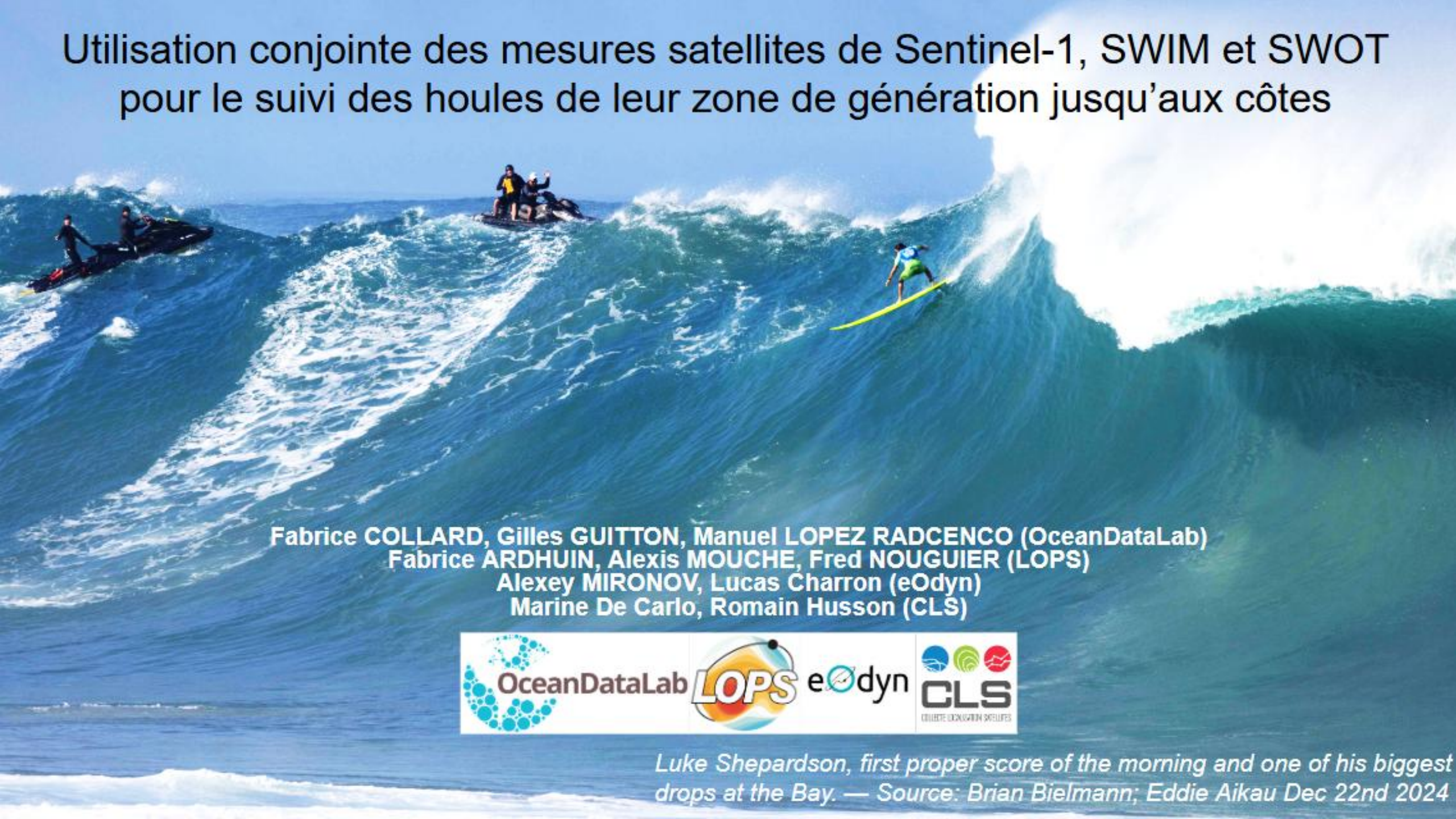
Utilisation conjointe des mesures satellites de Sentinel-1, SWIM et SWOT pour le suivi des houles de leur zone de génération jusqu'aux côtes



Fabrice COLLARD, Gilles GUITTON, Manuel LOPEZ RADCENCO (OceanDataLab)
Fabrice ARDHUIN, Alexis MOUCHE, Fred NOUGUIER (LOPS)
Alexey MIRONOV, Lucas Charron (eOdyn)
Marine De Carlo, Romain Husson (CLS)

Luke Shepardson, first proper score of the morning and one of his biggest drops at the Bay. — Source: Brian Bielmann; Eddie Aikau Dec 22nd 2024

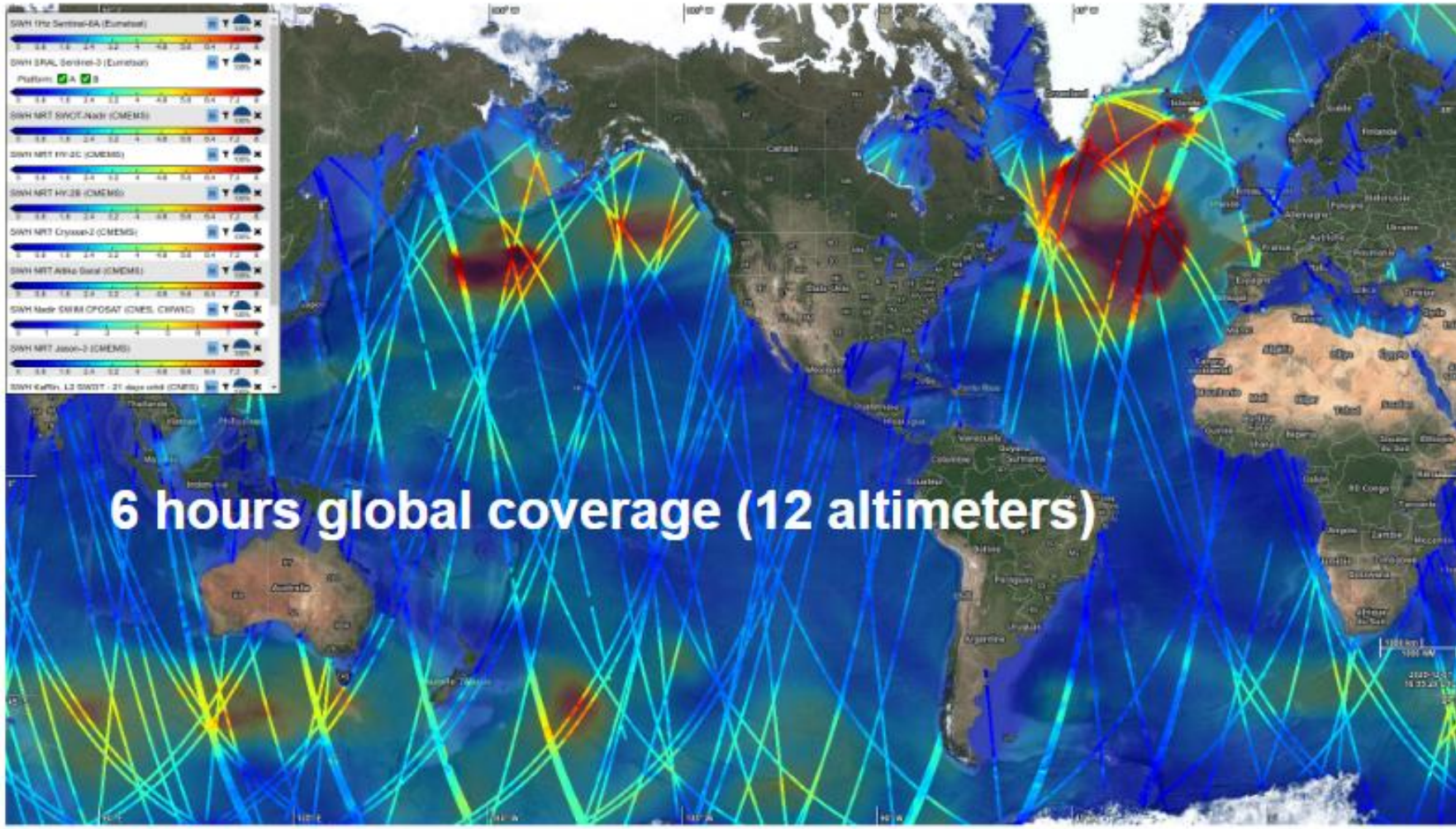
Mesures satellites de la hauteur significative des vagues

Aujourd'hui 12 altimètres

- Sentinel-6A/6B
- Sentinel-3A/3B
- HY-2B/2C/2D
- Cryosat-2
- Altika
- CFOSAT SWIM nadir
- Jason-3
- SWOT nadir et Karin swath

Demain 6 nouveaux

- Sentinel-3C/3D (2026/2028)
- Sentinel-9/Cristal A (2027)
- Sentinel-6C (2030)
- Sentinel-3 NG (2030)
- CFOSAT NG (2030) ?



all visible on https://aviso-calval.oceandatalab.com

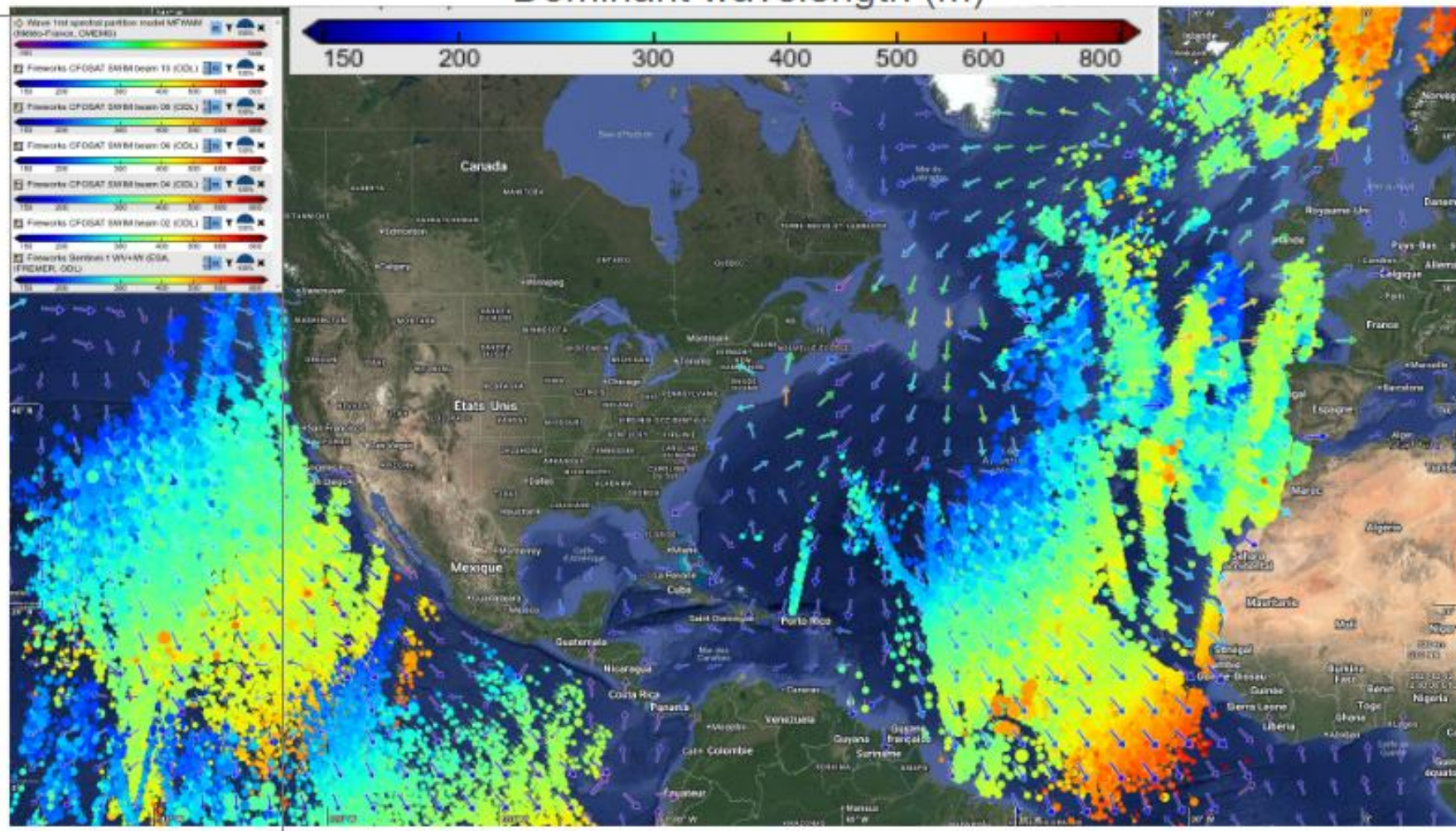
Mesures satellites du spectre directionnel des vagues

Aujourd'hui

- **Sentinel-1A/1C**
- **CFOSAT SWIM**
- **SWOT Karin (WI > 500m)**

Demain

- Sentinel-1D (commissioning)
- Harmony (2029)
- Sentinel-3 NG topo (2030)
- Sentinel-1 NG (2030)
- CFOSAT NG (2030) ?



