→ 5th ESA ADVANCED TRAINING ON OCEAN REMOTE SENSING AND SYNERGY

11–15 September 2017 | University of Porto | Porto, Portugal

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Interactive Lecture 10

Wave Current Interactions:

Internal waves from space

Da Silva (Part II)

Internal waves: why should we care?

- The dynamic equations that govern ocean fluid dynamics and deal with turbulence were developed in the nineteenth century, but they have no analytical solutions!

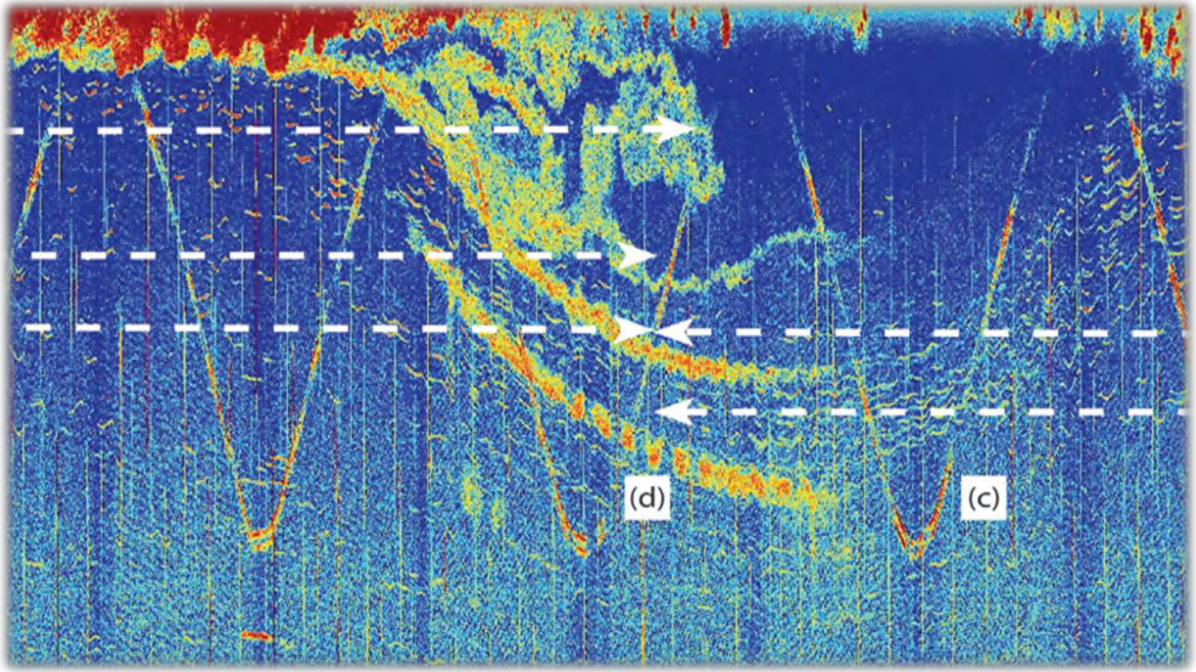
- The range of interacting turbulence scales is too large to practically solve by computational methods, particularly on a global 3D scale.

- Hence, it is necessary to parameterize or empirically model the effects of the smallest scales in the equations.

- Turbulence produced by internal waves when they break is now recognized as a vital aspect of the ocean's meridional overturning circulation.

- The magnitude and distribution of IW-driven mixing is of critical importance to ocean models, and hence a major motivation for the study of ISWs.

IW propagation direction



Oregon shelf – Lamb & Farmer, 2011

But… what is an "Internal Solitary Wave", and what do you mean by *Soliton*?

- Scotsman engineer Sir Scott Russell observed for the first time a solitary wave at the surface of a shallow water cannal, in Edinburgh. The wave was generated by a sudden deceleration of a boat, and propagated for more than a kilometer up the cannal *without changing its form*. Scott Russell called it (1834) "*Wave of translation*".

- In 1895 Korteweg & de Vries proposed a nonlinear wave equation (KdV equation) that describes the propagation of waves of finite amplitude at the surface of an inviscid and imcompressible fluid.

$$\eta_t + c_0\eta_x + \alpha\eta\eta_x + \gamma\eta_{xxx} = 0 \quad (1)$$

$$c_0 = \sqrt{gh}$$

α : coefficient of nonlinear term

$$\alpha = 3c_0/2h \quad (2)$$

γ : coefficient of dispersive term

$$\gamma = c_0 h^2/6$$

$$c = c_0(1 + \eta_0/2h)$$

Solution:

$$\eta(x,t) = \eta_0 \operatorname{sech}^2[(x - ct)/L] \quad (3)$$

$$L = \sqrt{4h^3/3\eta_0}$$

$$\frac{\partial \eta}{\partial t} + c_0 \frac{\partial \eta}{\partial x} + \alpha \eta \frac{\partial \eta}{\partial x} + \beta \frac{\partial^3 \eta}{\partial x^3} = 0$$

