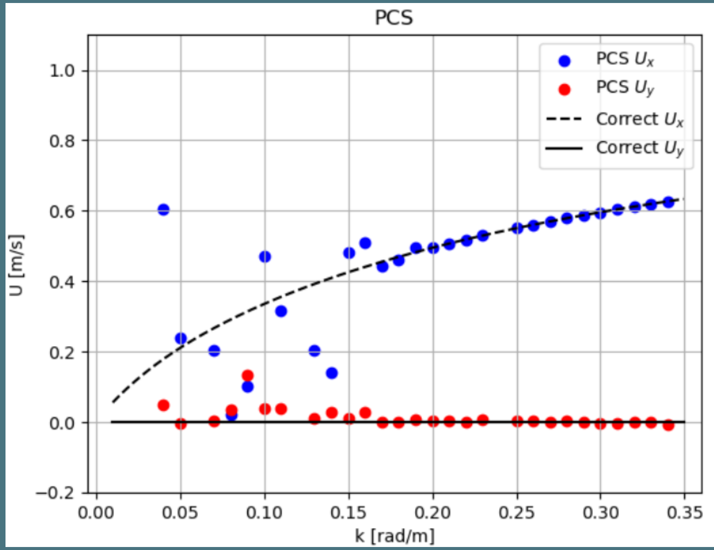
Involves the maximization of the normalized scalar product between the spectrum and the dispersion shell.



- Good agreement for higher wavenumbers.
- Lower wavenumbers have errors due to spectral leakage.

2) Use PCS Method

This algorithm considers the spectrum in polar co-ordinates and then performs a curve fitting using the dispersion relation.



- Higher wavenumber have similar accuracy to NSP method.
- More lower wavenumbers affected by spectral leakage caused by the difference in wavenumber resolution between the two.

NSP method provides more accurate Doppler shifts.

Simulated Results Current Profile

EDM – Old Method

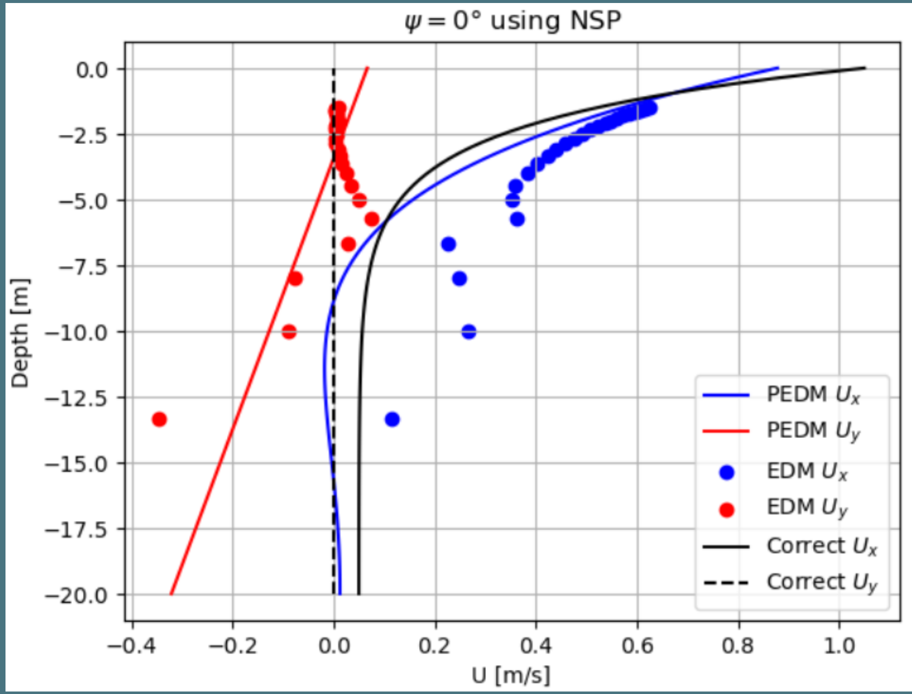
Assumes the profile varies linearly with depth meaning the previous integral can be solved to be:

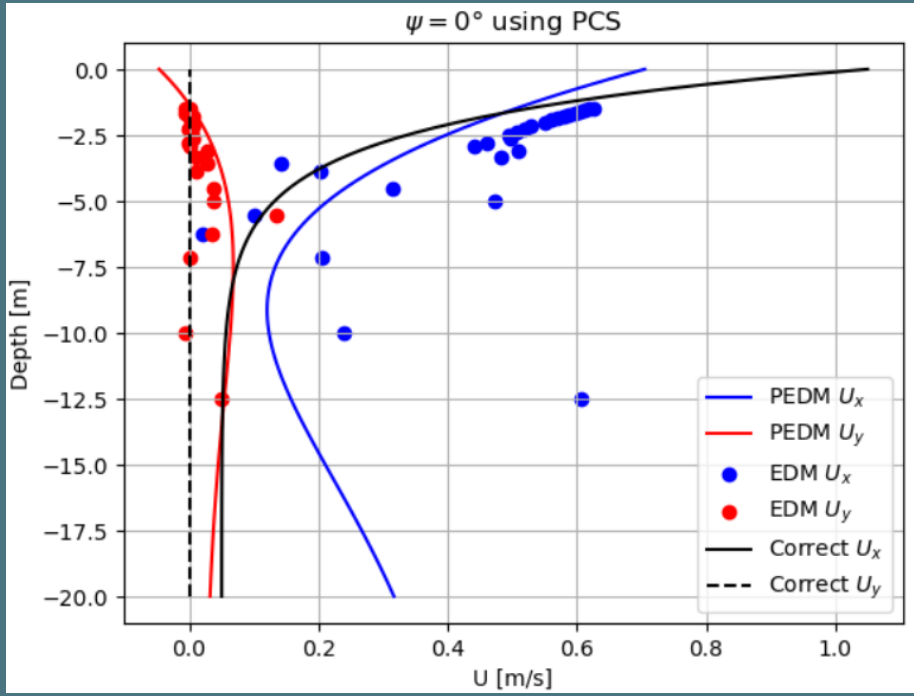
$$\vec{c}(k) = \vec{U}\left(z = \frac{1}{2k}\tanh(kh)\right)$$

PEDM – New Method

Developed by Ben Smeltzer in 2019 [10]. Starts from conventional EDM, fits the profile to a polynomial form and then scales the coefficients to produce an improved estimate of the true current profile.