Partitionnement du spectre pour en extraire longueur/direction et hauteur de la houle

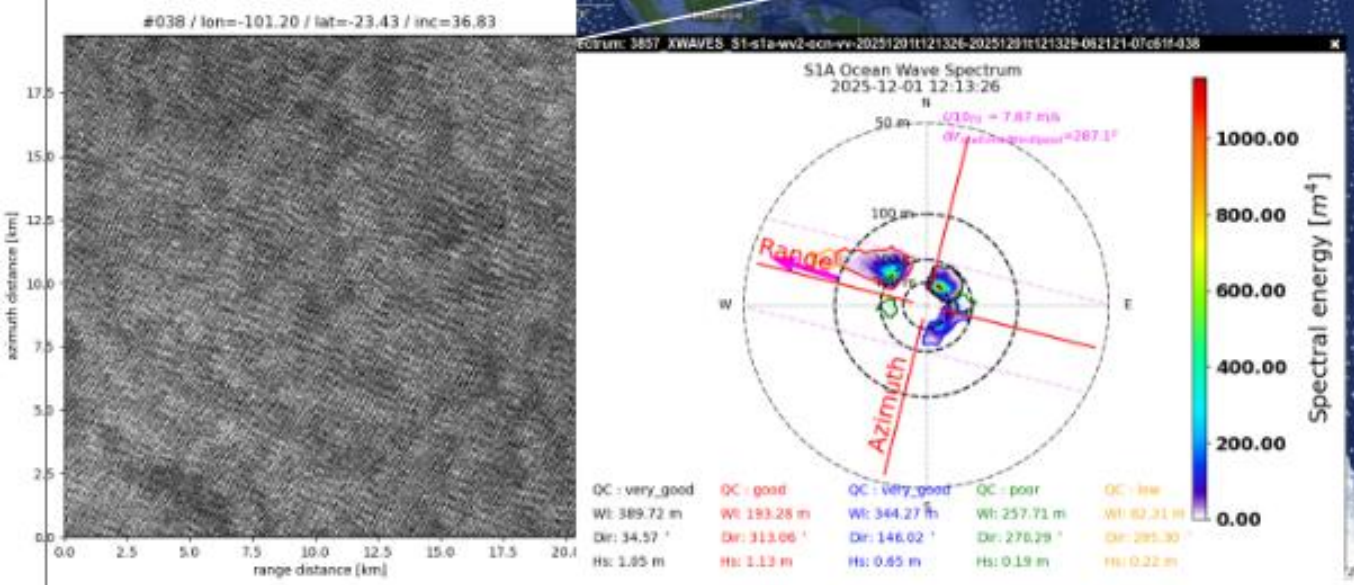
visible sur https://aviso-calval.oceandatalab.com

Sentinel 1 : produits de spectres directionnels de vagues

wave mode :

open ocean

imagette 20x20km



visible sur https://aviso-calval.oceandatalab.com

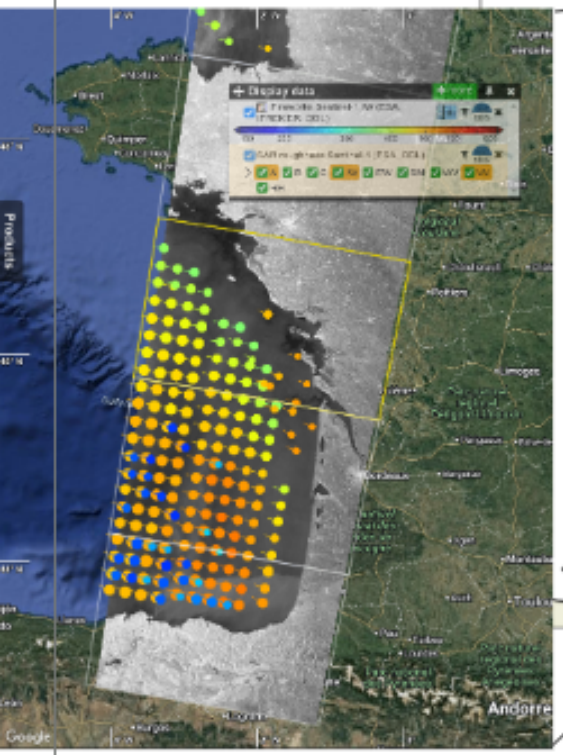
- ESA NRT L2 wave spectra : Traditional quasi-linear inversion of the theoretical Modulation Transfer Function
- **New 2025** ESA CCI Sea State in delay time : Unet based inversion using Machine Learning

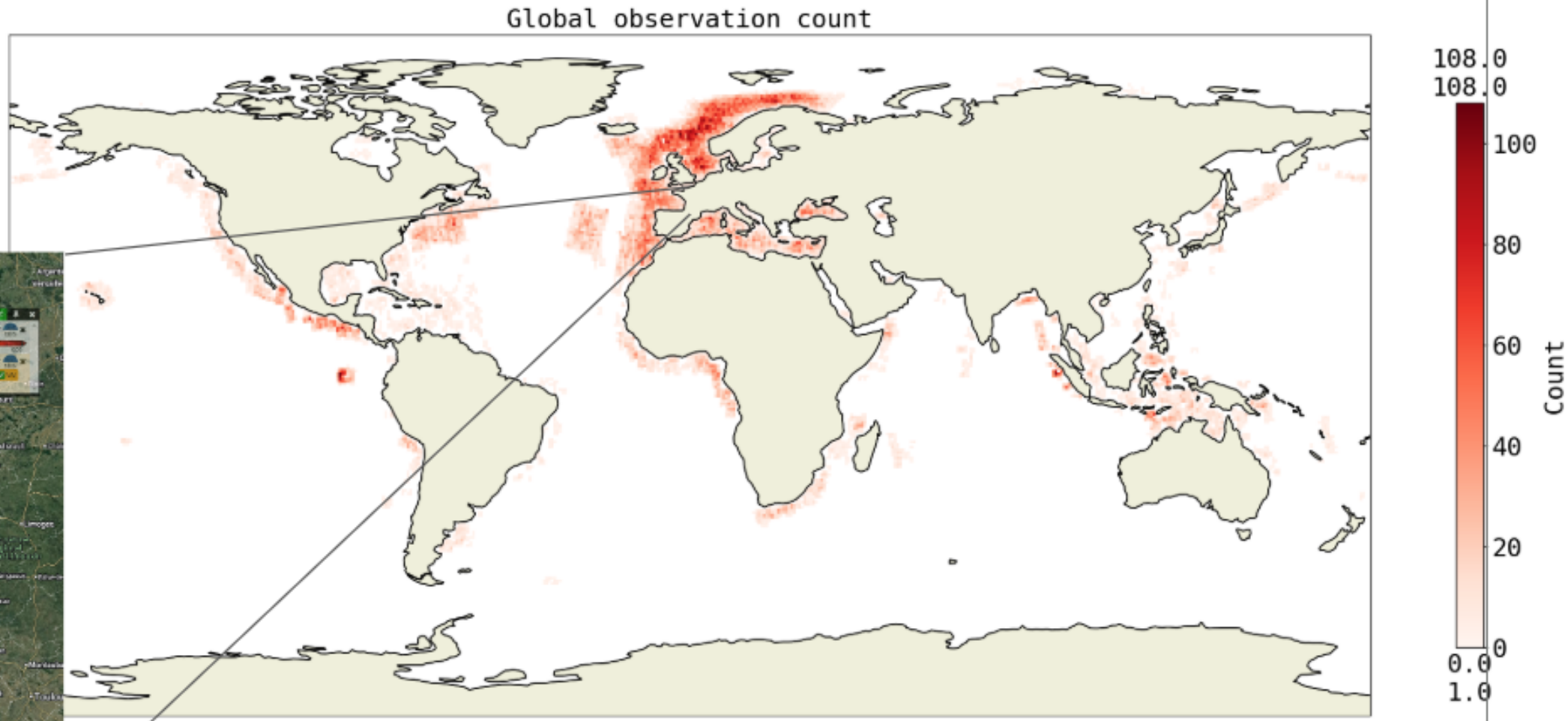
Sentinel 1 : produits de spectres directionnels de vagues

IW mode :

coastal and

& closed seas





- **New 2025 :** Prototype L2 2D wave spectra and partition parameters (Unet adapted from Wave mode), with partition integrated parameters (Wavelength, DIrection, significant wave height)

CFOSAT SWIM : produits de spectres directionnels de vagues

L2S (Ifremer)

géométrie d'acquisition

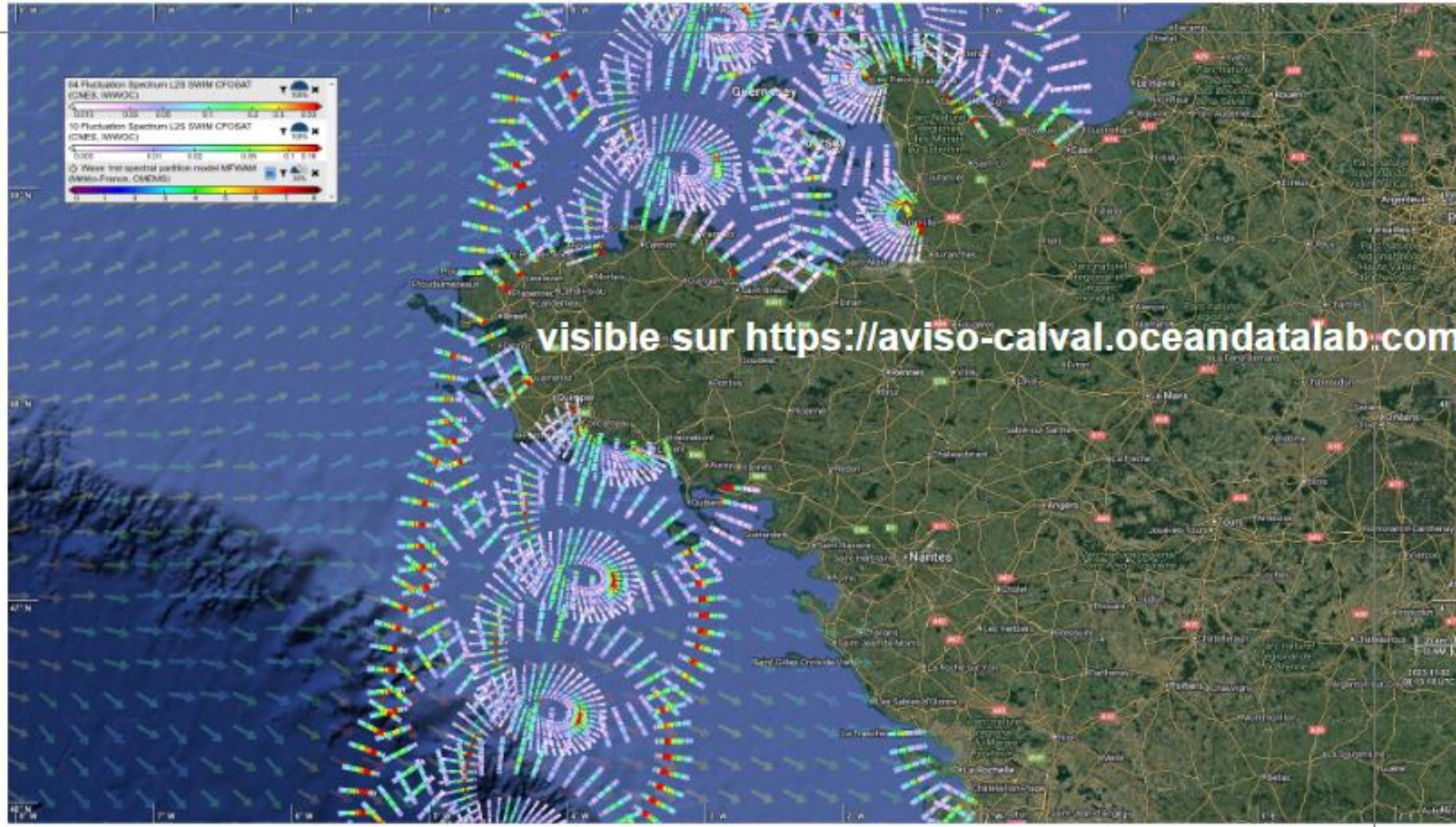
spectres 1D tous les

7° le long de la rotation

et de l'avancement

du capteur résultant en

une trace cycloïde au sol



- L2S (IFREMER/ODL) Version 2 **New 2025** (validated against SOFAR wave drifter network), avec partitionnement.
- L2 (CNES) : Spectre 2D interpolé sur des boîtes de 70x70km
- L2P (CLS) : L2 augmenté avec des flags de qualité et un partitionnement avec paramètres intégraux des partitions

