Presentation

Spectral swell characterization: Application to S6 tandem phase

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IN PARTNERSHIP WITH

Sea spectra

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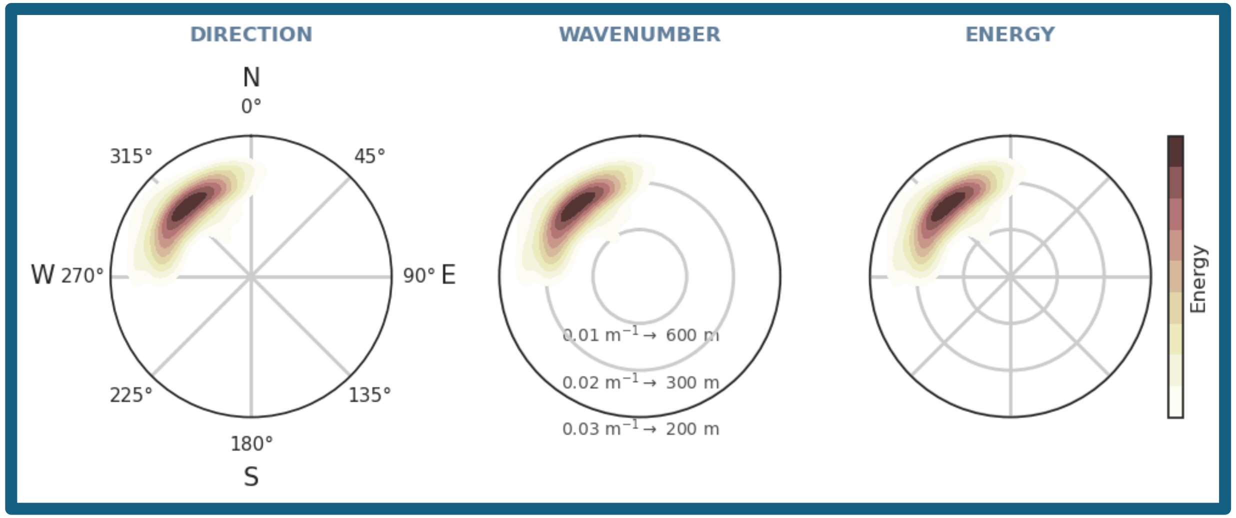
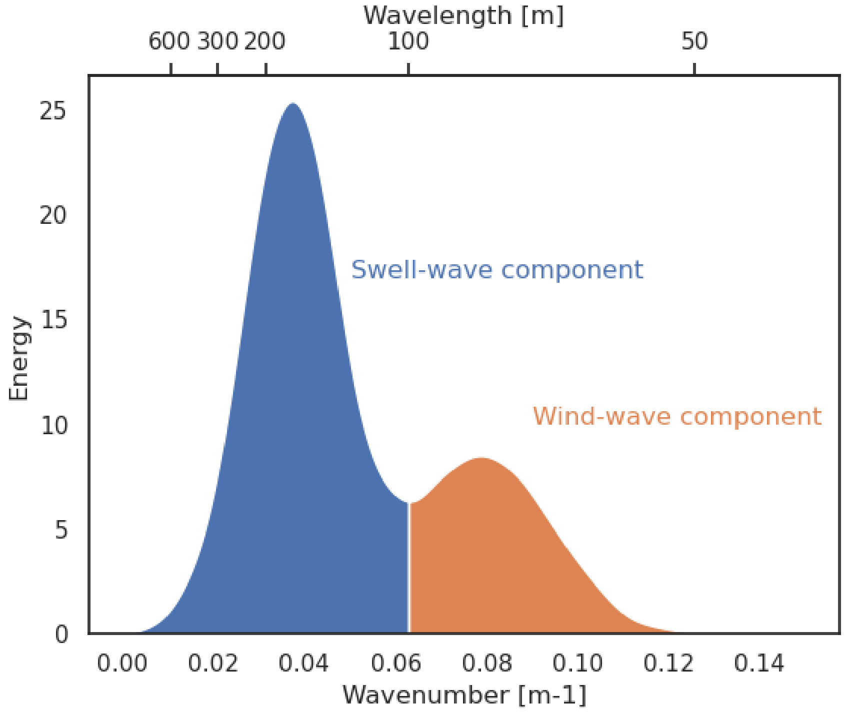
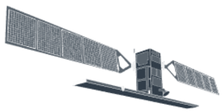
In a given sea state, there are wind waves and a few partitions of swell, each characterized by a peak wavelength (typically 100—600 m) and direction.