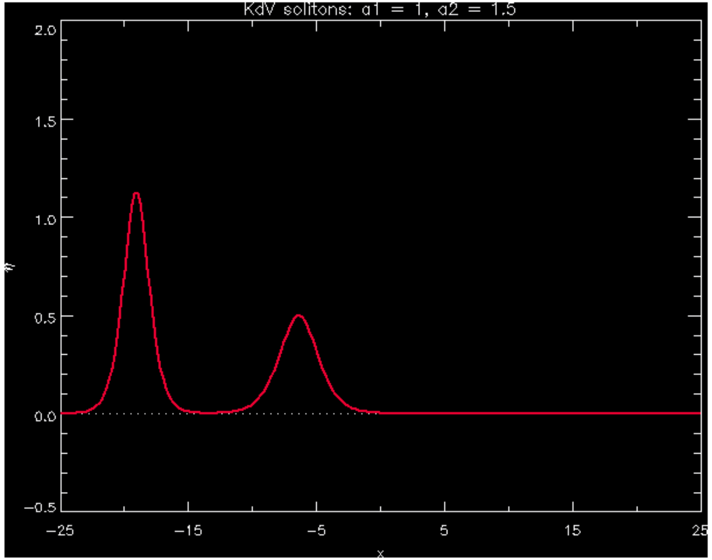
Nonlinear steepening

or, *amplitude dispersion*

linear dispersion

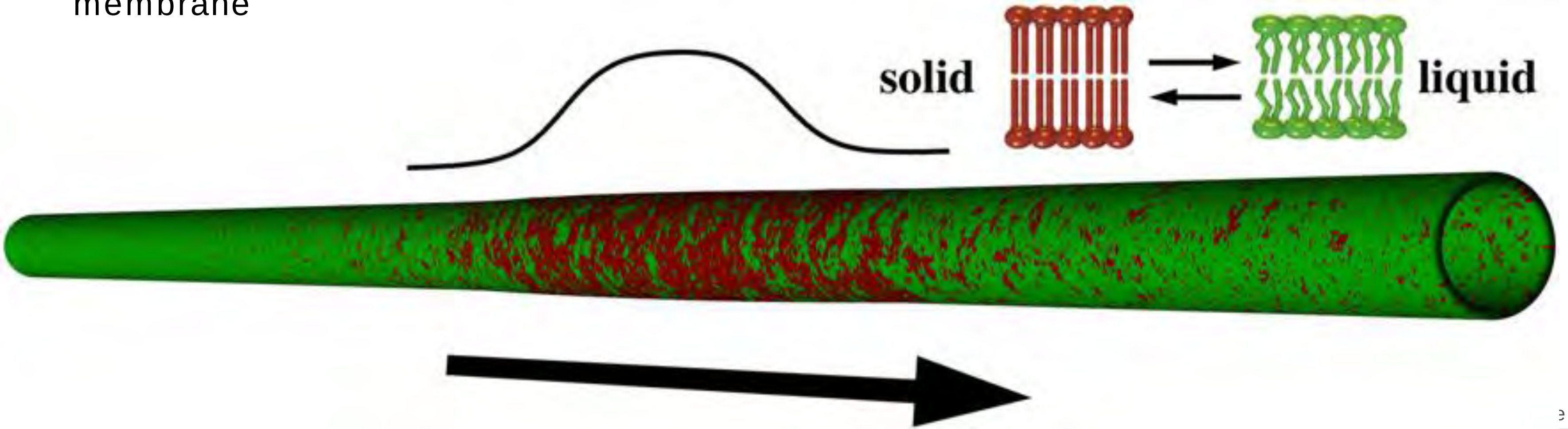
Dispersion in frequency

For decades KdV solitary waves were mere mathematical curiosities, until 1965, when *Zabusky & Kruskal* discovered, through numerical simulations, that these waves conserve their form and velocity after colliding or interacting with each other!



- Nervous impulses can be described as an electromechanical wave that travels along nerve fibres
- A soliton model in neuronscience proposes to explain the signal conduction within neurons as pressure solitons
- Initiation of a nervous impulse displaces the membrane inwards just behind it
- This triggers an accelerating mechanical wave that precedes the impulse as it is propagated along the axon and constricts the fibre as it moves

- During a nerve pulse no heat (or only very little) is dissipated, and the entropy of the membrane is basically conserved
- This implies that the propagated nervous impulse is not a wave of irreversible chemical breakdown, but a reversible change of a purely physical nature
- Two colliding pulses pass through each other without dissipation
- The soliton consists of a region of ordered lipid membrane traveling in the otherwise liquid membrane with a speed somewhat less than the speed of sound in the membrane