SWOT Karin : produits de spectres directionnels de houle longue

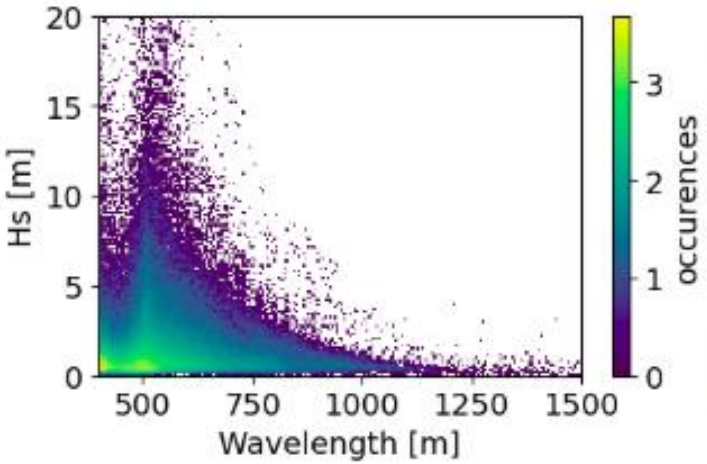
Spectre directionnels

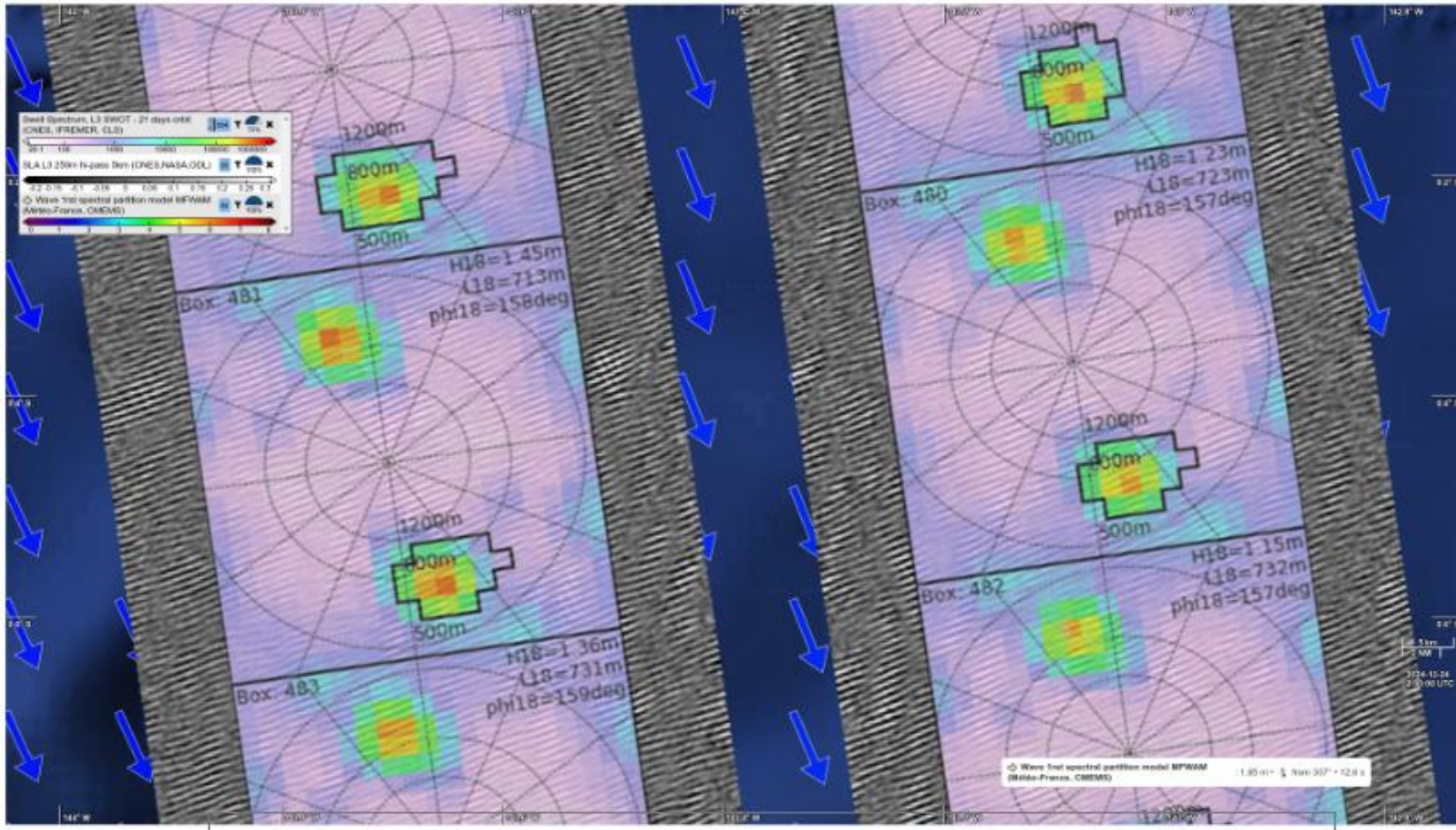
de houle longue

issu du produit

L3 SSH Karin à 250m ->

longueur onde > 500m



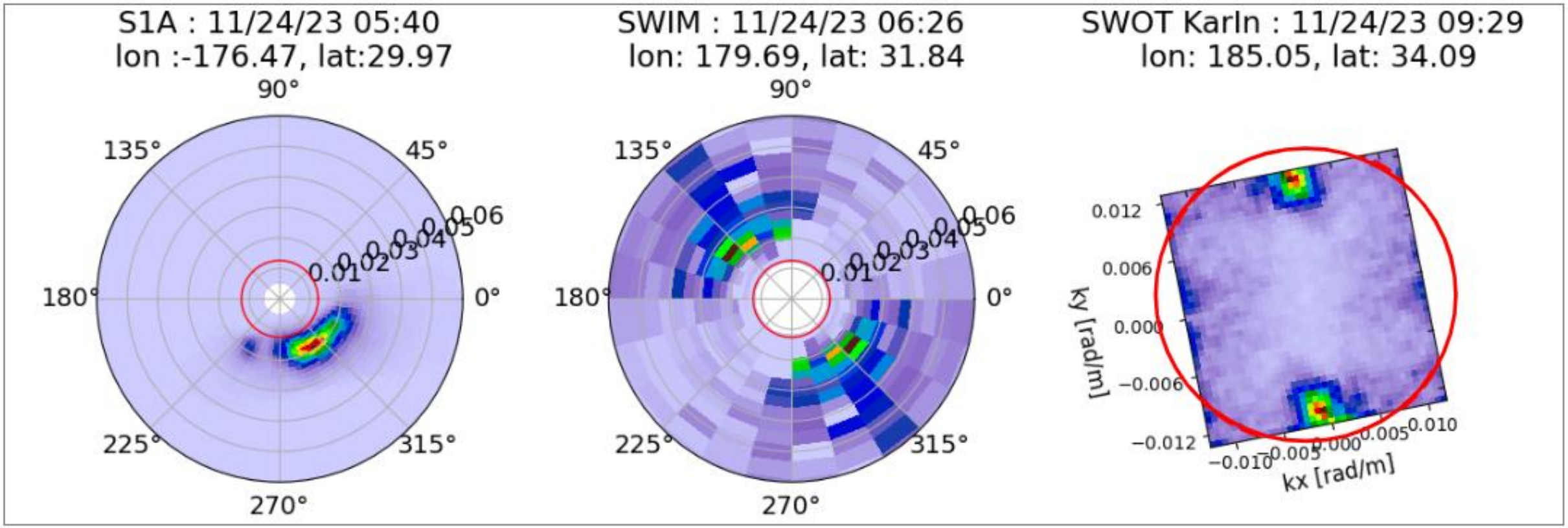


visible sur https://aviso-calval.oceandatalab.com

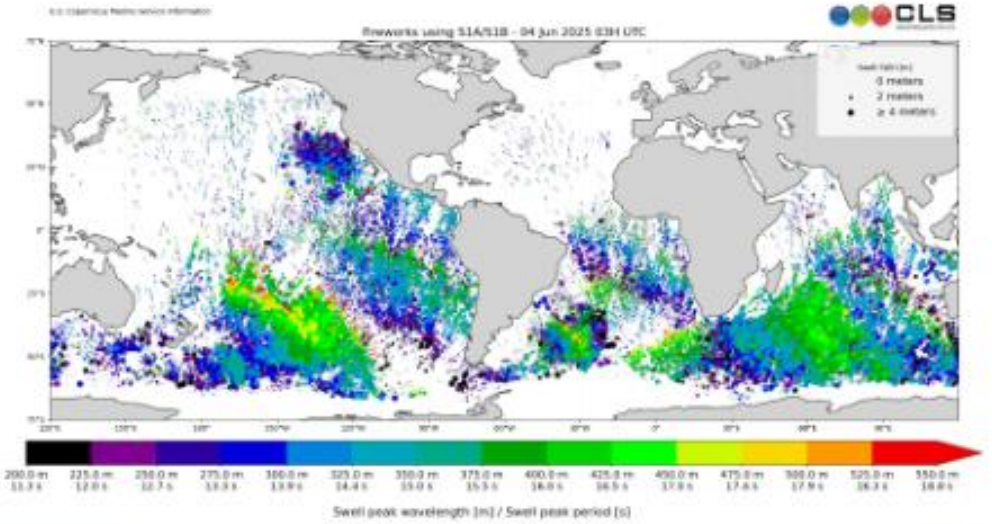
Développement LOPS 2024, un an disponible sur FTP AVISO

Directional spectra from Sentinel1, SWIM et SWOT

=> Aim : to combine the different observations to see the complementarity and add these to a multi sensor product.



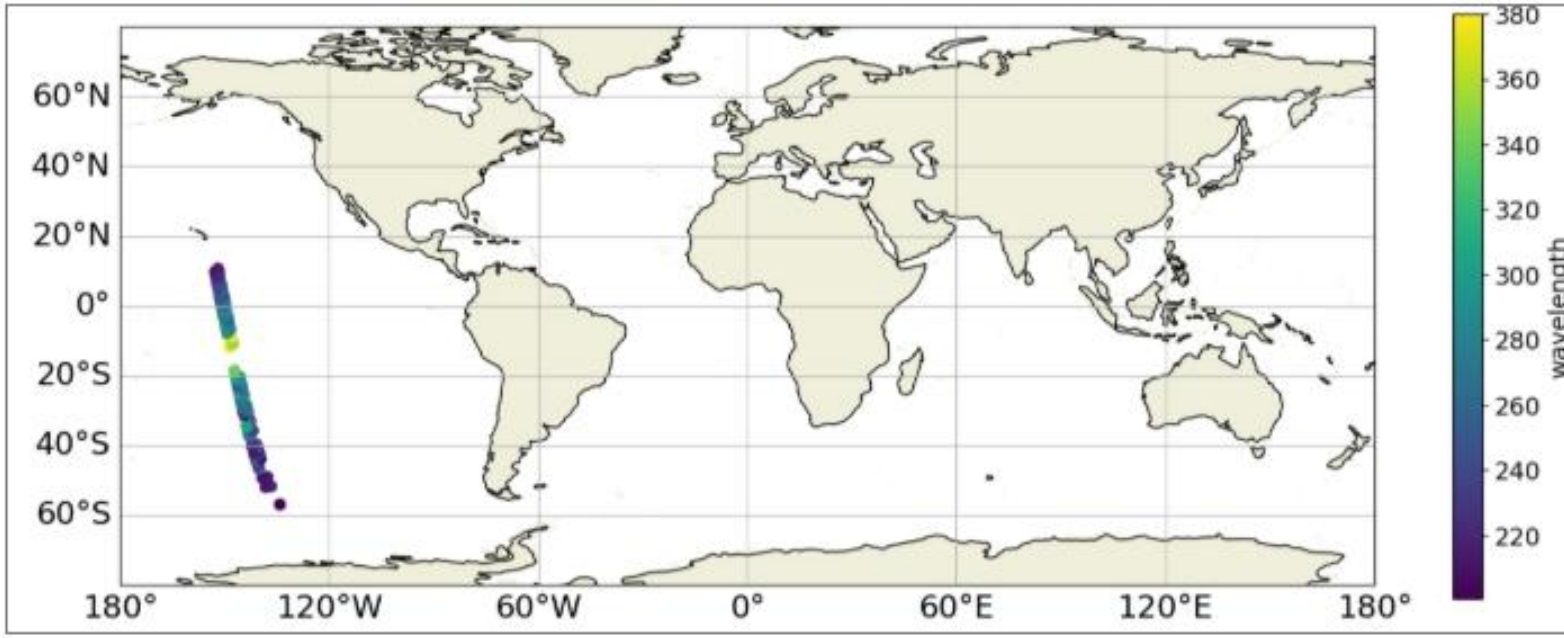
Fireworks processing (suivi de houles)



- Spectral wave product
- Part observation, part modelisation
- Input: estimated integral parameter by swell partition

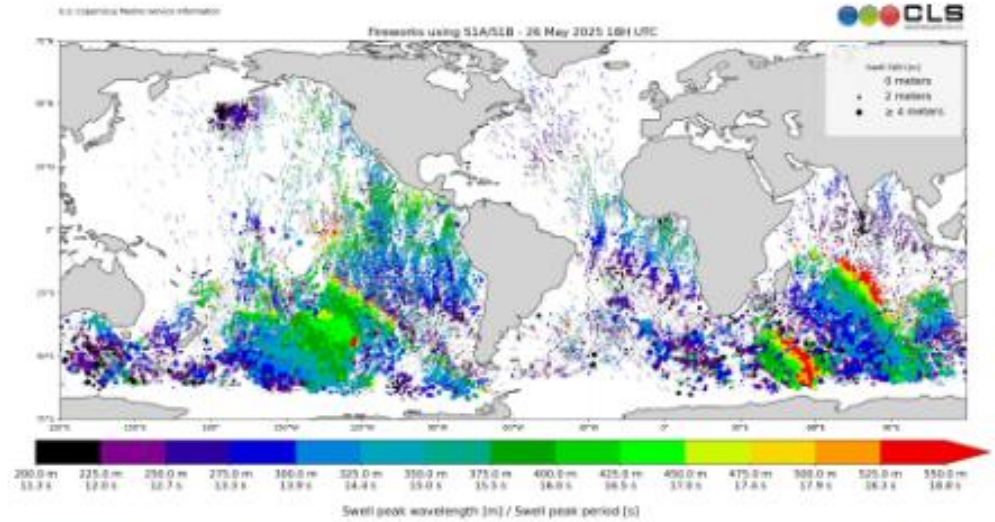
Main principle:

1) Observations = swell partitions (Hs, wavelength, direction)



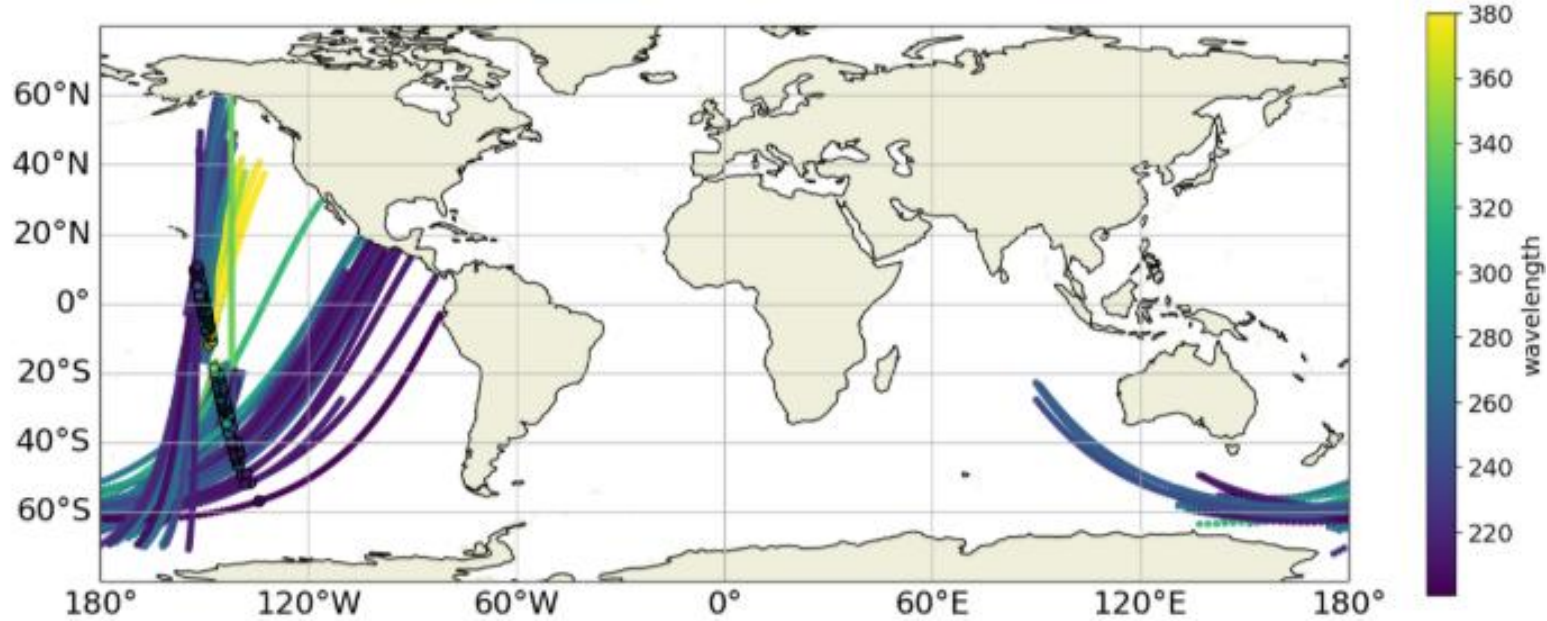
Fireworks processing (suivi de houles)

- Spectral wave product
- Part observation, part modelisation
- Input: estimated integral parameter by swell partition



Main principle:

1) Observations = swell partitions (Hs, wavelength, direction)
2) Linear propagation along Great Circle using the dispersion relation ==> pseudo observations