They can be estimated locally using buoys and are computed globally by wave models such as ERA5 and MFWAM using assimilated wave heights from SAR satellite data. Moreover, two satellites have operational spectral capabilities: CFOSAT and Sentinel-1.



Nadir altimetry: radargram modulation

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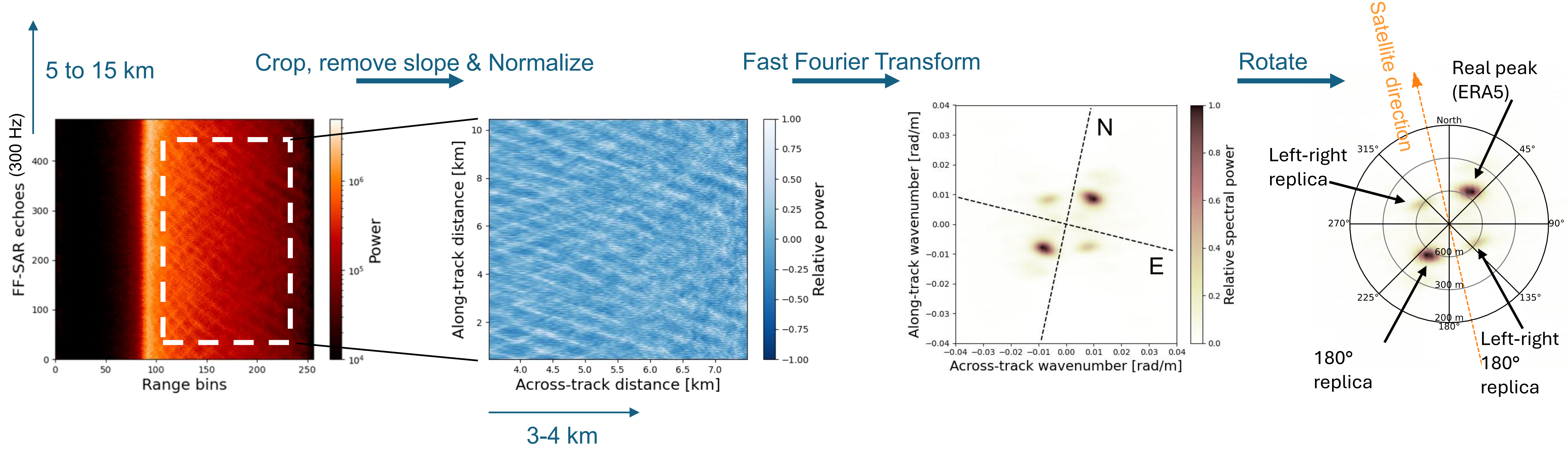
Nadir altimetry has the potential to measure swell spectra over their footprint using PF-SAR or FF-SAR processing. Our algorithm follows the approach described in Altiparmaki et al. 2022: the radargram is normalized, interpolated and a 2-D FFT is performed to access the 2-D spectrum.



S3A, California Gulf (23° 8’ N, 106° 36’ W), 18/07/2022 3:00 am

Due to non-linearity and blurring linked to wave slopes and vertical velocity dispersion, this method works for swell larger than 200 m for calm sea states and 400 m for moderate sea states.