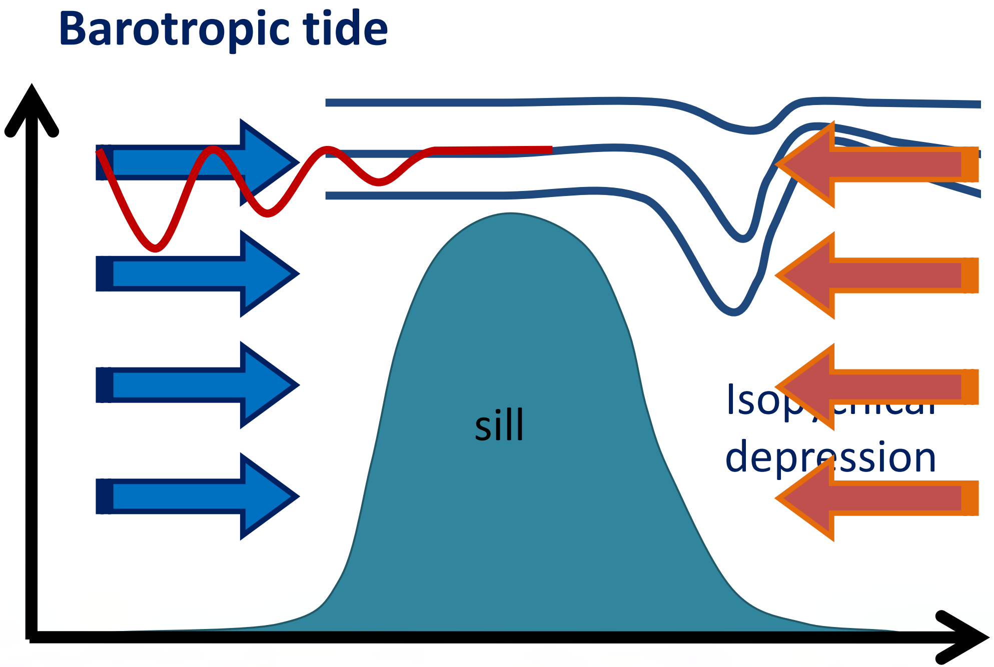


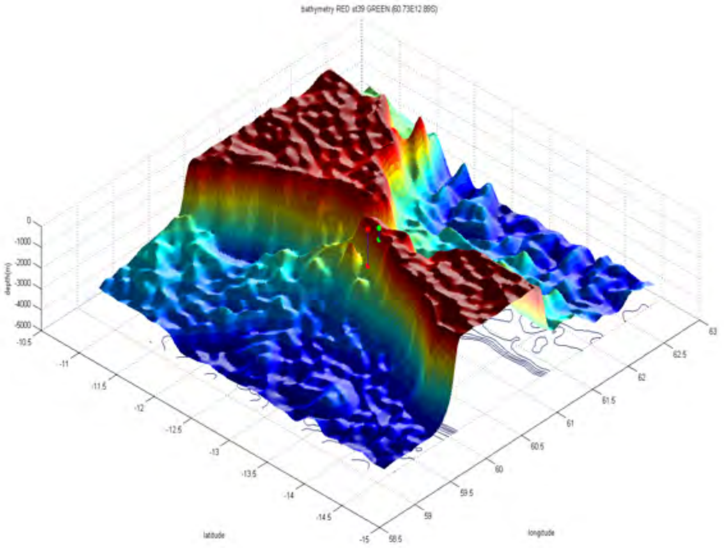
You are only coming through

in waves

Lee wave generation mechanism

1. “Lee wave”
generation mechanism

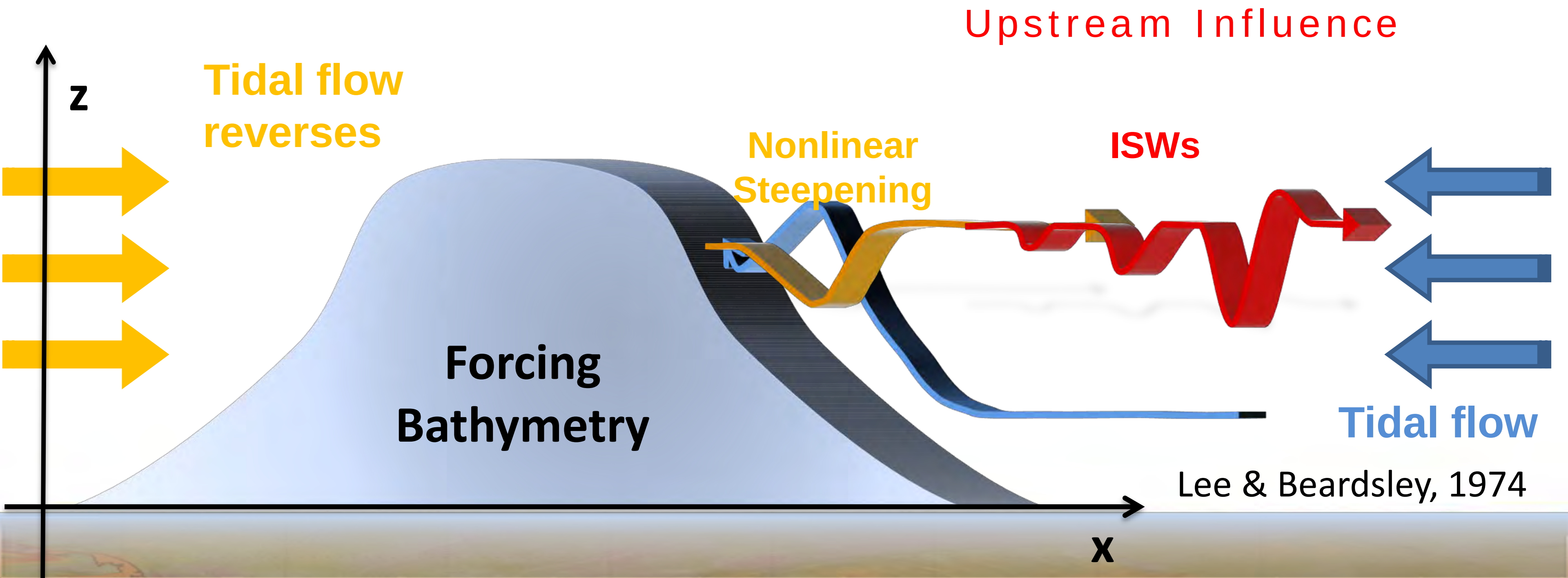


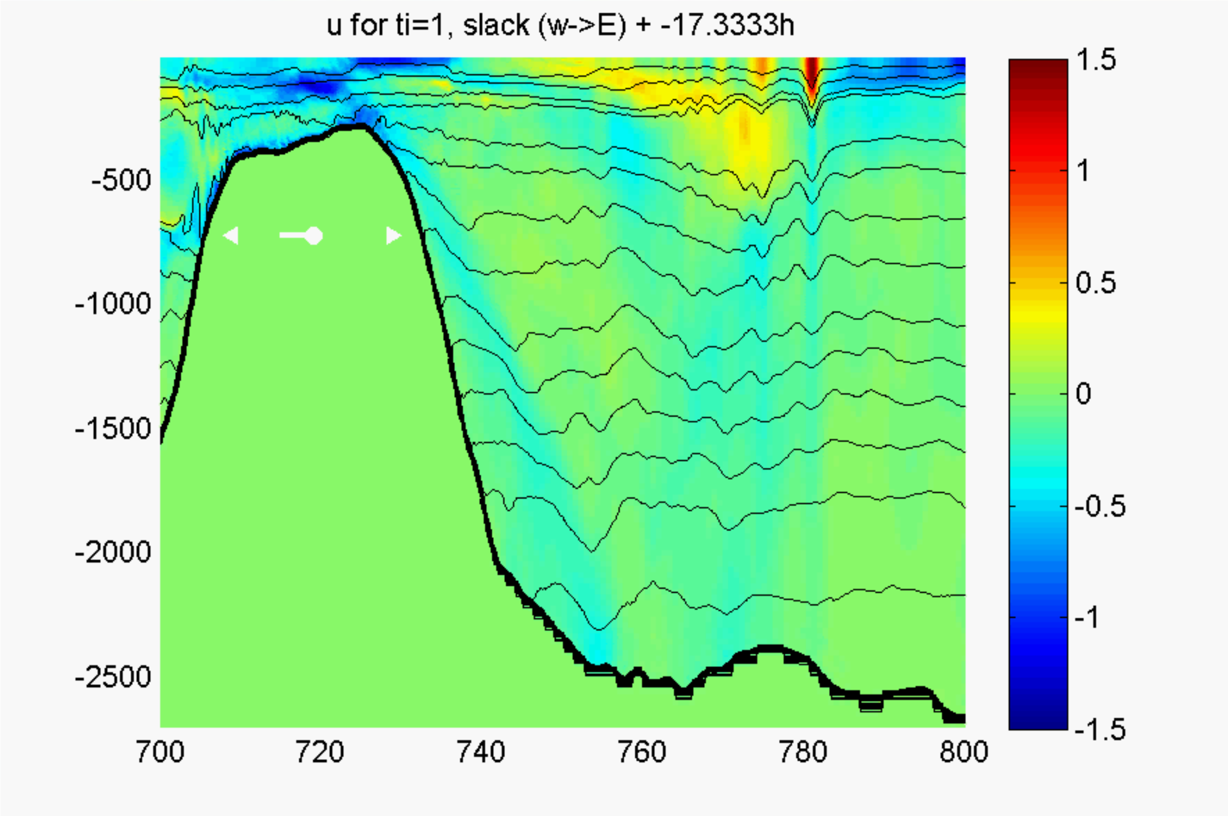


Maxworthy, 1979

Internal tide Release Mechanism Schematics (Buijsman et al., 2010)