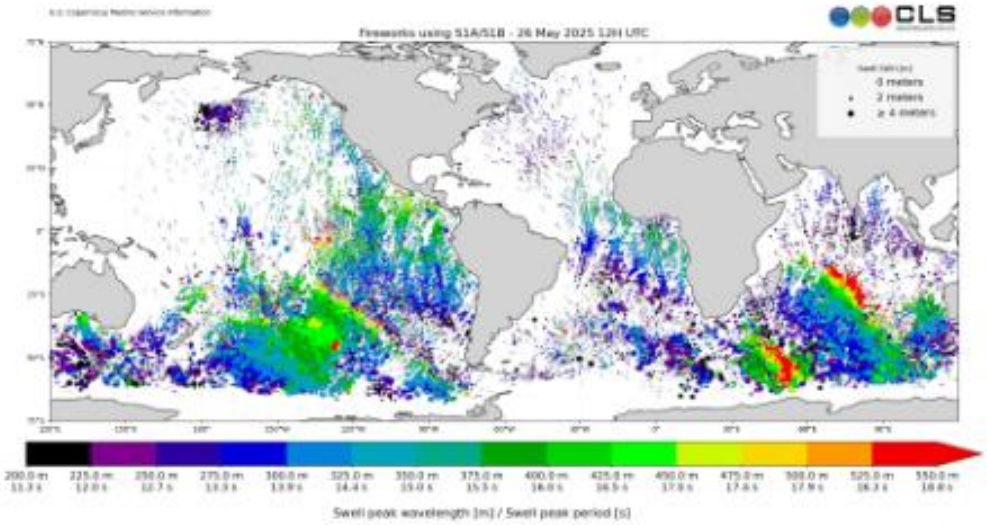


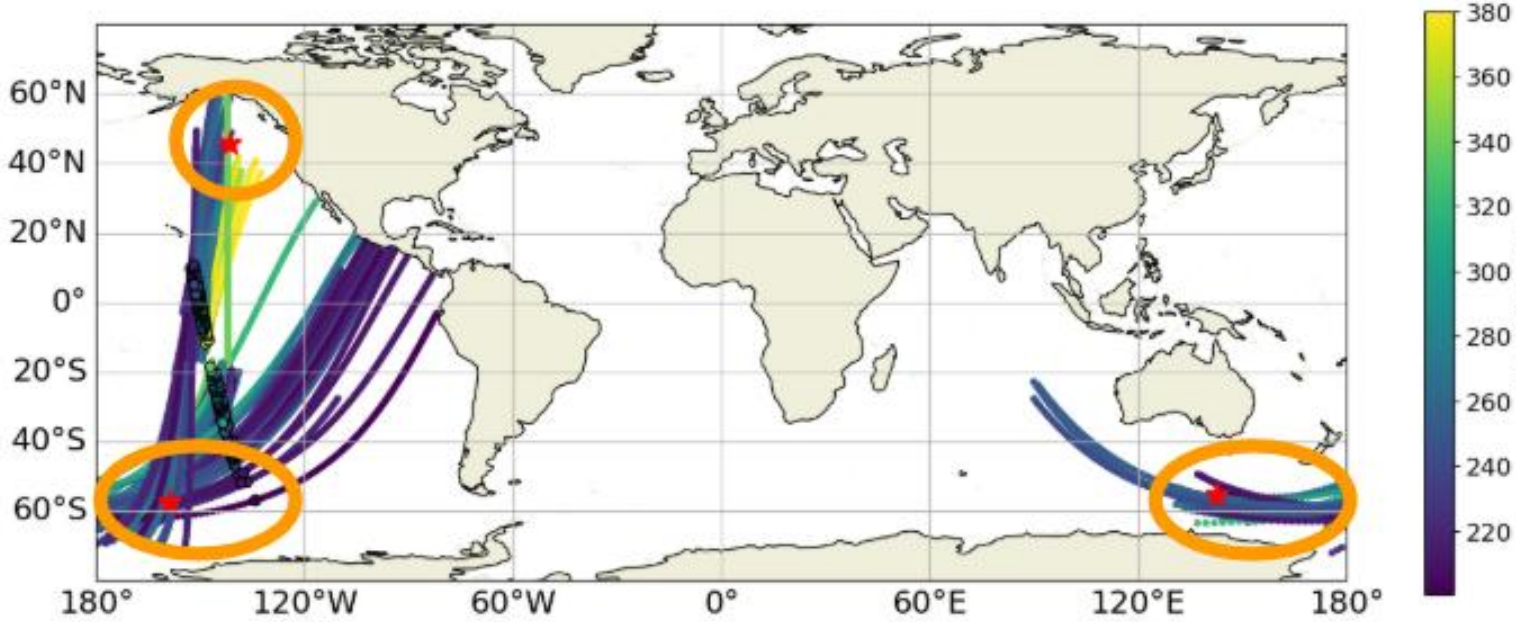
Fireworks processing (suivi de houles)

- Spectral wave product
- Part observation, part modelisation
- Input: estimated integral parameter by swell partition

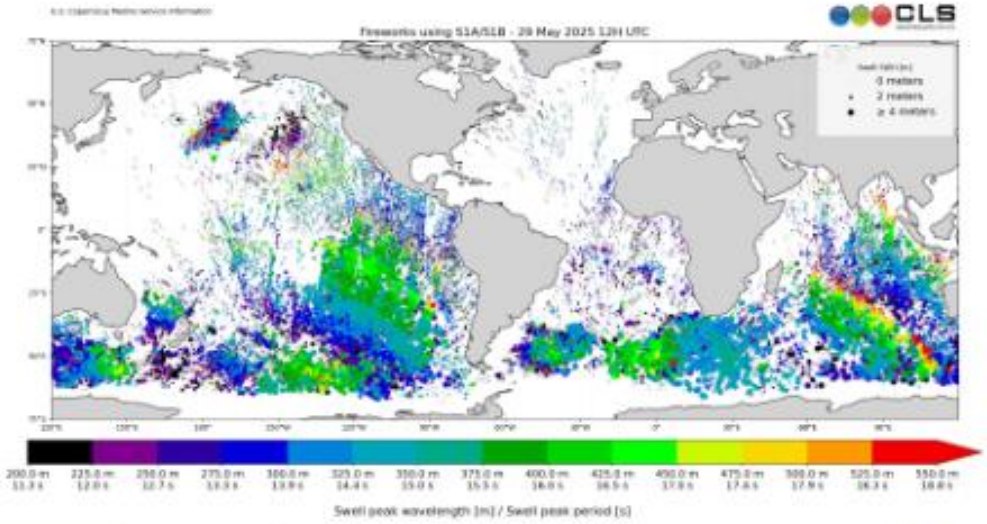
Main principle:

1) Observations = swell partitions (Hs, wavelength, direction)
2) Linear propagation along Great Circle using the dispersion relation ==> pseudo observations
3) Identification of zones with high density of pseudo observation ==> generation area = storm





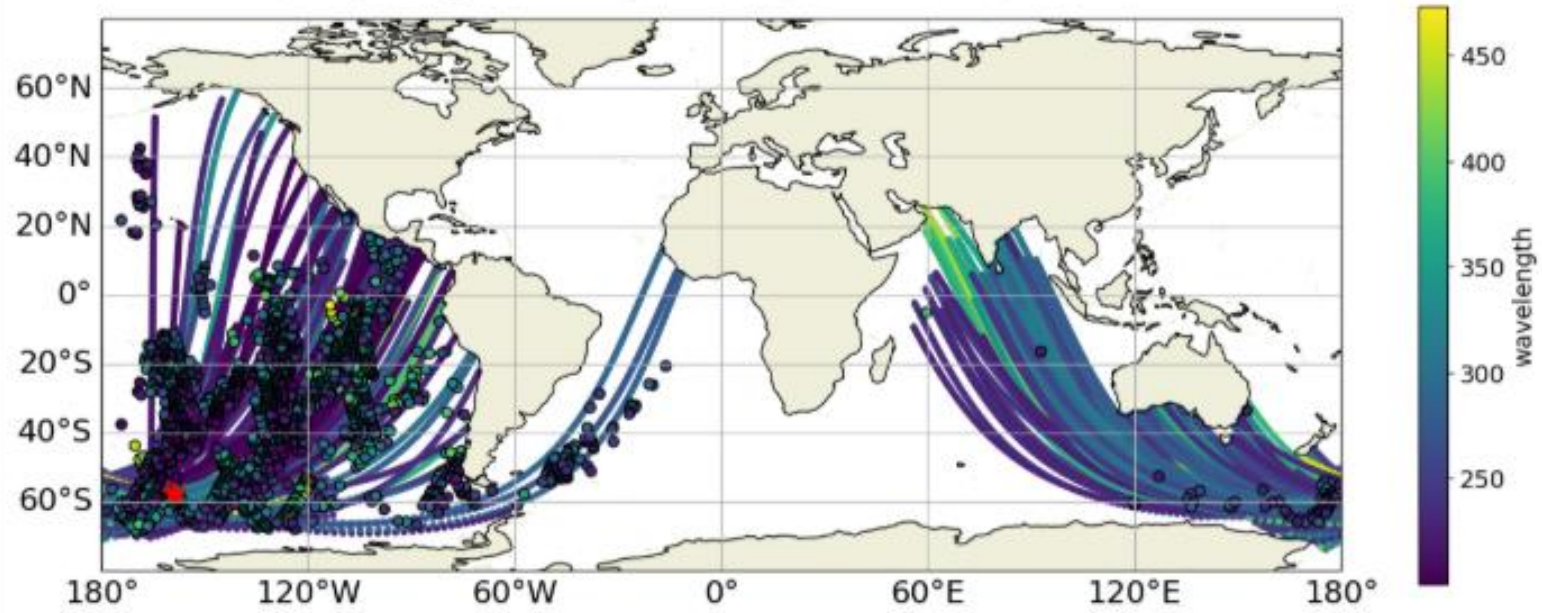
Fireworks processing (suivi de houles)



- Spectral wave product
- Part observation, part modelisation
- Input: estimated integral parameter by swell partition

Main principle:

1) Observations = swell partitions (Hs, wavelength, direction)
2) Linear propagation along Great Circle using the dispersion relation ==> pseudo observations
3) Identification of zones with high density of pseudo observation ==> generation area = storm
4) Selection of obs and pseudo obs associated to storms → **L3 product generation**

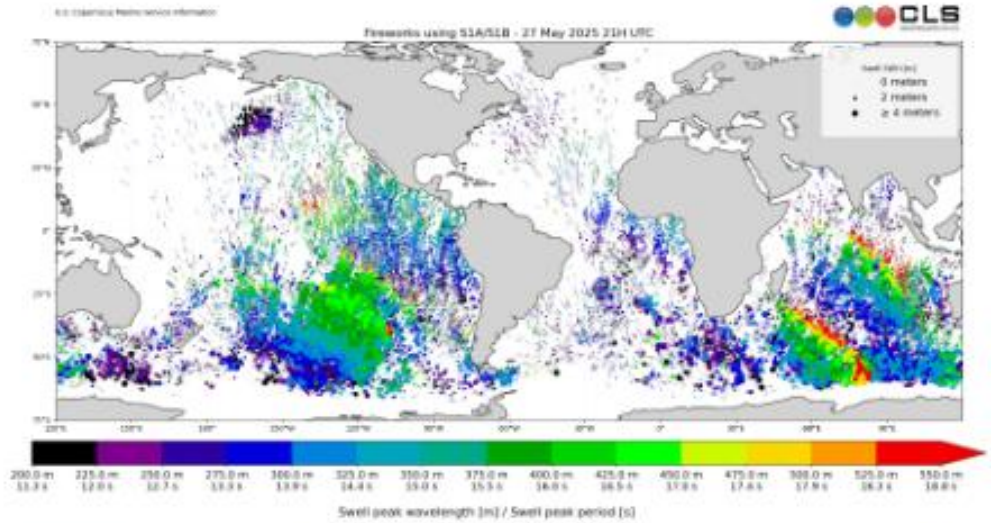


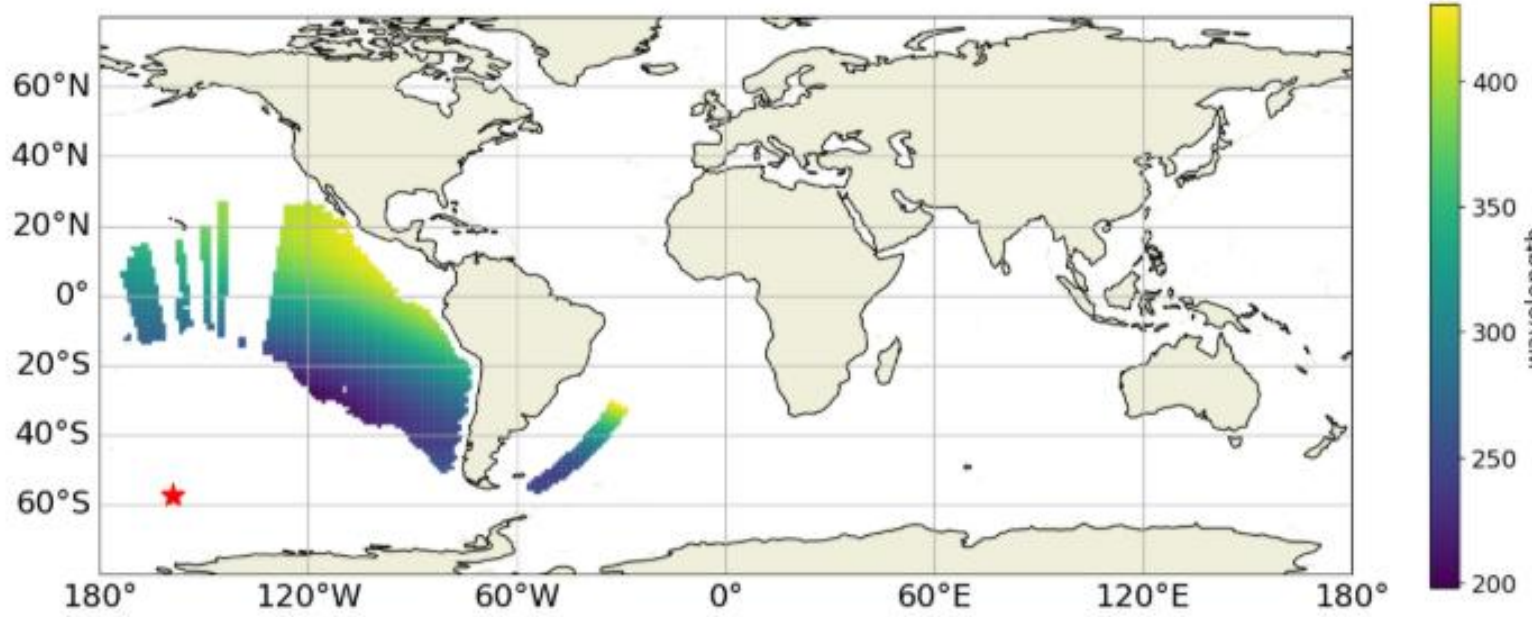
Fireworks processing (suivi de houles)