Applying both methods to each component of the current using the Doppler shifts from the NSP (left) and PCS (right).



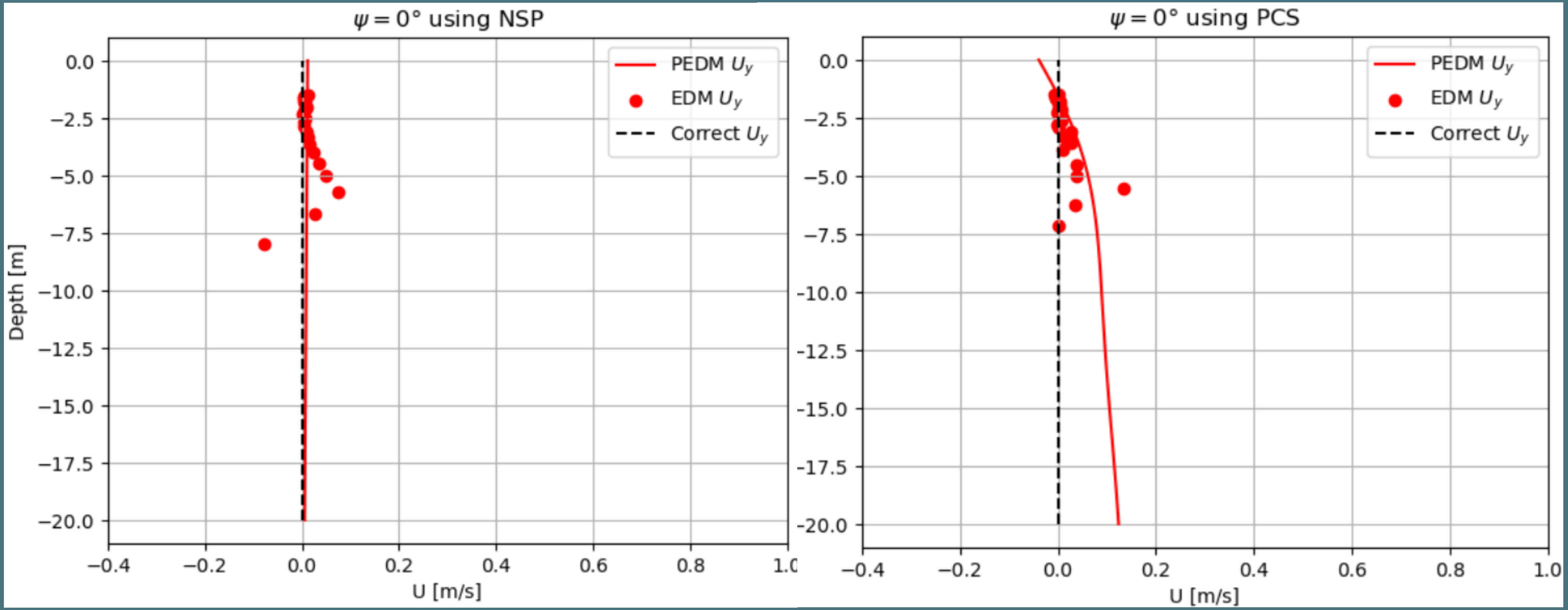


Simulated Results Current Profile

The $U_y(z)$ component is not reconstructed well in either case. This is due to the sensitivity to lower wavenumbers.

To improve this, we can neglect the lowest two wavenumbers.

Again, we can see the improved performance of the new way using the NSP Doppler shifts over the PCS doppler shifts.



- New method (PEDM) improves the old method (EDM) in all cases.
- New method (PEDM) performs better using the NSP points than using the PCS points.