Generation of ISWs eventually occurs as nonlinear steepening and dispersion balance. at the rear slope.





u for ti=1, slack (w->E) + -17.3333h
-500
-1000
-1500
-2000
-2500
700
720
740
760
780
800
1.5
1
0.5
0
-0.5
-1
-1.5

Student’s Project

Location: Stellwagen Bank Marine Sanctuary, Massachusetts, USA

Date: 2017.07.09

Time: 16:36 UTC

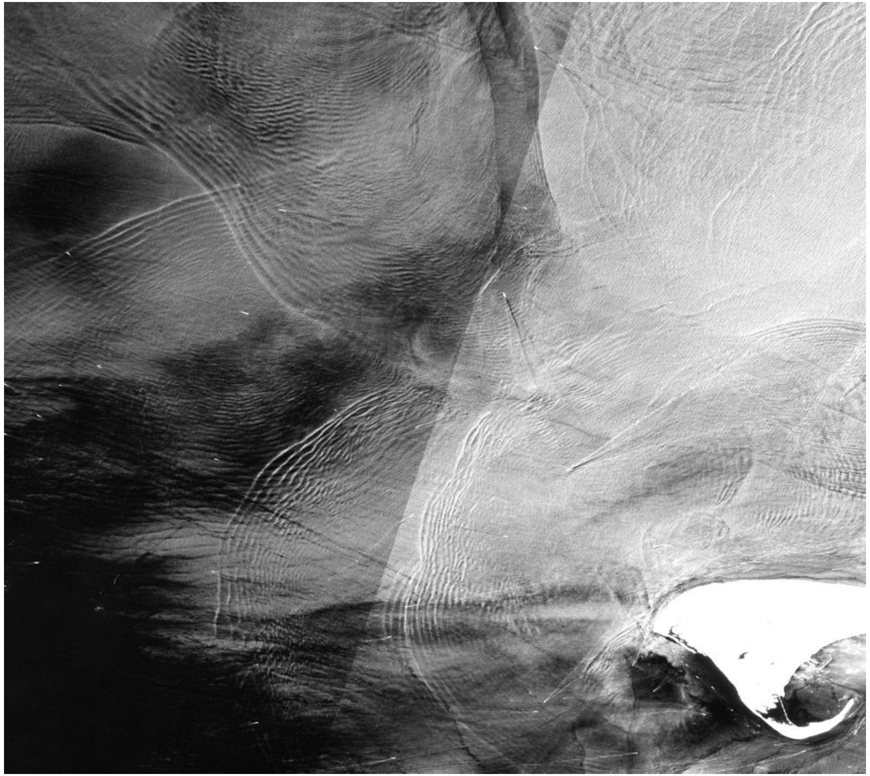
Sensor: MSI (Multi-Spectral Imager)

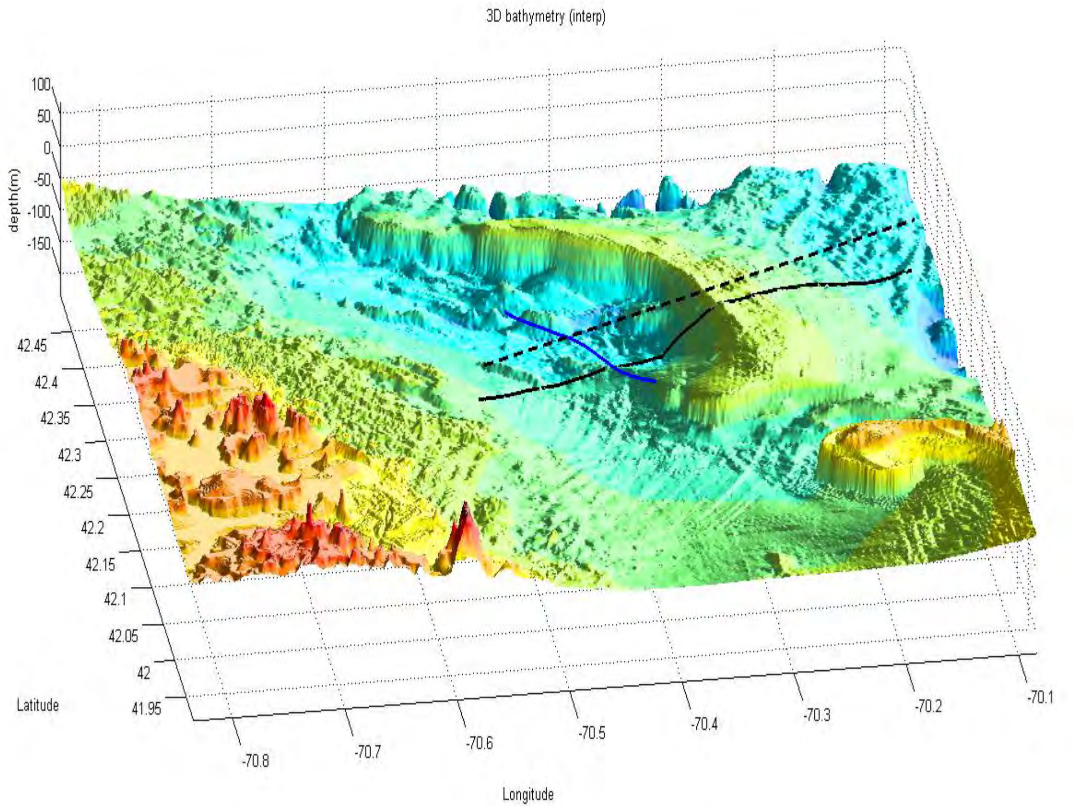
Satellite: Sentinel-2A (European Space Agency)