- Spectral wave product
- Part observation, part modelisation
- Input: estimated integral parameter by swell partition

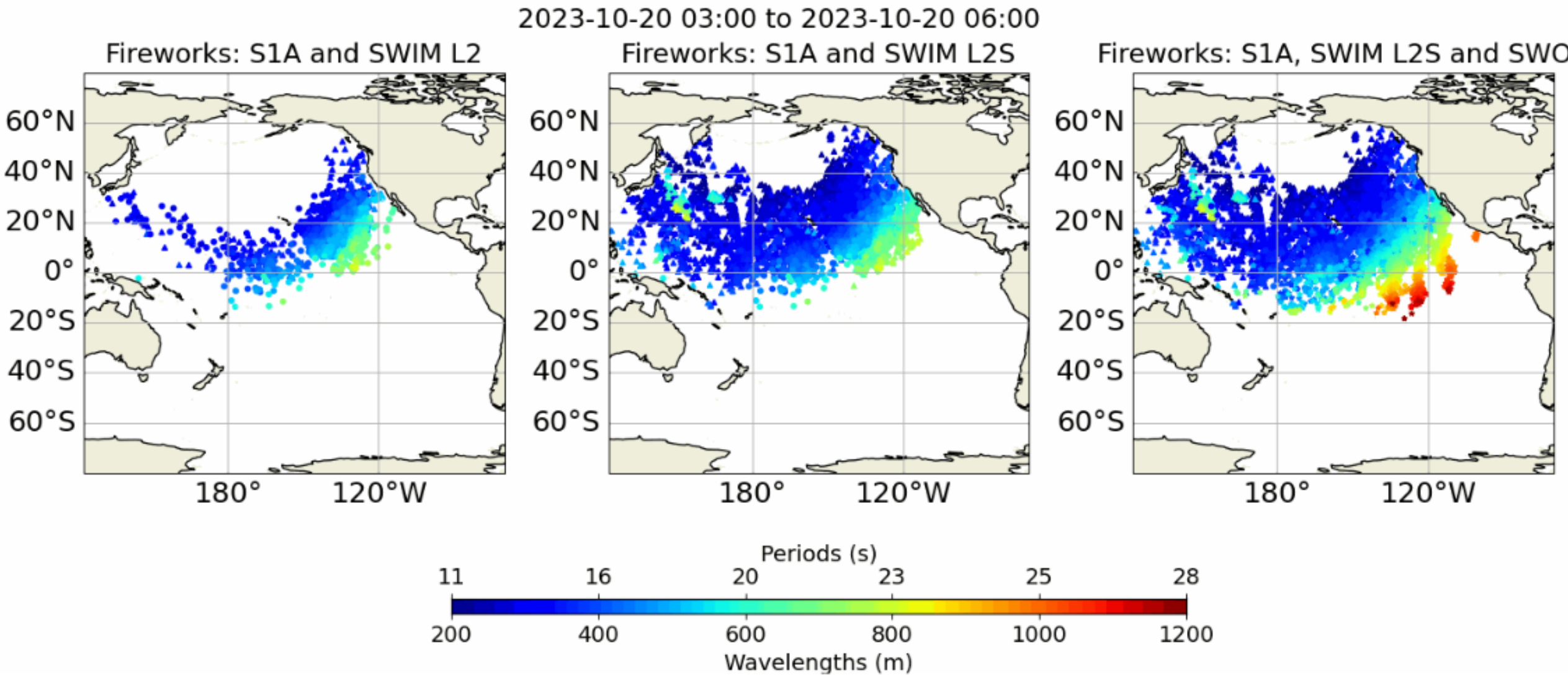
Main principle:

1) Observations = swell partitions (Hs, wavelength, direction)
2) Linear propagation along Great Circle using the dispersion relation ==> pseudo observations
3) Identification of zones with high density of pseudo observation ==> generation area = storm
4) Selection of obs and pseudo obs associated to storms → **L3 product generation**
5) Creation of a synthetic field by interpolation of the pseudo-obs on a (r,ϑ) centered on the storm
   → **L4 product generation**





Etude de cas - Tempete Bolaven



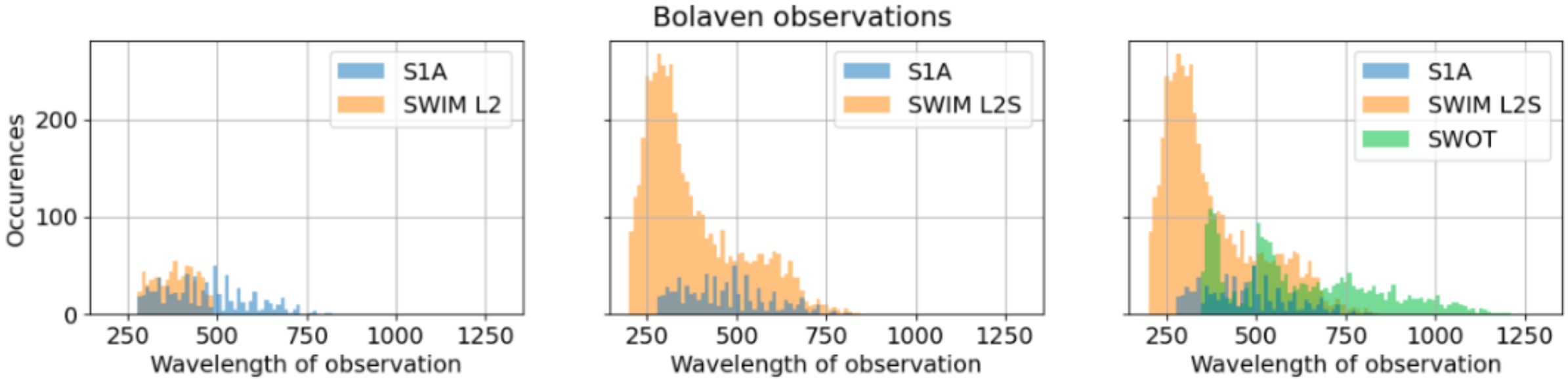
Complémentarités Sentinel-1 , SWIM, SWOT

Repartition of the observations' wavelength by satellite

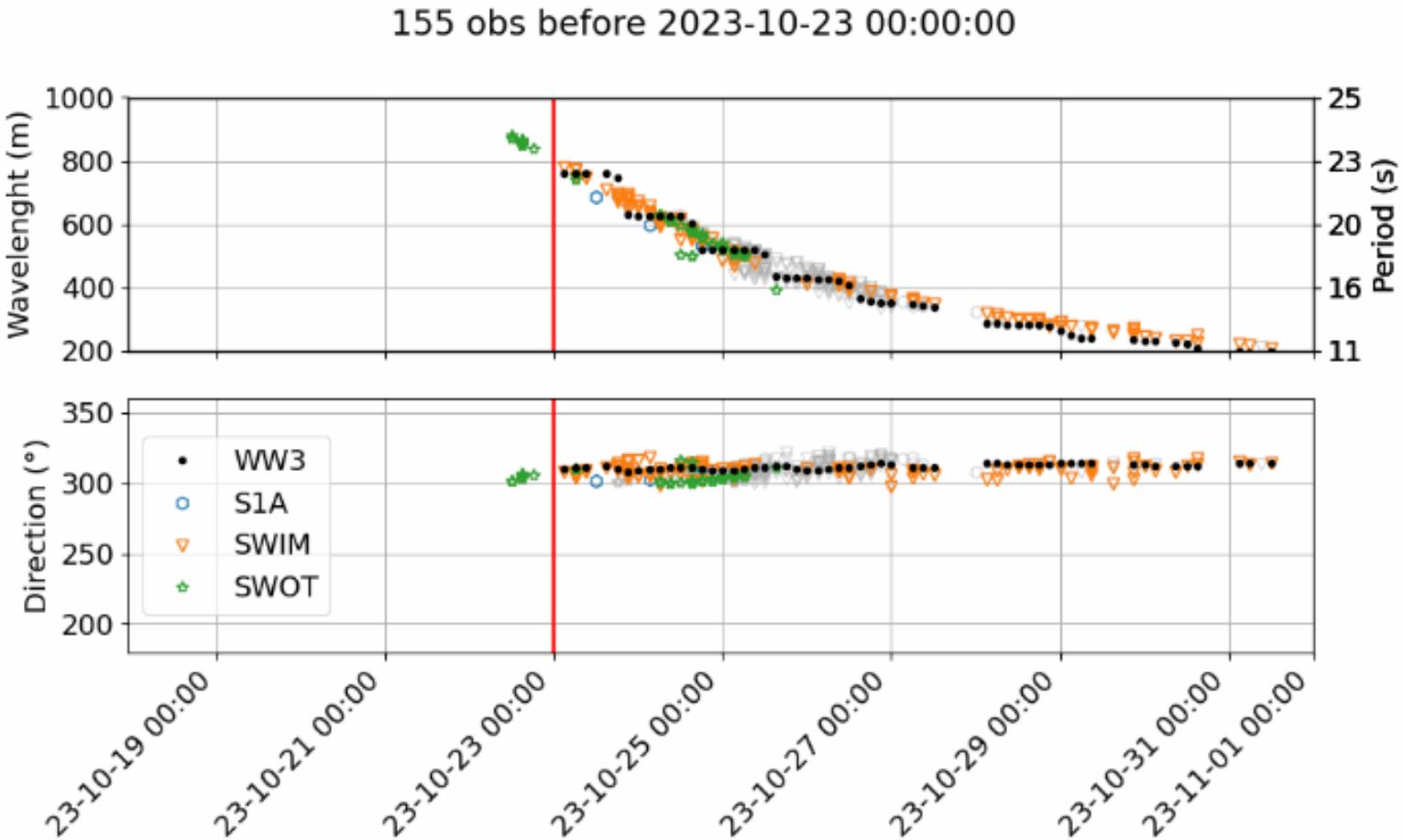
- Complementarity between satellites
- SWIM L2S covers wavelength that were not seen by classical product
- SWOT enables to cover a large range of wavelength where we the other satellites are "blind"

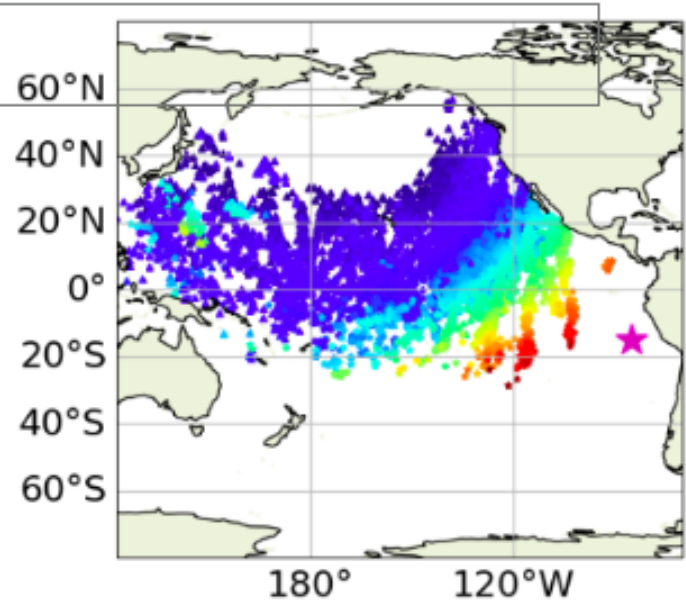
==> **SWOT is a game changer** for fore-runners (long swells of small amplitude that propagate faster)

==> **SWIM L2S is a great improvement** compared to the classical product



Towards Early Warning System





- Virtual buoy offshore Peru
- Compared to WW3 model

=> Good agreement in Wvl and dir

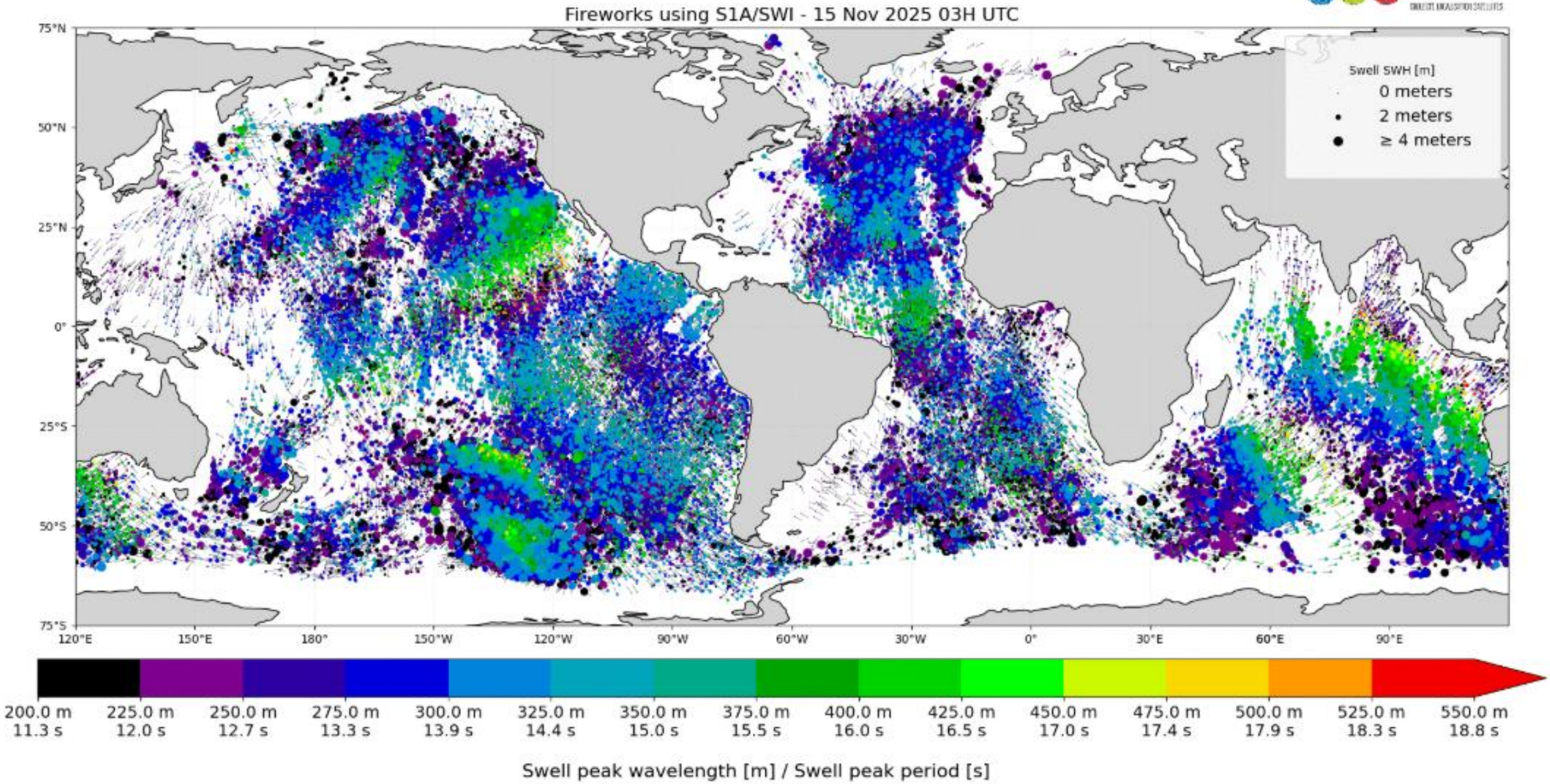
The arrival of the swell is well captured by the Fireworks