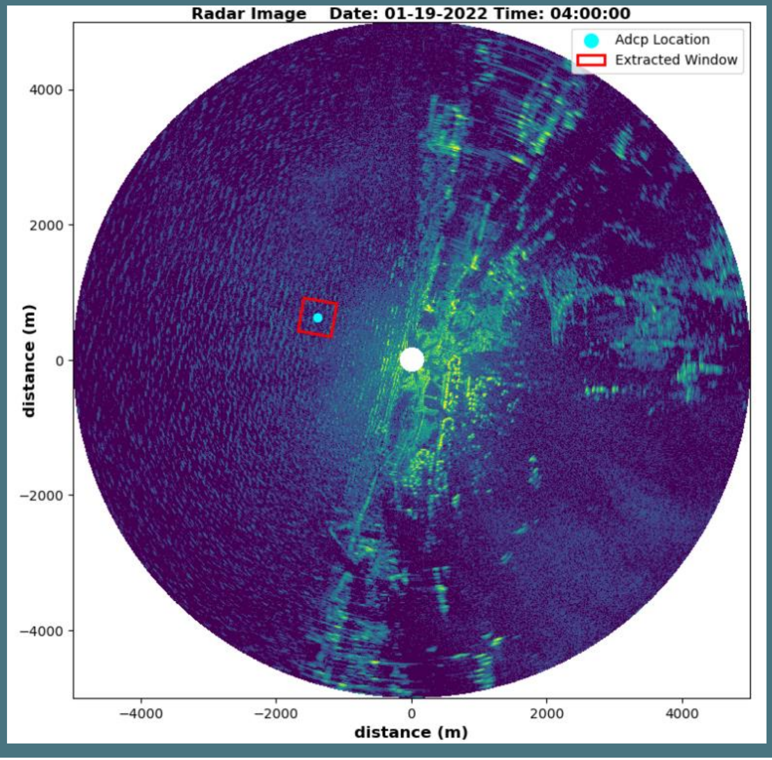
Data from the Field

Radar Images

An X-band marine radar captured a circular region with radius of approx. 4 km located in the Eastern Mediterranean Sea.

A radar sequence of 15 minutes was collected every hour from 9 pm on the 18th to 6 pm on 20th of January 2022.

We took a 500 x 500 m extraction window around the ADCP.

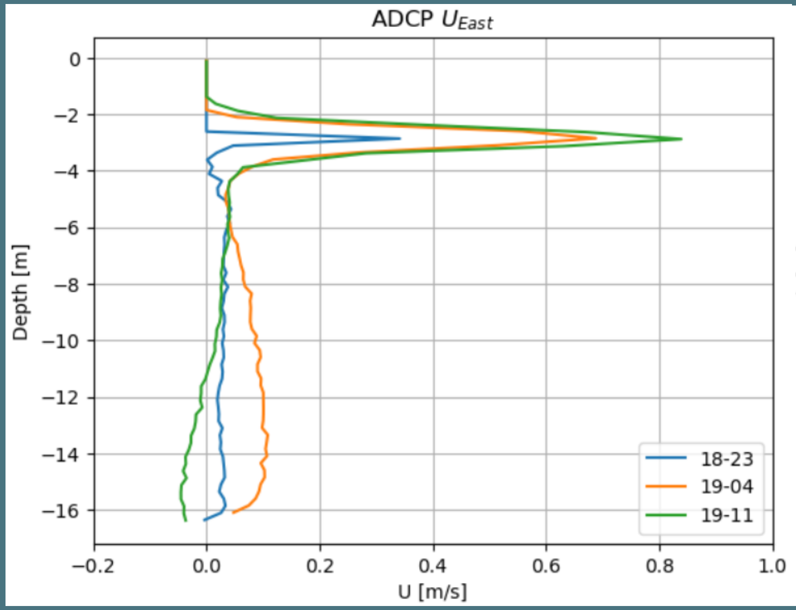


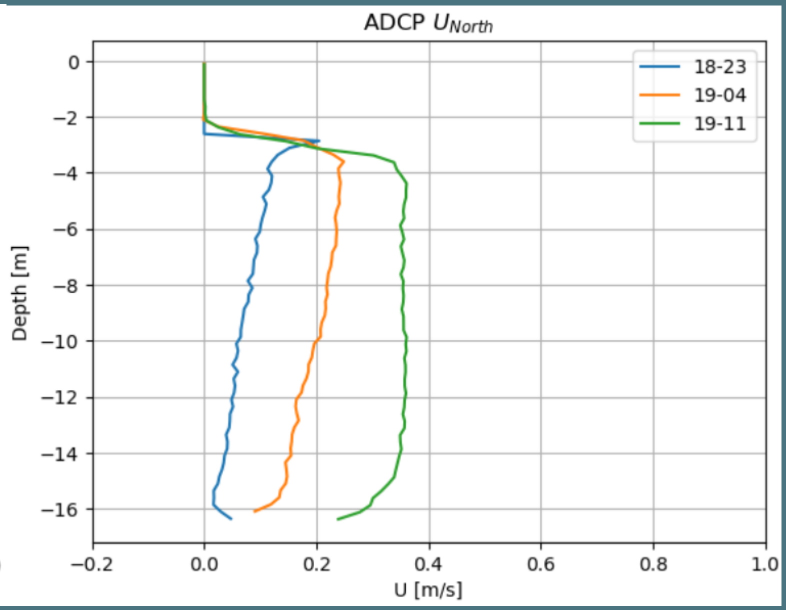
ADCP

An acoustic doppler current profiler (ADCP) was placed on the ocean floor to measure the current in the water column.

This research will focus on three hours taken in January 2022: 11 pm on the 18th, 4 am on the 19th and 11 am on the 19th .

These hours were chosen to be studied due to the varying levels of shear in both current components.