Computing mono-mission cross-spectra

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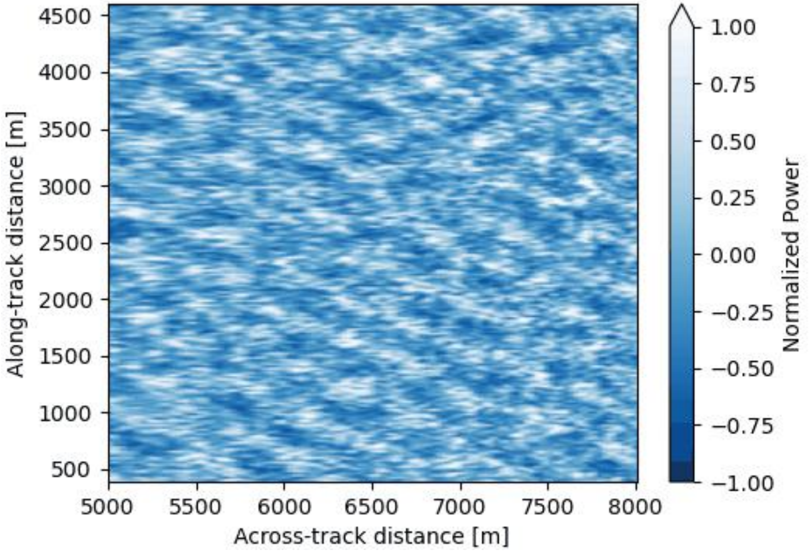
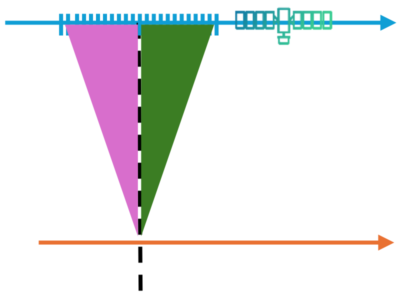
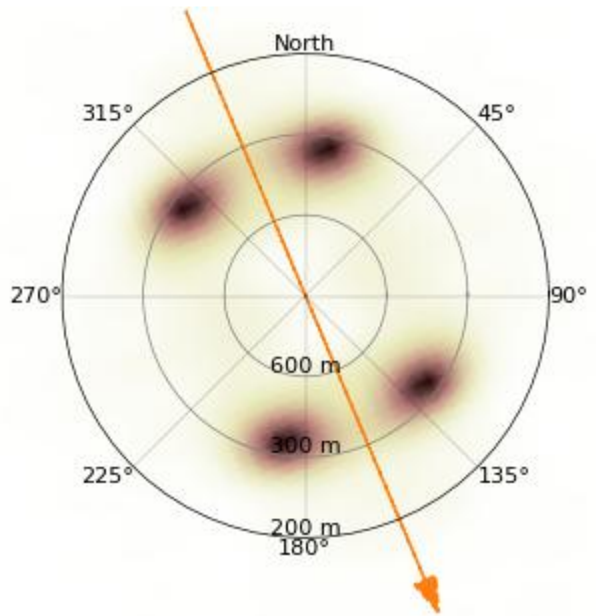
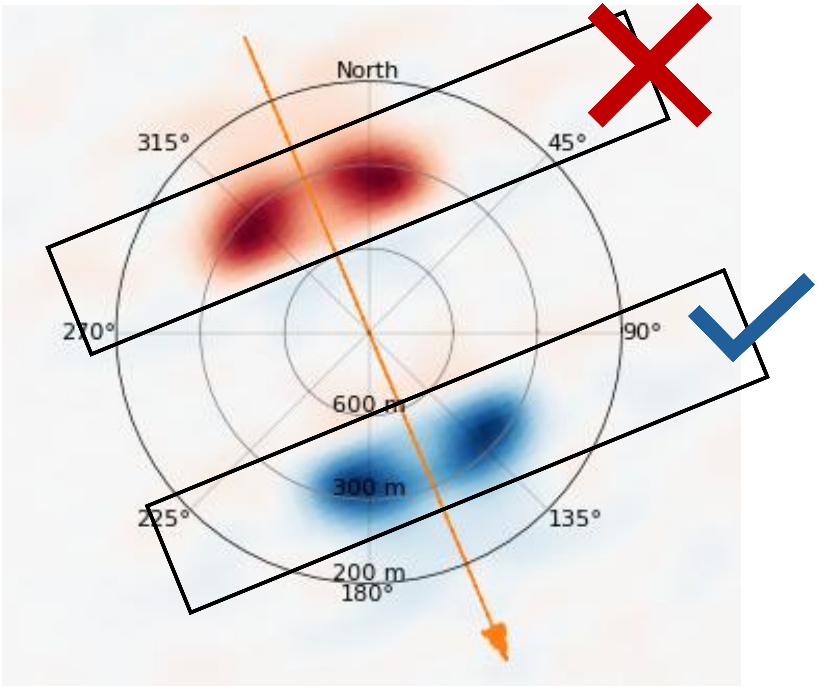
By looking at the same scene with a small time difference and performing their cross-spectra, we can improve the SNR and remove the 180° degree ambiguity (Kleinherenbrink et al. 2024).