Observation: trains of Internal Solitary Waves

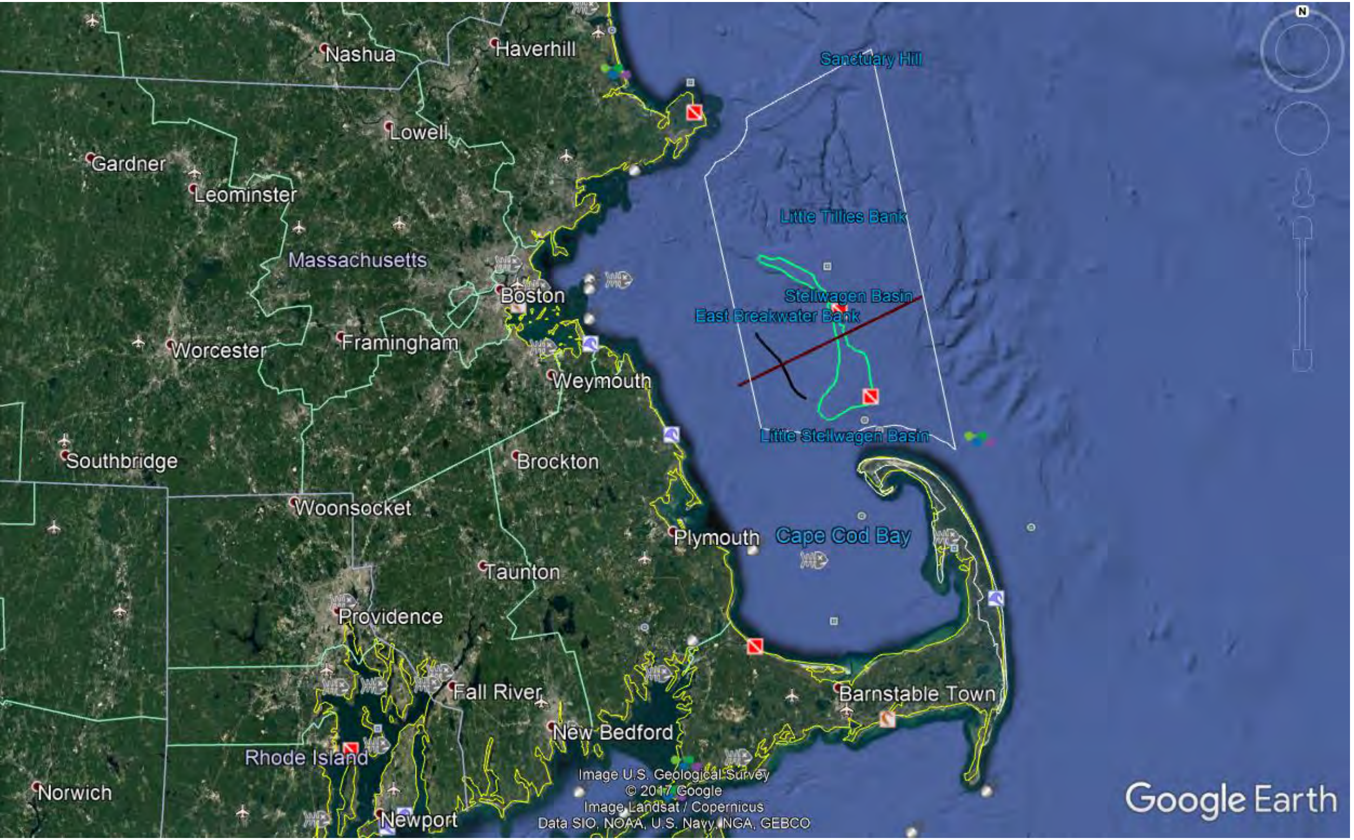
Problem to be solved:

Suppose you are in an ocean going research cruise and are requested to predict the location and time of generation of an internal wave train, which was captured in a provided Sentinel-2A image in near real time (just 1 hour after the satellite overpass).





Step 1: Open GoogleEarth filename: Class_file01.kmz



You should obtain a screen like this, where the wavefront of interest is marked in black for reference.

The green curves represent the 30 m isobath, which represent the summit of Stellwagen Bank

Step 2: Open band 06 in SNAP of the Sentinel-2 MSI image that is provided, and perform a contrast enhancement in order to enhance the sea part of the image and get the most contrast for the various internal wave trains in Massachusetts Bay.

Step 3: Make a reprojection of the image in a geographic (longitute, latitude) system (WGS84).

Step 4: Export the image in .kmz format; make sure to name the file as "Class_file02.kmz".

Step 5: Estimate internal wave phase speed based on linear theory and assuming the density vertical destribution that is provided (next slide).

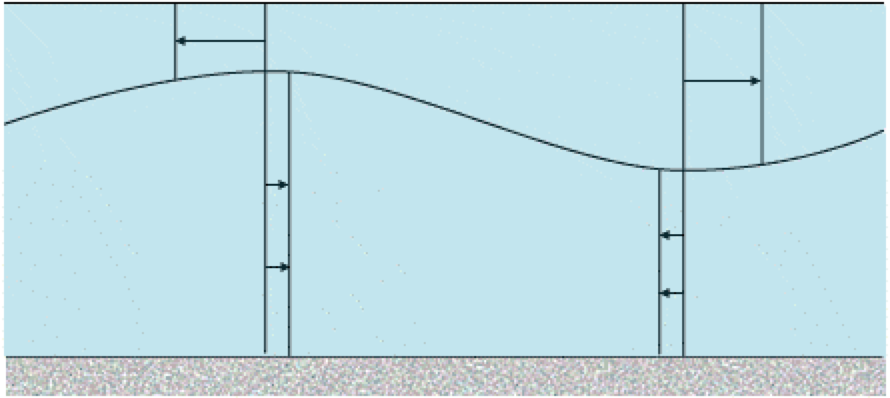
- Assume a two-layer model

$$c = \sqrt{g \frac{\Delta\rho . h_1 . h_2}{\rho\left(h_1 + h_2\right)}}$$

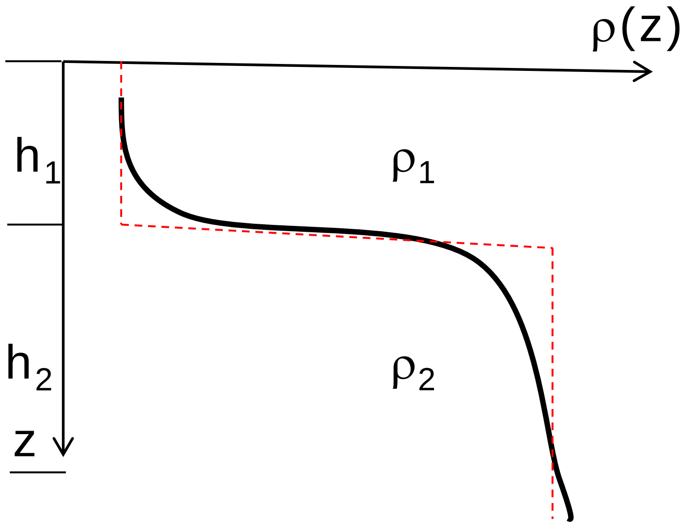
- Assume the depth of the pycnocline where the Brunt-Vaisala frequency achives the maximum value