=> First step towards Early Warning System

In colour, pseudo obs. already integrated by 21/10/2023

CMEMS operational Satellite based swell monitoring system

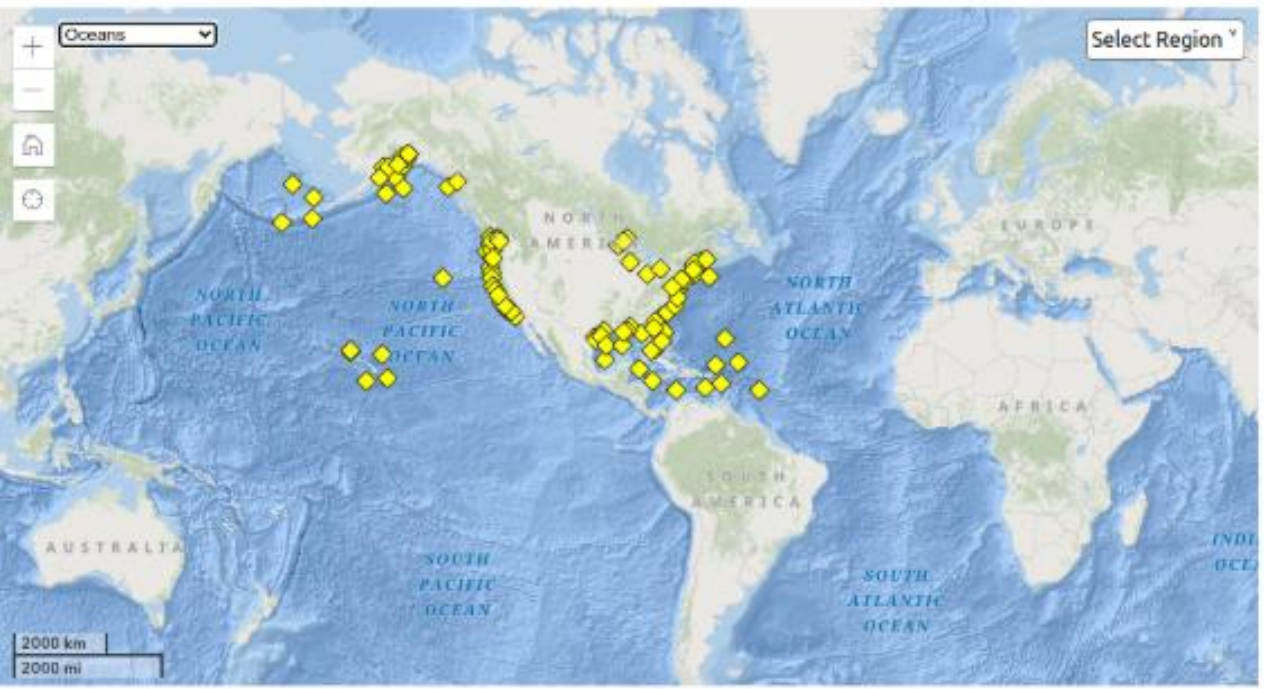
E.U. Copernicus Marine Service Information



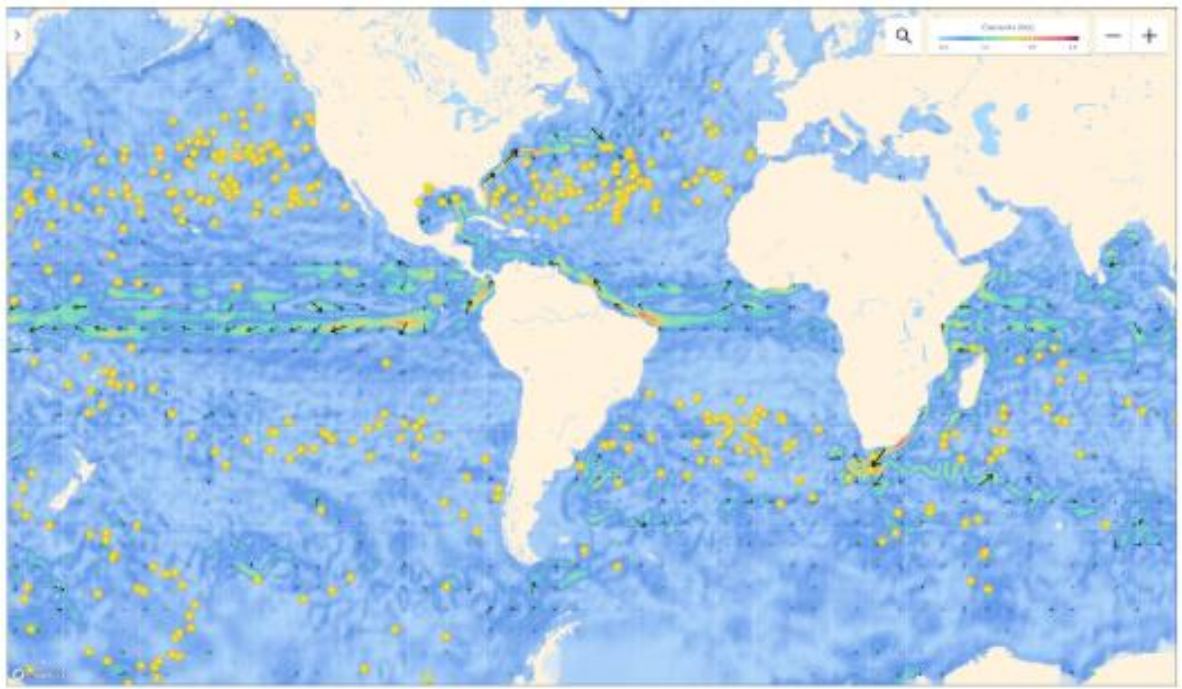
Journée états de mer 2025, 11 Décembre, Brest, Pôle numérique

Global validation dataset for 2D wave spectra.

Coastal (moored buoys) ex: NDBC



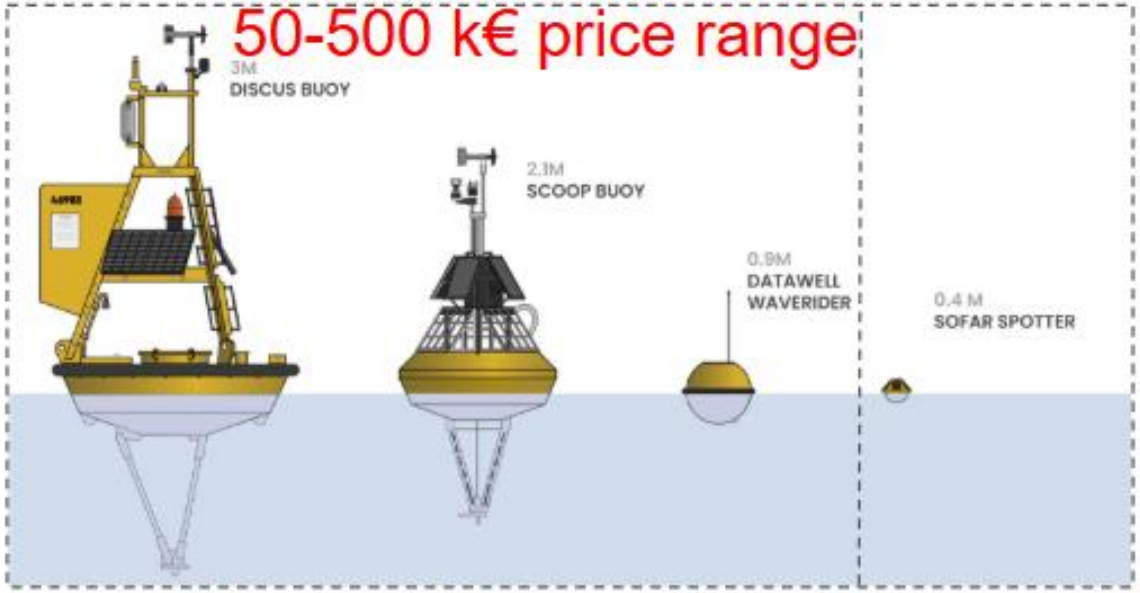
Open Ocean (wave drifters) ex: Sofar



Existing wave buoys

price range includes manufacturing communication installation & maintenance

50-500 k€ price range



wave drifters

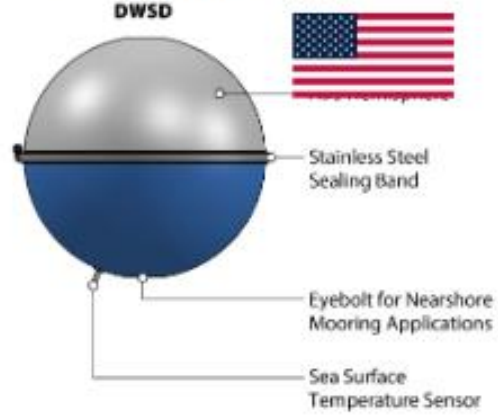
Met.No
OMB

Eodyn
MELODI

2-5 k€ price range

Sofar
Spotter

Scripps



7-15 k€ price range

Essential wave buoys parameters for validation

Time and position every hour or better

First-5 Directional Fourier coefficients a0, a1, b1, a2, b2 for a large frequency range (0.03Hz to 1Hz)

First-5 coefficients can be used to compute wave parameters such as significant wave height, swell direction, and directional spread, among others.

Also allows to reconstruct 2D wave spectra by MLM or MEM techniques and estimate wave partitions parameters (dominant period, dominant direction, significant wave height)

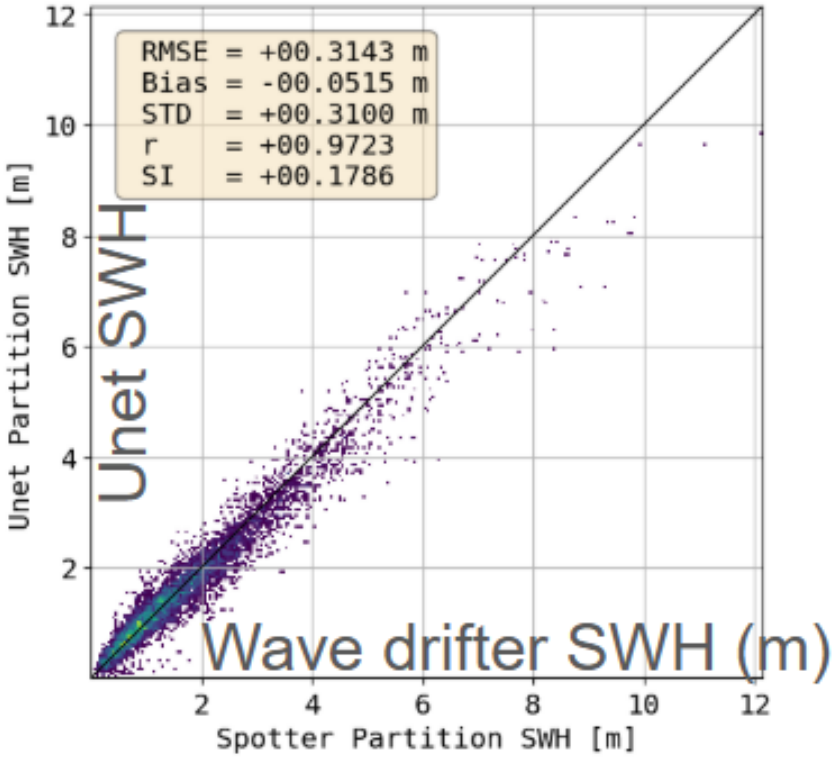
Two technologies for wave spectra measurements :

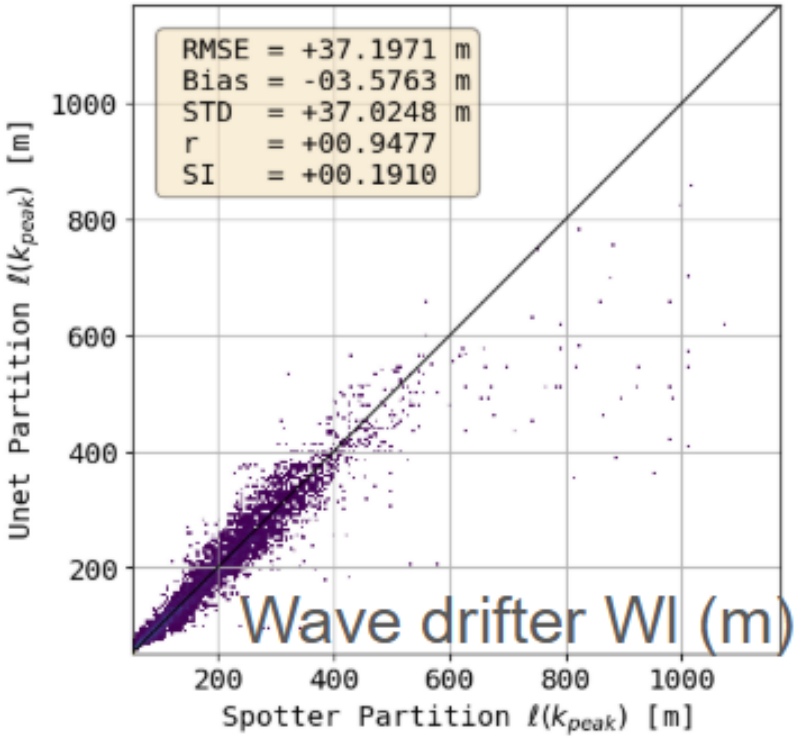
- GPS : Scripps DWSD, Sofar Spotter todays deployments about 1000 units
- accelerometers : Met.No, Eodyn, todays deployments about 100 units each