Field Results Anti-Aliasing

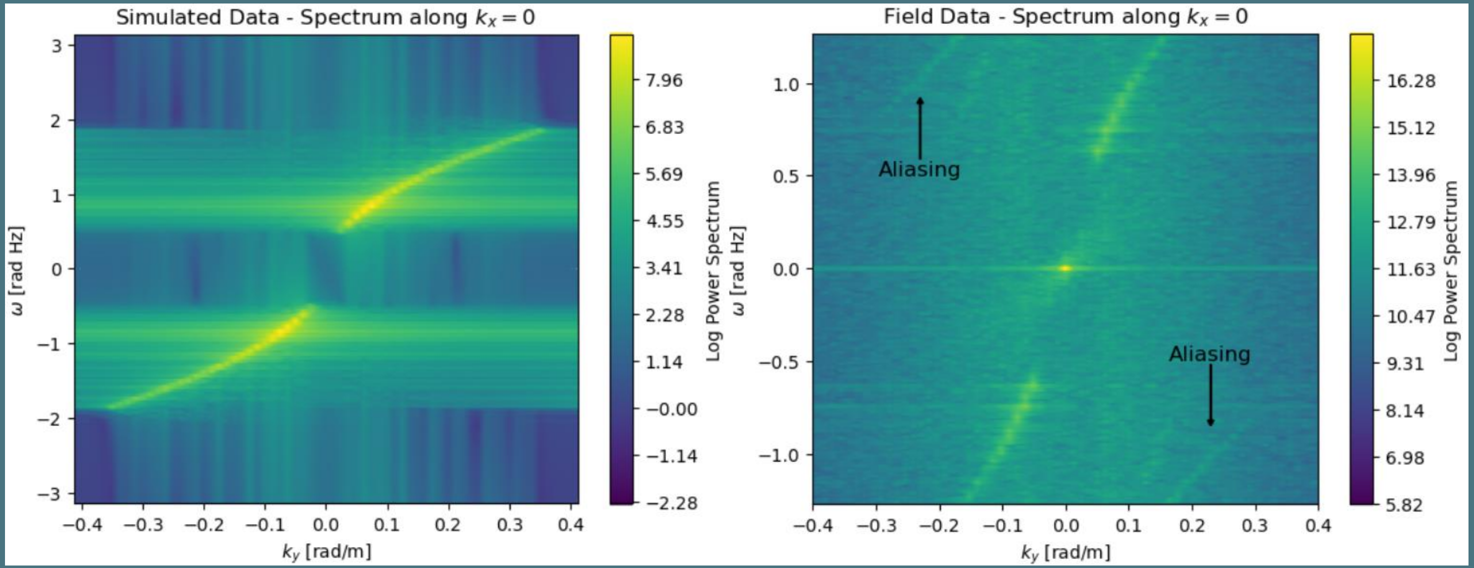
Aliasing is the under-sampling in time due to the rotation rate of the radar for marine radar spectra. Aliasing appears as extra artifacts of energy located away from the linear dispersion relation.

1) Aliased Spectrum

As an example, we can look at the power spectrum along the $k_x = 0$ slice.

Left Image: In the simulated data aliasing was not present. Only the linear dispersion relationship is visible in the spectrum.

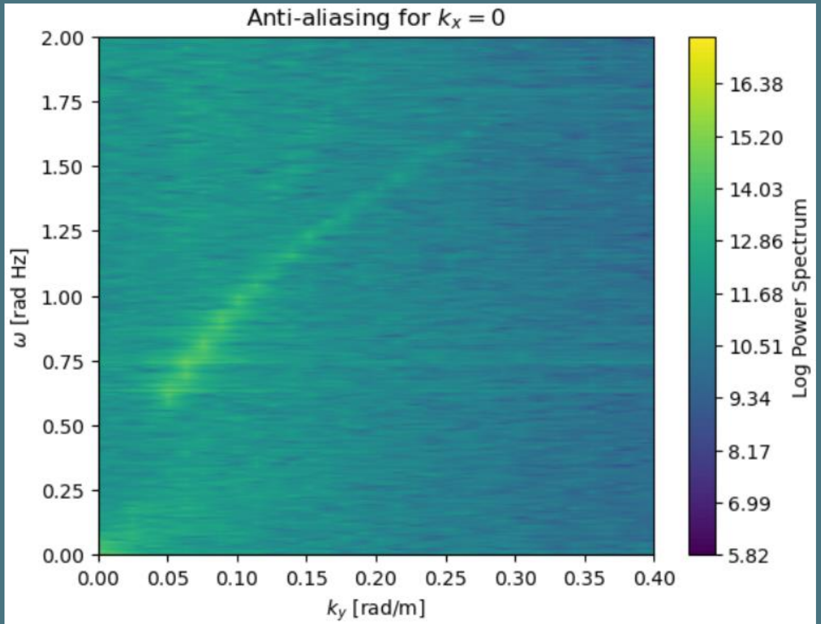
Right Image: In the field data there is aliasing visible which is energy away from the dispersion relation.



2) Anti-Aliased Spectrum

A 3D anti-aliasing is performed by following the 1D anti-aliasing method along each slice of the spectrum.

This finds a new extended spectrum.



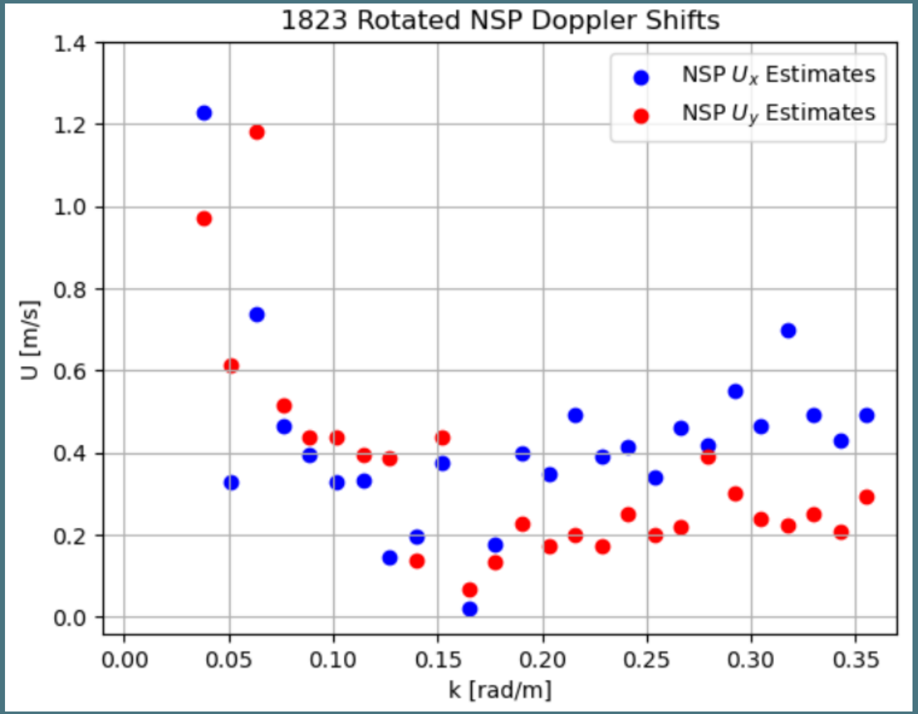
Field Results Doppler Shift Curves

Raw Doppler Shifts

The NSP method is applied to the extended spectrum.