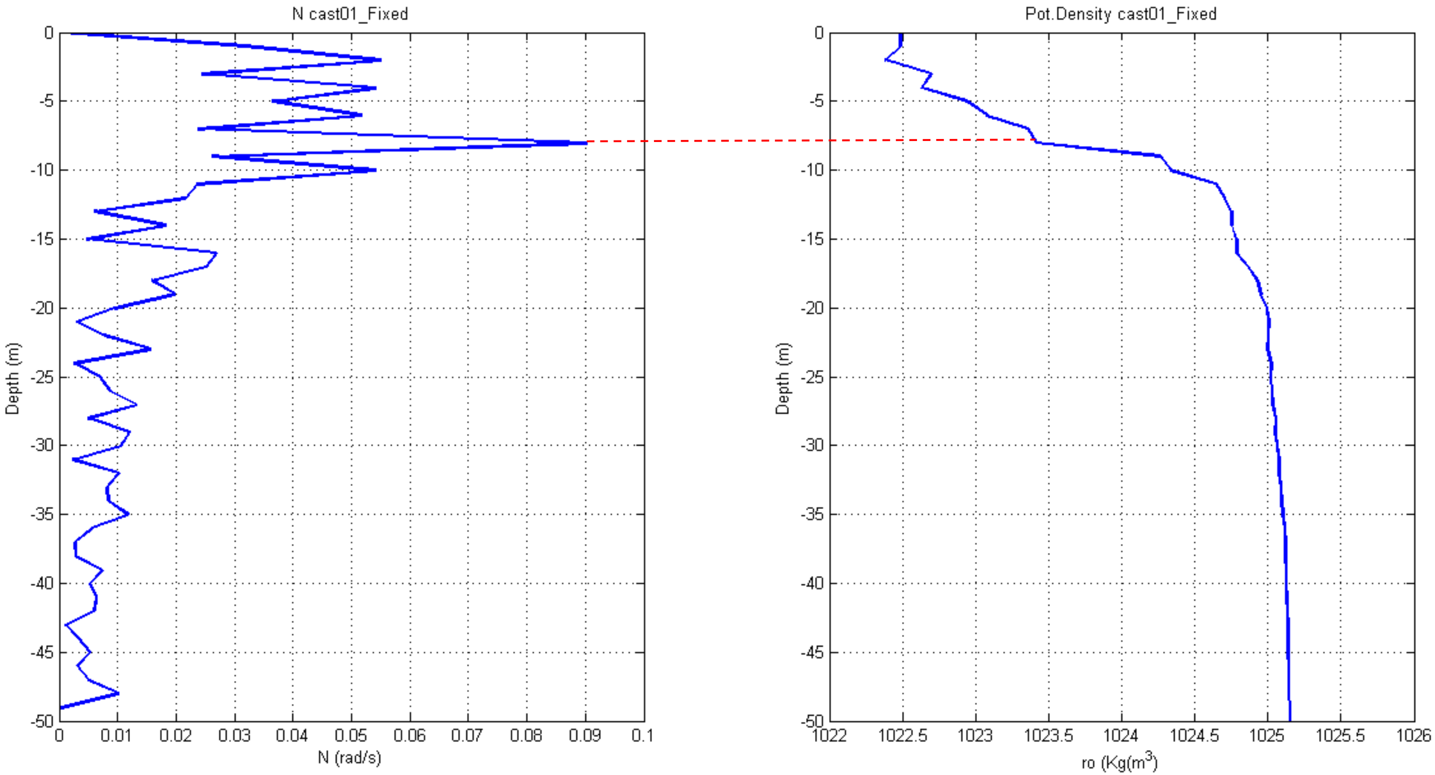
- Assume average depth of 70 m in the study region