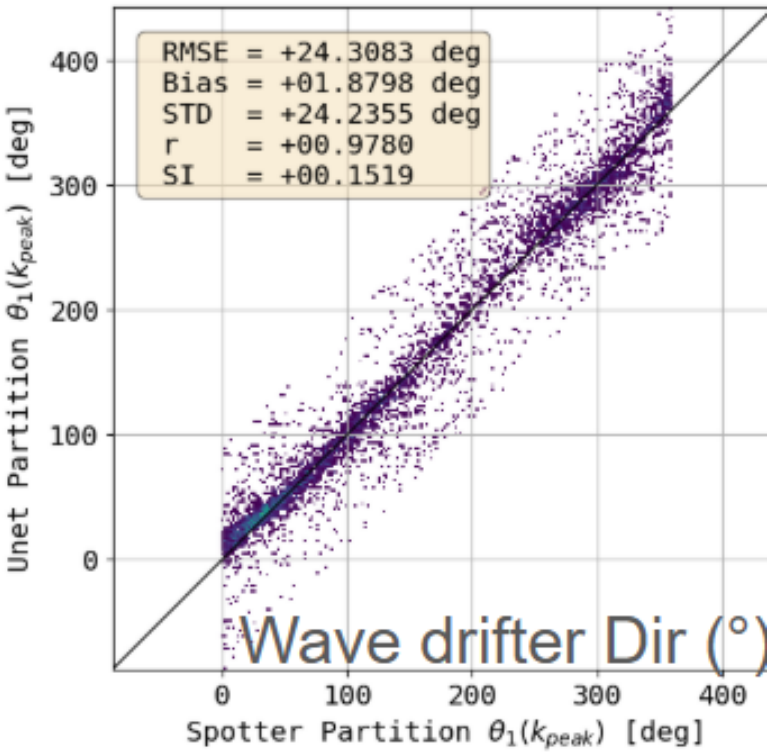
Sentinel-1 wave mode validation

2 years of historical SOFAR spotter data released for scientific Dominant wave partitionanalysis

Collocations: 50 km maximum distance and 60 minutes maximum time interval between Spotter and SAR: 4336 collocations







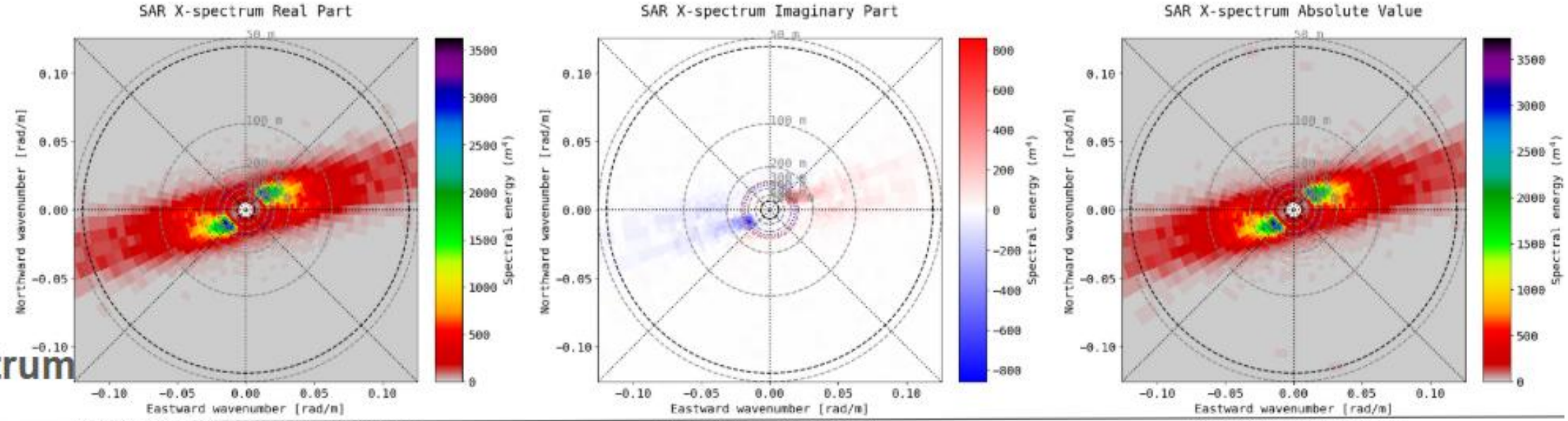
Sentinel-1 WV || UNET-00 || Partition θ_{sp} best case (Case number 2992 [2992 on global dataset])
Unet partition θ_{sp} = 79.0761 deg, WW3 partition θ_{sp} = 79.3334 deg, Spotter partition θ_{sp} = 79.0762 deg
Unet partition θ_{sp} error = 0.0001 deg, WW3 partition θ_{sp} error = 0.2573 deg

Spotter:
01/08/2021 14:38:31
lon = +053.48
lat = -039.18
SWH = +085.60 m

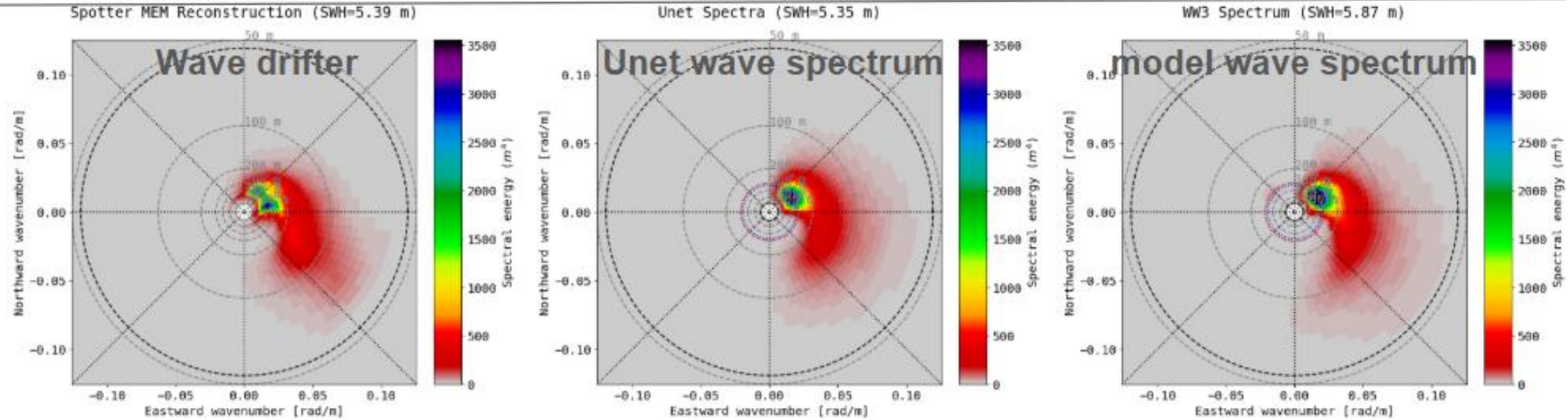
SAR:
01/08/2021 15:05:04
lon = +053.96 deg
lat = -039.18 deg
$|W|$ = +015.33 m/s
θ_w = +156.93°

Spotter/SAR colocation:
D = +41.43 km
dt = +00 H 26 min 33 sec

SAR Cross-spectrum



Partition limits
Weighted partition k_{peak}
Partition k_{peak}



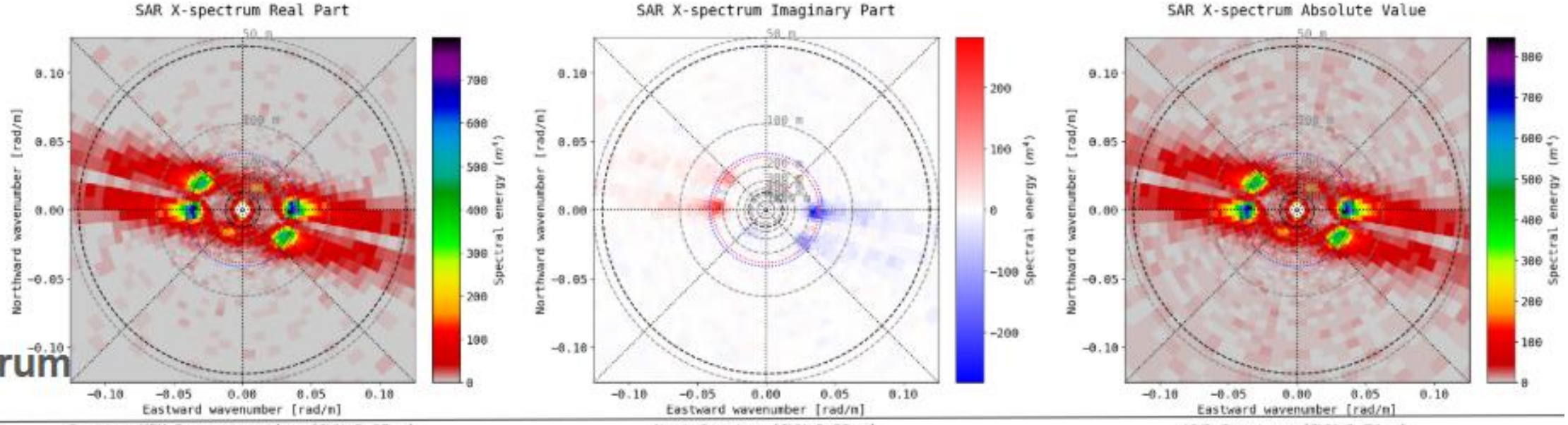
Sentinel-1 WV || UNET-00 || Partition $r_2(k_{peak})$ best case (Case number 2824 [2824 on global dataset])
Unet partition $r_2(k_{peak})$ = 0.7081 rad/m, WW3 partition $r_2(k_{peak})$ = 0.7262 rad/m, Spotter partition $r_2(k_{peak})$ = 0.7081 rad/m
Unet partition $r_2(k_{peak})$ error = 0.0000 rad/m, WW3 partition $r_2(k_{peak})$ error = 0.0182 rad/m

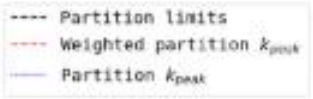
Spotter:
11/10/2020 14:00:19
lon = -119.99
lat = -008.65
SWH = +003.13 m

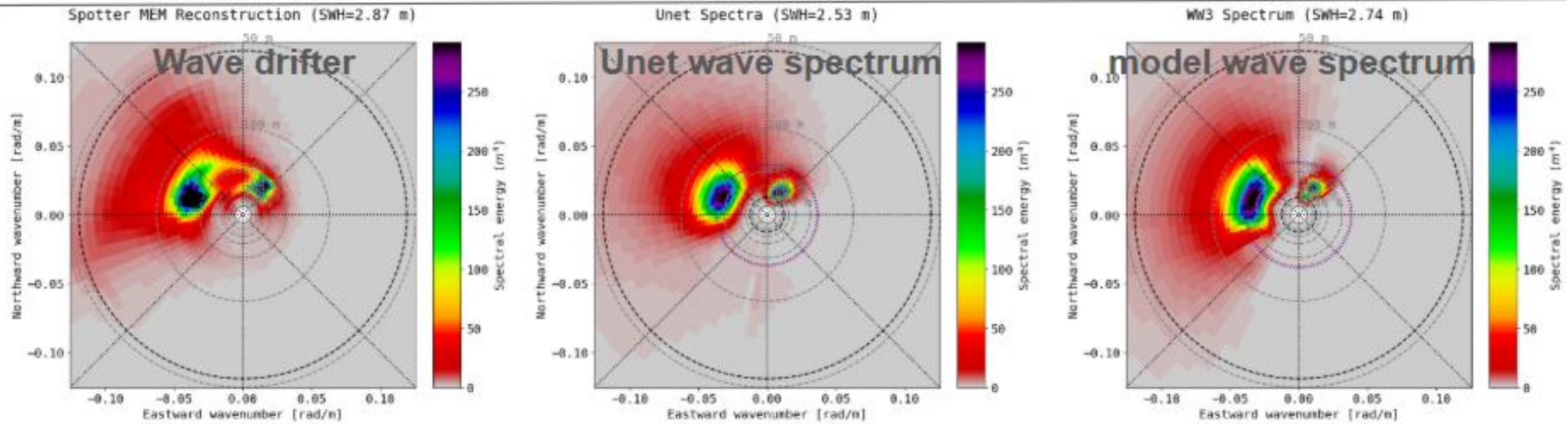
SAR:
11/10/2020 13:39:52
lon = -120.19 deg
lat = -008.73 deg
|W| = +089.23 m/s
θ_w = +343.23°

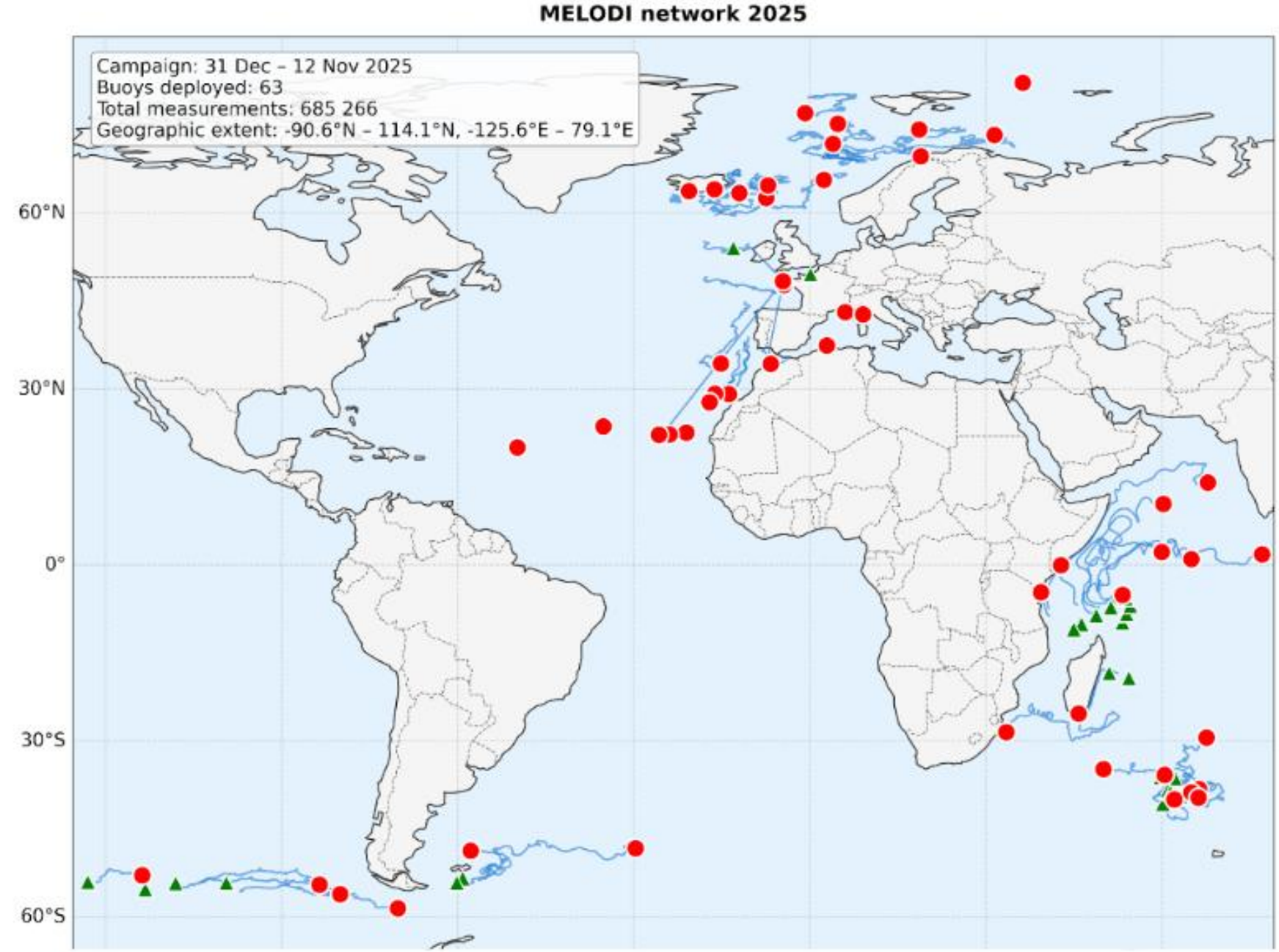
Spotter/SAR colocation:
D = +24.84 km
dt = -00 H 20 min 27 sec