Curves are fitted to these points for 2 reasons:

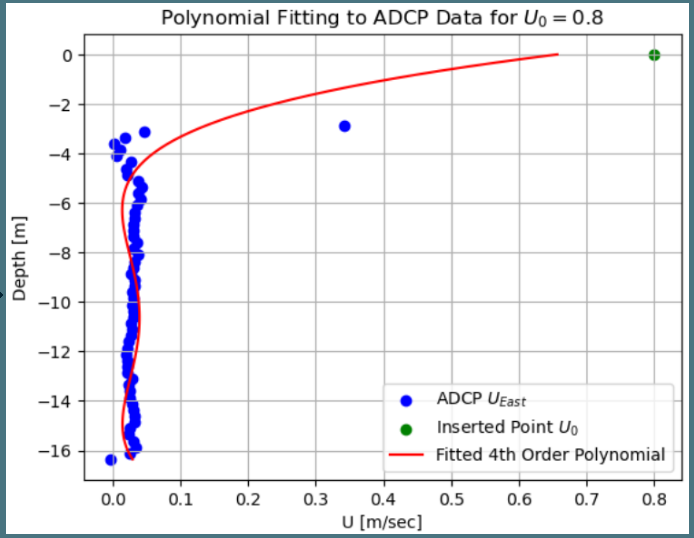
1. Doppler shifts are a smooth quantity.
2. The lower wavenumber points are affected by spectral leakage.



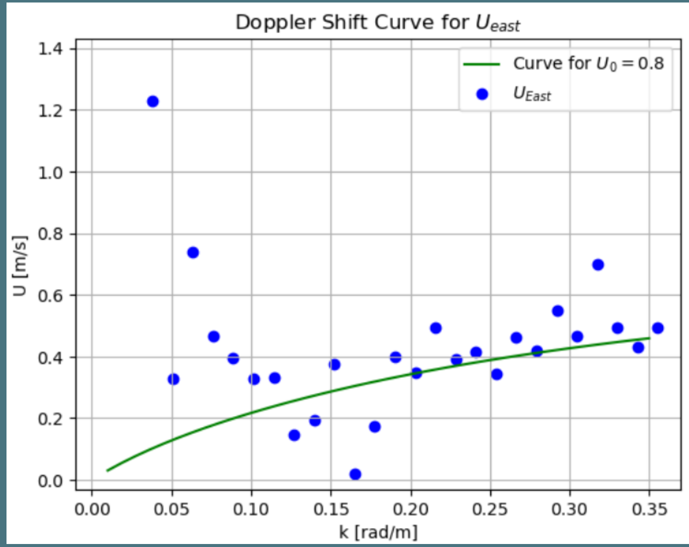
Fitting Process

A fitted curve is found using 3 steps:

1. Some velocity is added at $z = 0$ (green point). Then perform a 4th order polynomial fit to this point and the ADCP data.



2. This polynomial profile is used in the integral to find the Doppler shifts.



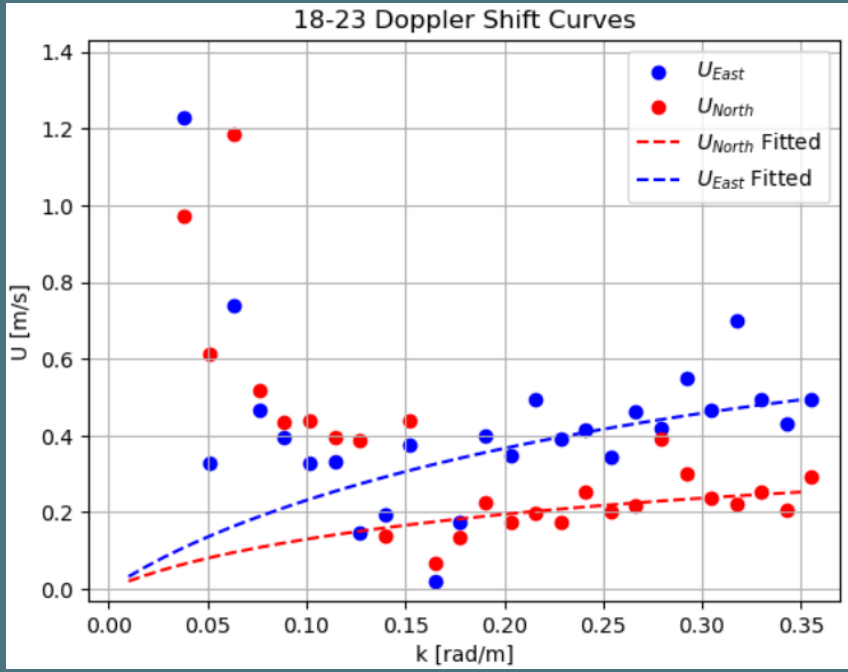
3. Repeat for many different velocities at $z = 0$. For each one the root mean square error is found. The Doppler shift curve with the lowest RMSE value is used as the fitted Doppler shift curve.