Two-layer model



Baroclinic Wave



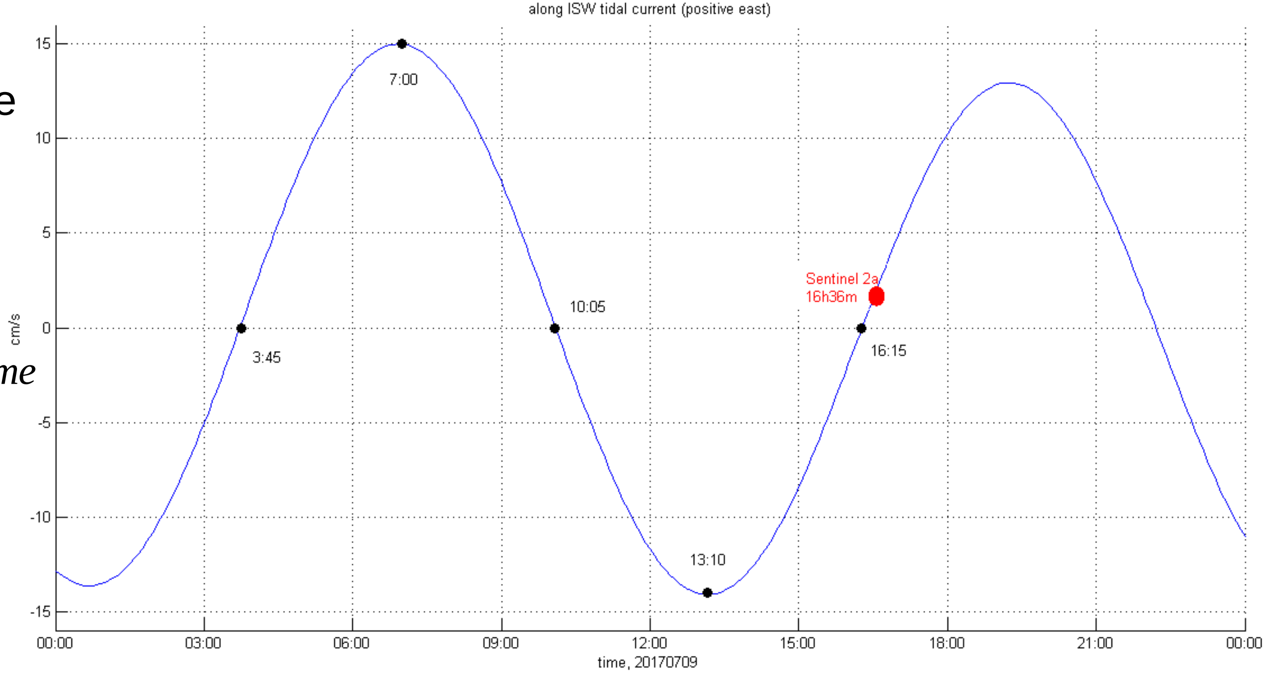

N cast01_Fixed
Depth (m)
N (rad/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Pot.Density cast01_Fixed
Depth (m)
ro (Kg(m3)
1022
1022.5
1023
1023.5
1024
1024.5
1025
1025.5
1026

Step 6: Choose a suitable generation time for the train observed in the image (assume semidiurnal tides are dominant!)

Step 7: Estimate time difference Δt between Generation time and satellite observation?

$$\Delta t = 16h36\min - Generation\ Time$$

(use units in seconds!)



Step 8: Assuming the estimated time travel of the internal waves (Δt), estimate the distance (Δx) travelled by the internal waves in the image, since their generation!

i.e., where was the position of the waves when they were generated!

$$\Delta x = c.\Delta t$$

Now that you have a fair estimate of the position where the waves were generated (mark this in your GoogleEarth map with a PIN), we can proceed...

But wait!!!

- Are we sure of the position where the waves are generated?
- Do we know which mechanism is at work? Upstream Influence OR lee wave generation; in other words: upstream or downstream of the bank?

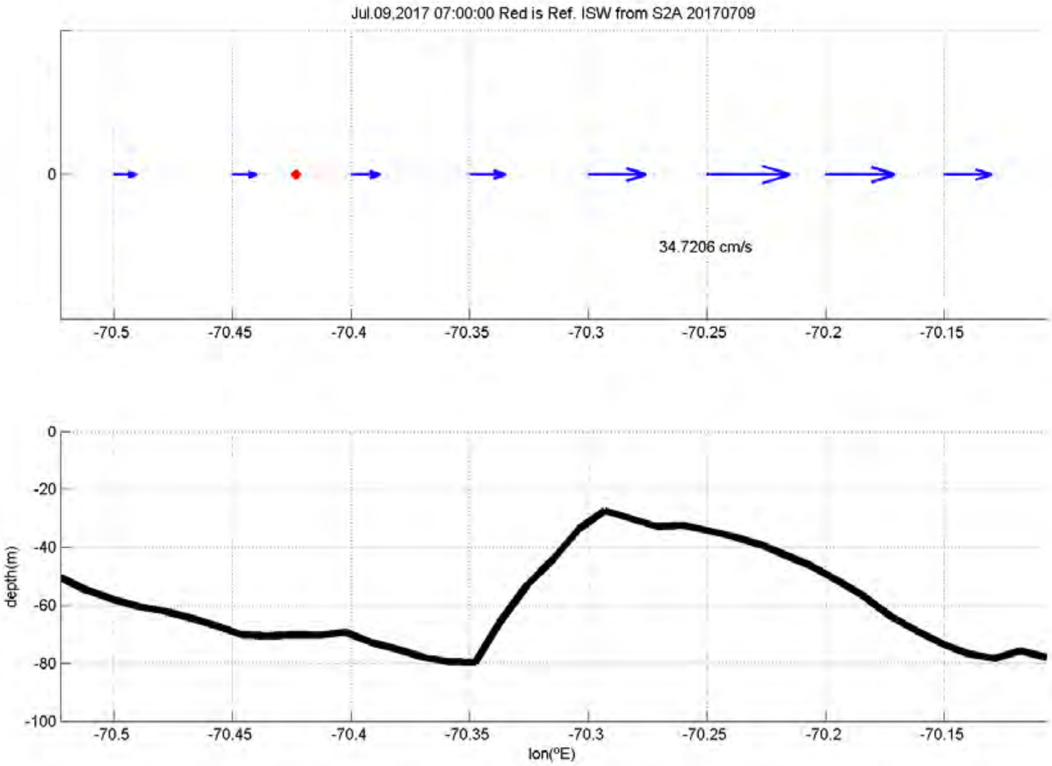
But we can check which mechanism is at work, by calculating a densimetric Froude number at the most likely location!

$$Fr = \frac{U_{barotropic}}{c}$$

You can do this using the tidal currents that are provided in the next slide:

Step 9: Now you can estimate the Froude number over the bank, close to where the waves are generated!

Ok then, what generation mechanism do you think is at work?



Question: do we need to correct for the location where the generation occurs? (if so, do that in your GoogleEarth map)