SAR Cross-spectrum





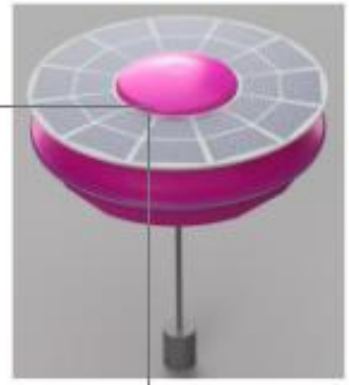




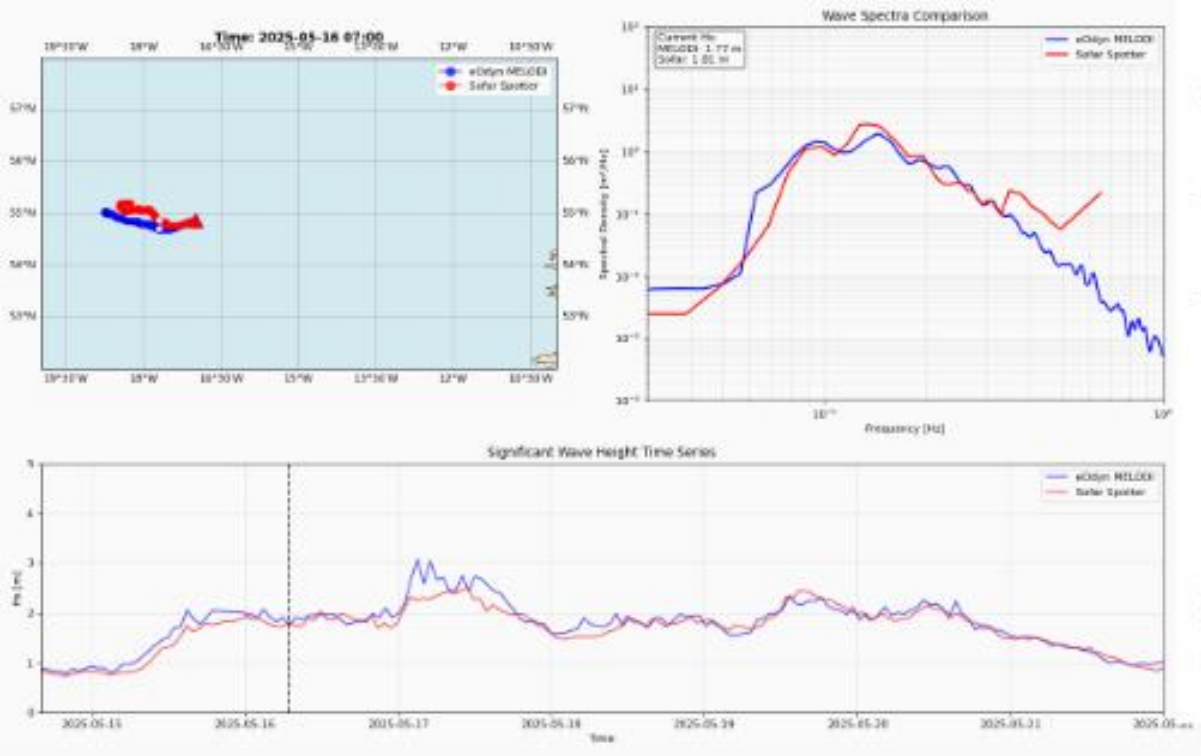
- A total of 63 buoys were deployed in 2025.
- Buoys were deployed in the Mediterranean Sea and all the world's oceans, including the Southern and Northern hemispheres.
- All data could be monitored in NRT.
- Almost half of the buoys were deployed from the small boats.

MELODI Wave drifter measurements

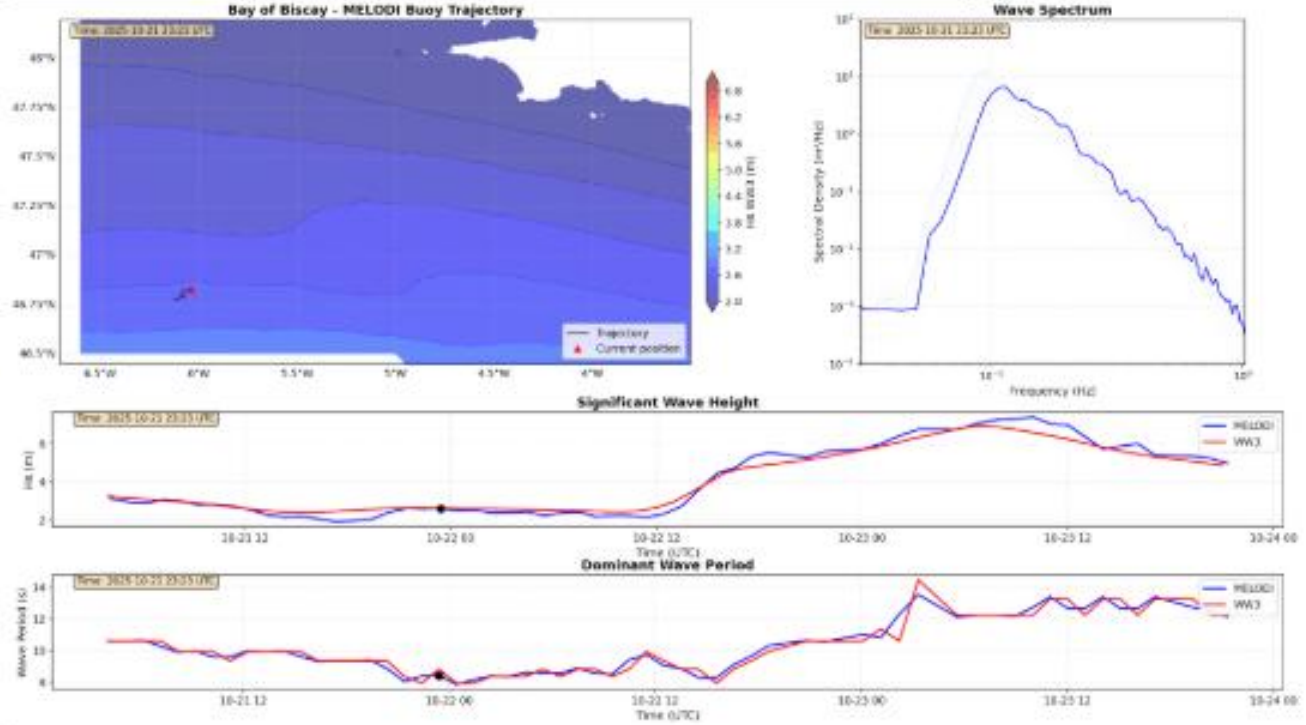
Omnidirectional wave spectrum: 0.04-1 Hz
SWH: every 30 min
Resistant to high sea states: data transmission completeness: 99.8%



Collocation avec Sofar Spotter



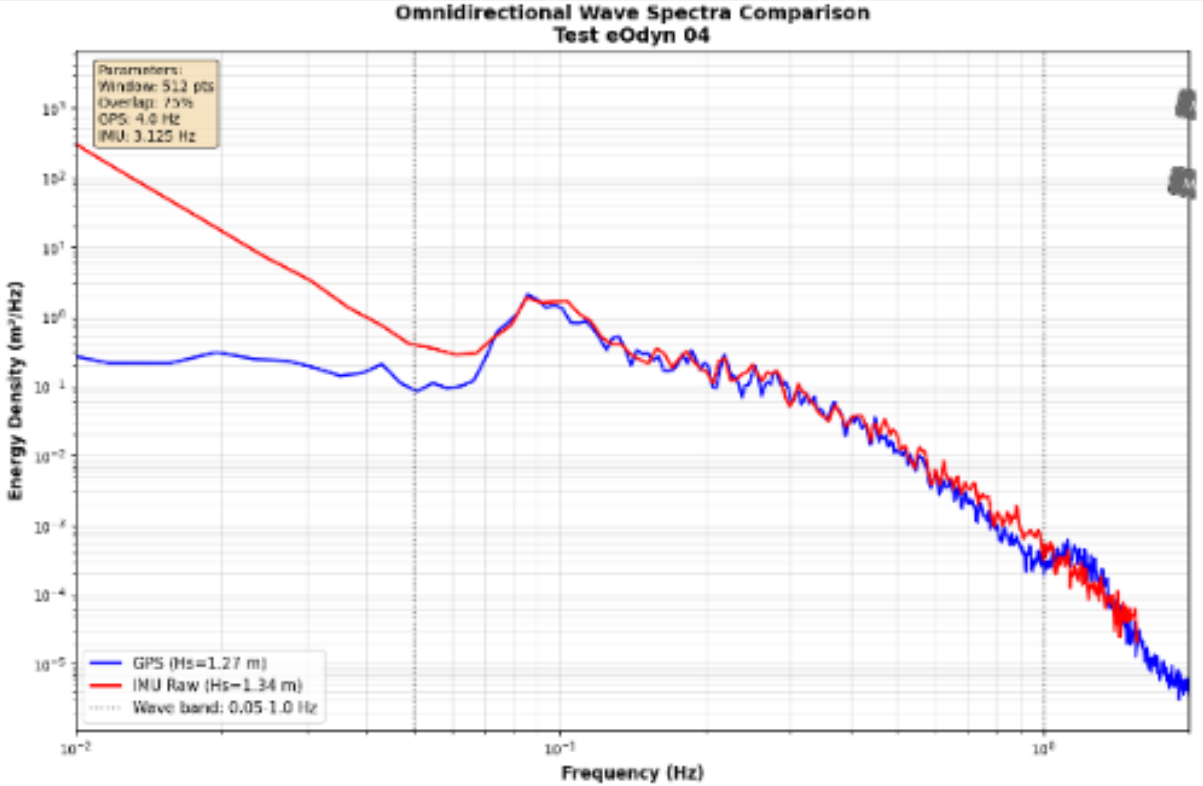
Observations in Extreme Conditions - Storm Benjamin



MELODI Future improvements (ongoing works)

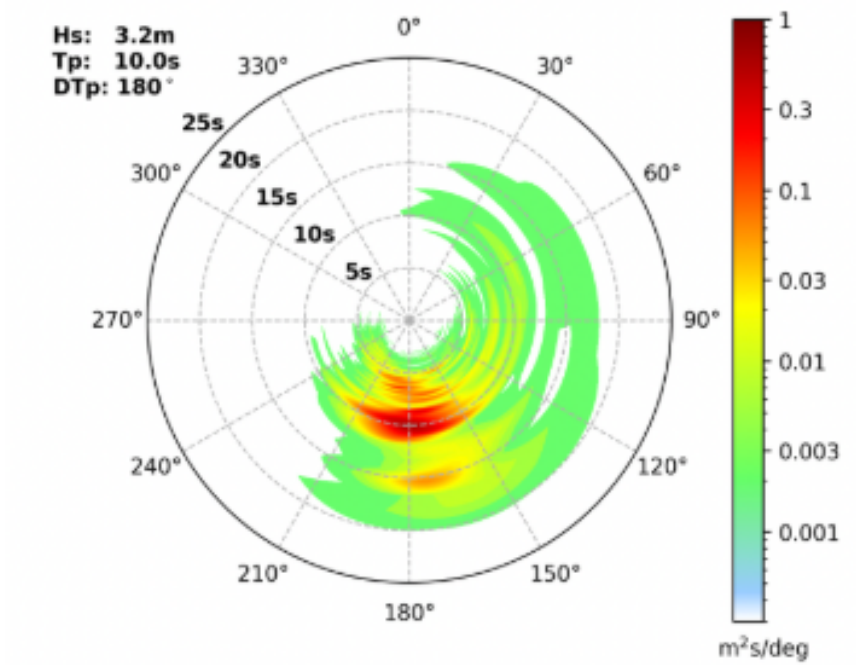
GPS vs IMU based measurements

Original design based on IMU (3 axis accelerometers) is providing a good quality spectra for short waves down to 1m wavelength but suffer from low frequency noise amplification resulting from double integration. Despite smart filtering technique, the accuracy of low frequency part of the wave spectra is unmatched by the use of more energy consuming GPS. However recent progress in GPS energy consumption makes it now ready to integration on MELODI buoy for an optimal hybrid GPS/IMU measurement.



Directional wave spectrum

By combining GNSS-derived orbital velocities with IMU measurements, it also becomes possible to capture the full directional wave spectrum across a wide range of scales—from long-period swell to short wind-generated waves. The GNSS data provide accurate estimates of low-frequency orbital motions, while the high-frequency response of the IMU resolves shorter, wind-driven components. Their joint analysis improves spectral continuity, enhances directionality estimates, and reduces ambiguities in mixed sea states.



Bouée MELODI arrivée cette semaine sur la plage du Linès au sud de Lorient

Distance totale parcourue ≈ 4651 km (vol d'oiseau 1000 km)
Durée de dérive ≈ 7 mois
Portions en couleur de la trajectoire quand la communication des spectres est désactivée (économie de communication et énergie)