Field Results Doppler Shifts

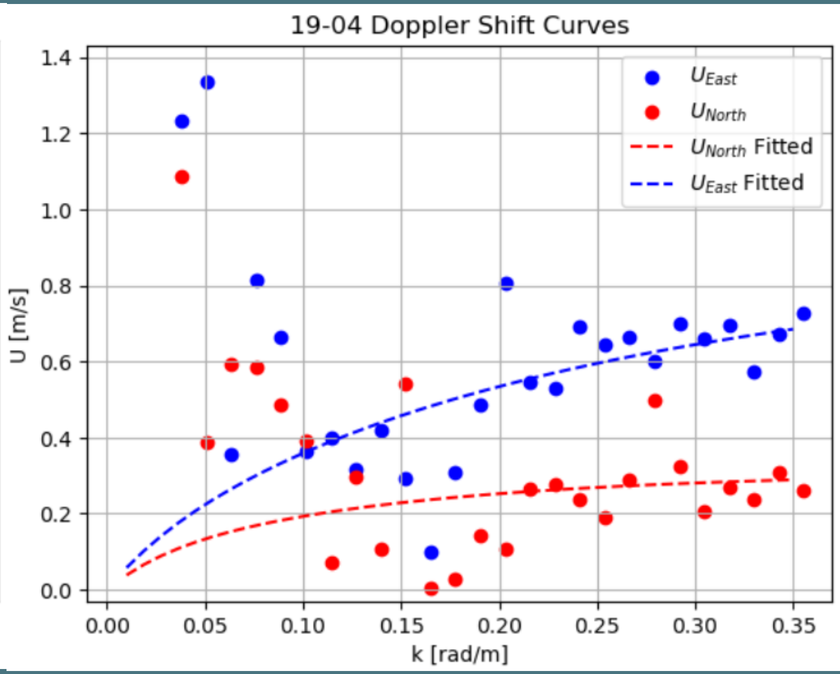
The Doppler shifts with the fitted Doppler shift curves are plotted below for the 3 radar sequences studied.

Using the Doppler shift curves will:

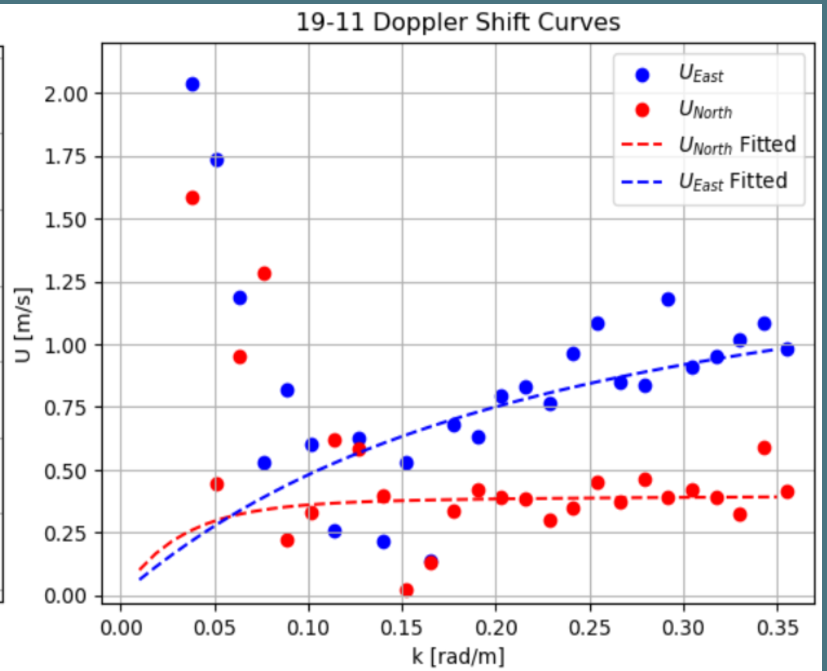
- Help to reduce the effect of spectral leakage in the Doppler shifts, particularly for the lower wavenumbers.
- Ensure that the Doppler shifts are a smooth quantity with no large jumps in the data.