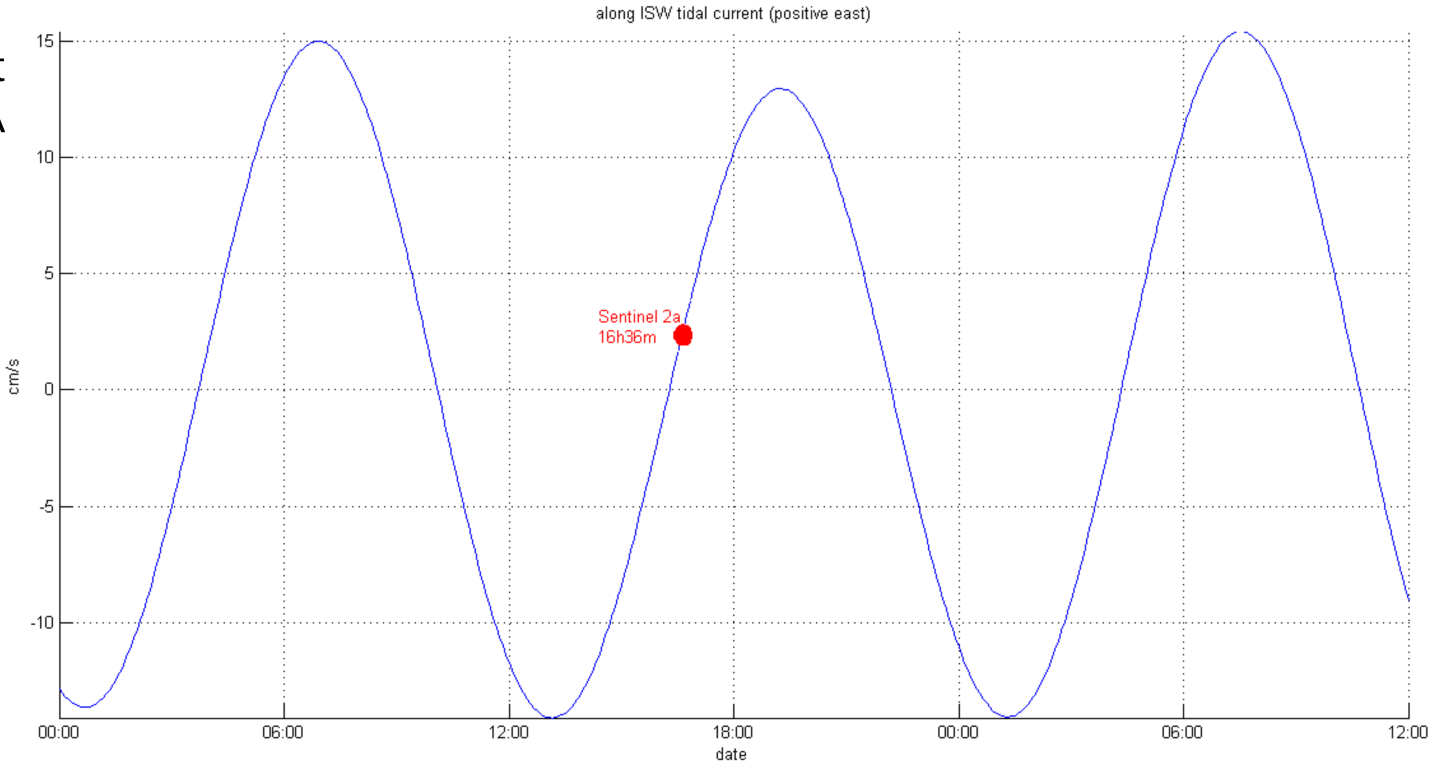
Why do you think the estimate of the generation location was slightly off?!

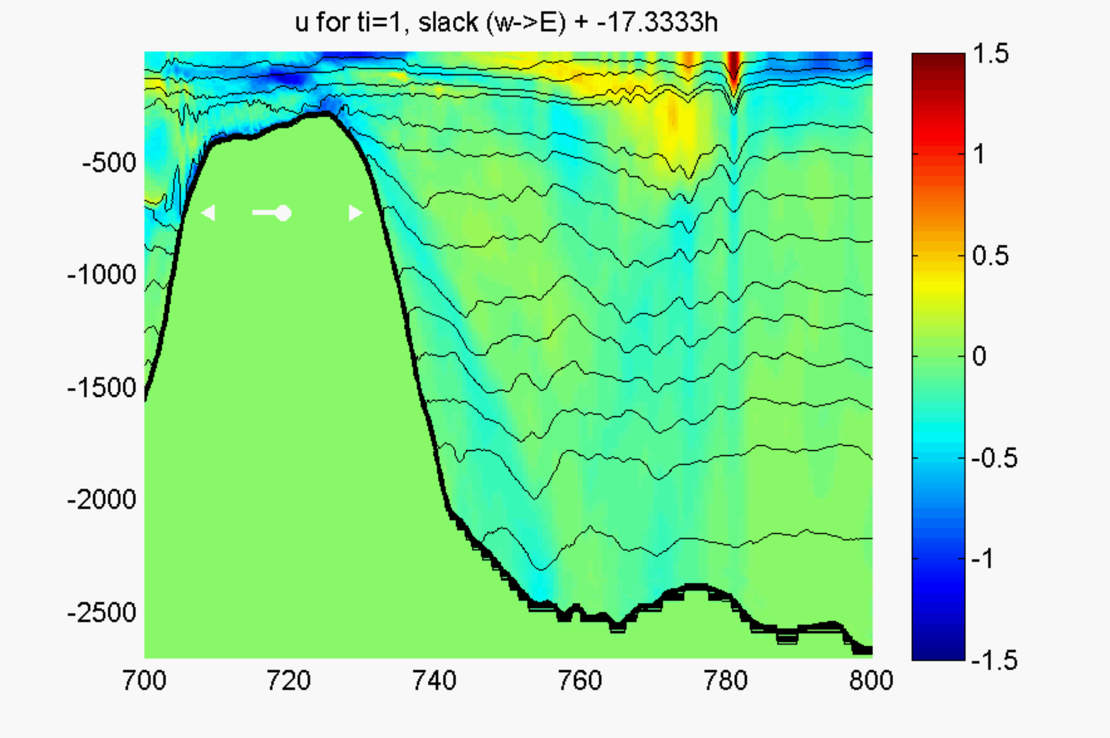
Now... it’s your call!

Problem: where and when would you position the research vessel (assume a stationary station) in order to measure the early stages of the generation of the Internal Solitary Waves?

Your answear should be based on the tidal currents provided in the next slide (and, do not forget to justify your answear!)

Remember that the Sentinel-2A image was received on board at 17h36m UTC!

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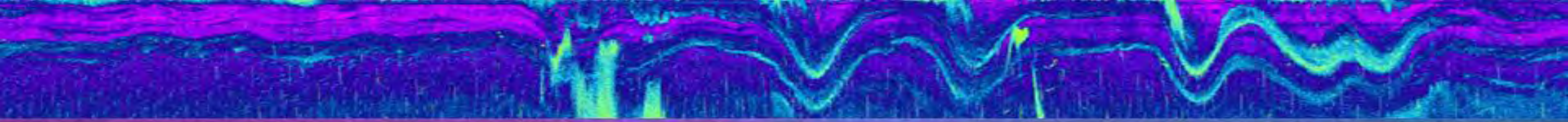

Thank You!