11pm on 18th



4am on 19th



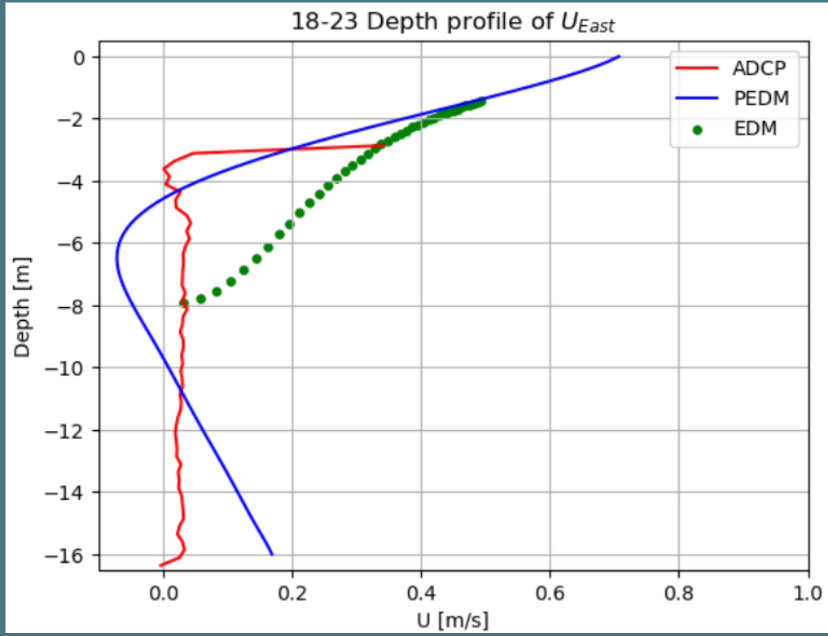
11am on 19th

Field Results Current Profile U_{East}

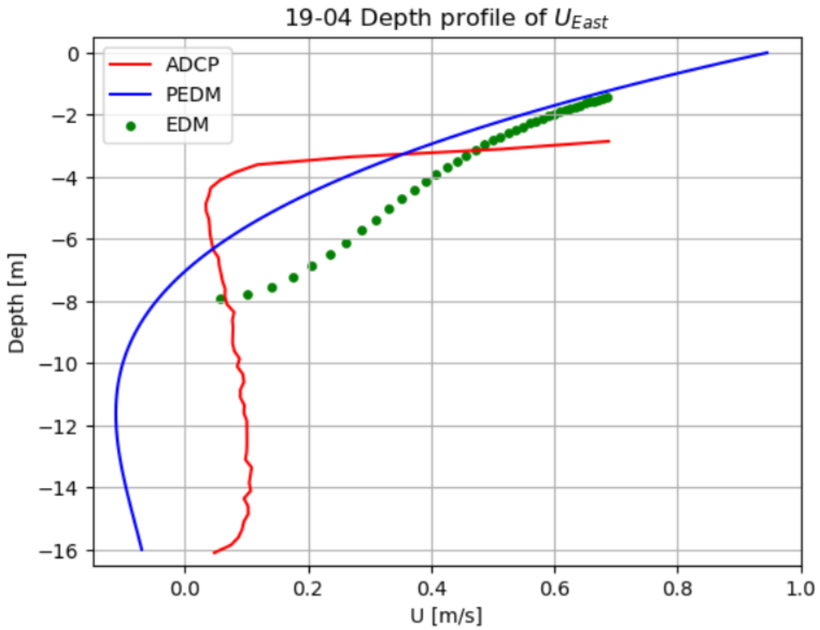
The inversion algorithms are used on the Doppler shift curves to find the depth dependent current. Each component is calculated separately.

- The ADCP suggest there is a high amount of shear in this component.
- Both methods do not find the current depth profile for this component.

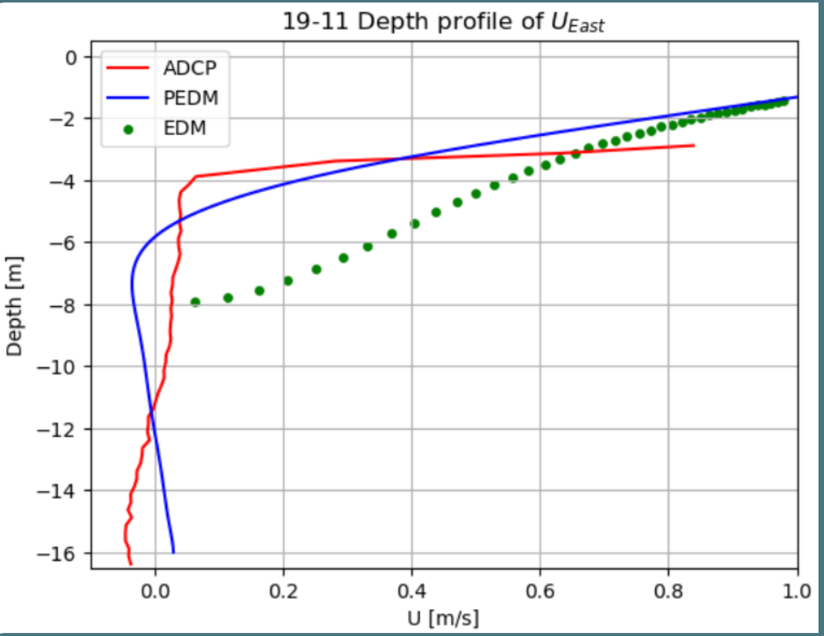
- The best performance of the PEDM occurs for the 11am on the 19th radar sequence in the bottom right.
- This is also the radar sequence with the least amount of shear in the current.
- This could point to the PEDM struggling for high shear profiles.



11pm on 18th



4am on 19th



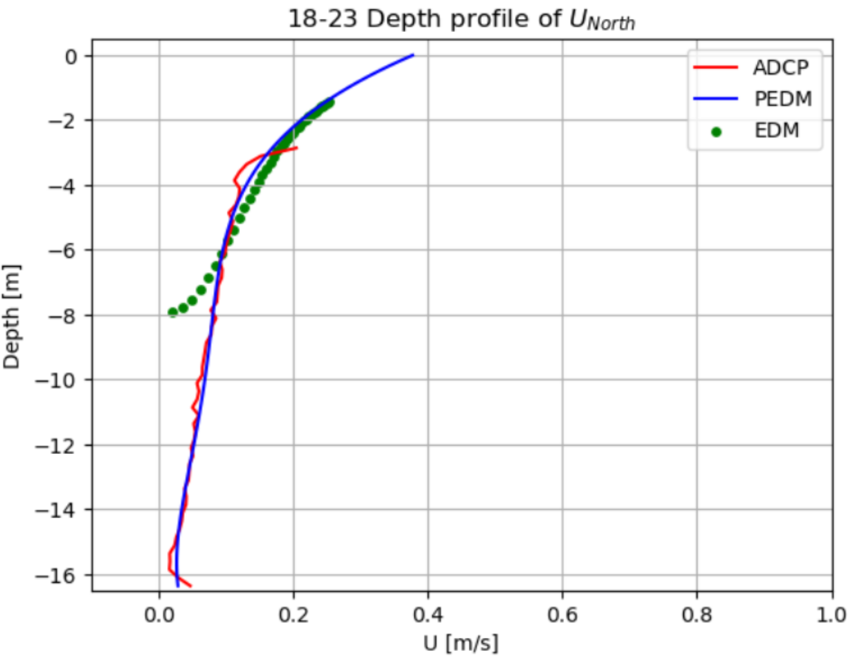
11am on 19th

Field Results Current Profile U_{North}

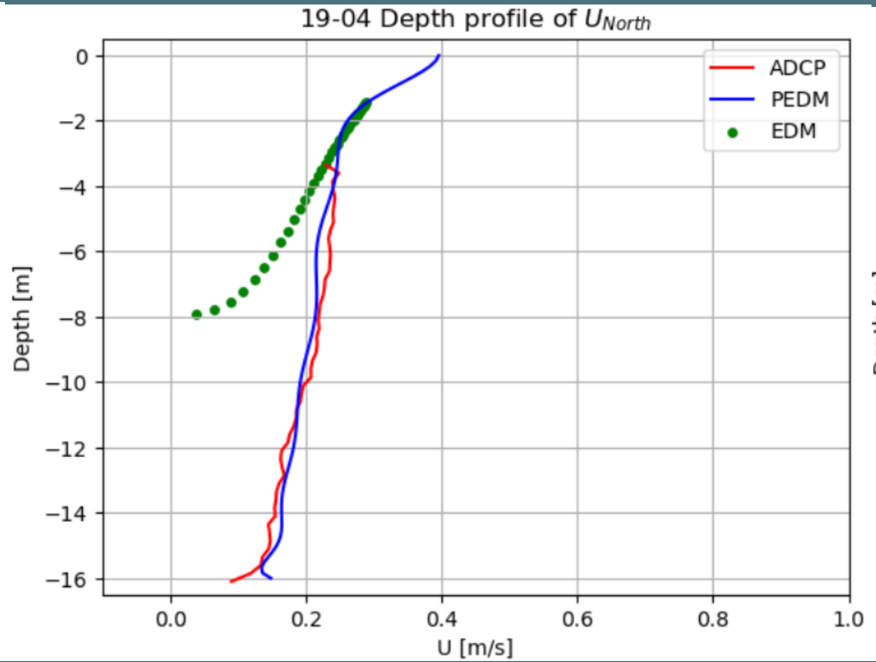
- On the other hand, the North component is reconstructed well by the new method (PEDM) shown for all radar sequences.
- The new method fits the ADCP very closely to greater depths meanwhile the old method struggles.
- These profiles have significantly less shear than the East component.

Conclusions:

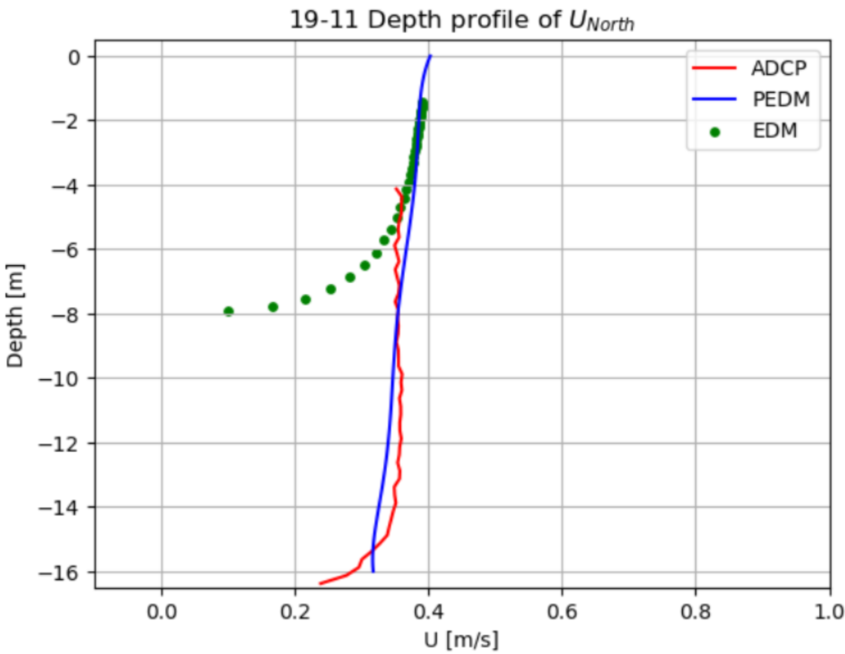
- The new method performs better than the old method for all radar sequences observed.
- The East component which has strong shear is not reconstructed well by the new method.
- The North component which has limited shear is reconstructed very well by the new method.



11pm on 18th



4am on 19th



11am on 19th

Summary of our Results

Simulated Waves

- We found that the NSP method is preferred to the PCS method due to the amplification of spectral leakage.
- We studied the importance of the Doppler shifts for low wavenumbers on inversion methods for simulated data.

Real Wave Data

- This has been the first study of the Polynomial Effective Depth Method on real world ocean wave data.
- We have shown the improvement the PEDM offers over the EDM in both simulated and real ocean wave data.
- We have uncovered a limitation of the PEDM for currents with particularly high shear.

Potential Avenues for Further Research:

- Use artificial current profiles to quantify the amount of shear required for the PEDM to break down.
- Improve the PEDM to work for high shear situations by building a method which uses in situ data at greater depths.

Thank you!

I hope you enjoyed my presentation.

Any Questions?

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