Mono-mission: 1 second difference









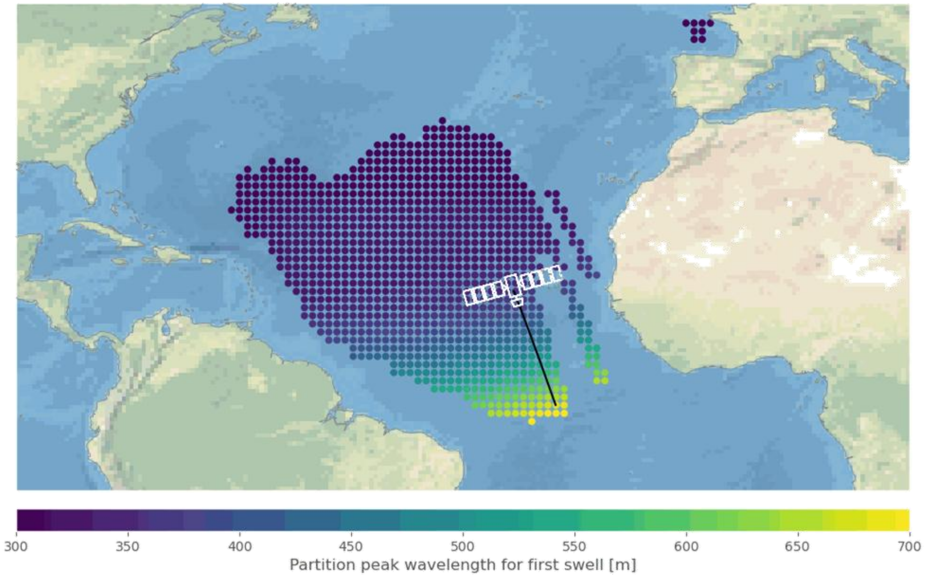
S6B, Hawaï (21° 28’ N, 154° 27’ W), 30/01/2026 16:56

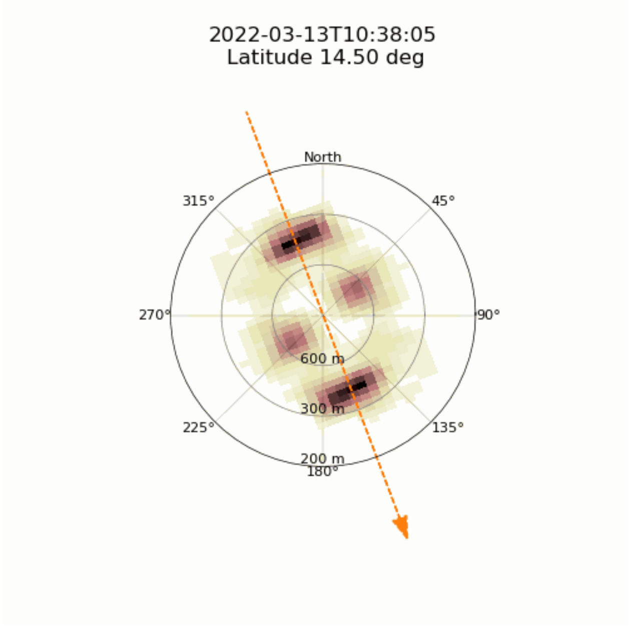
Computing mono-mission cross-spectra

By looking at the same scene with a small time difference and performing their cross-spectra, we can improve the SNR and remove the 180° degree ambiguity.

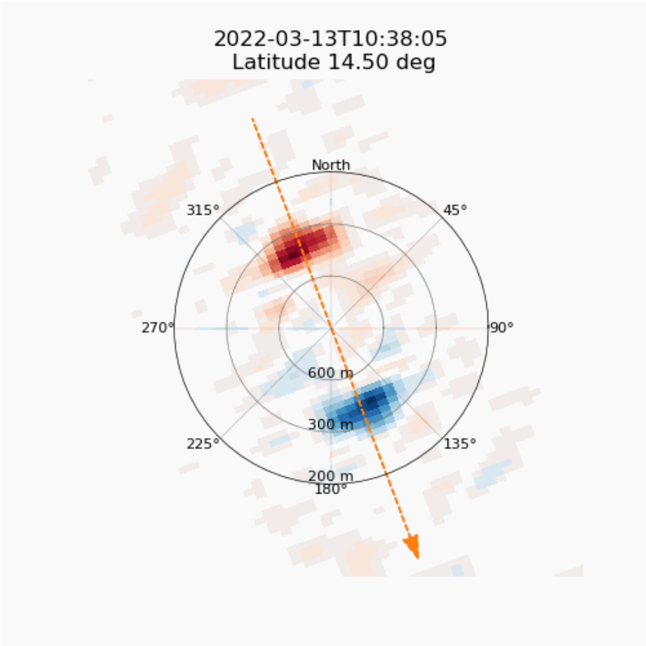
Mono-mission: 1 second difference

Storm product (S1/CFOSAT) + S6A





Blue corresponds to a positive phase

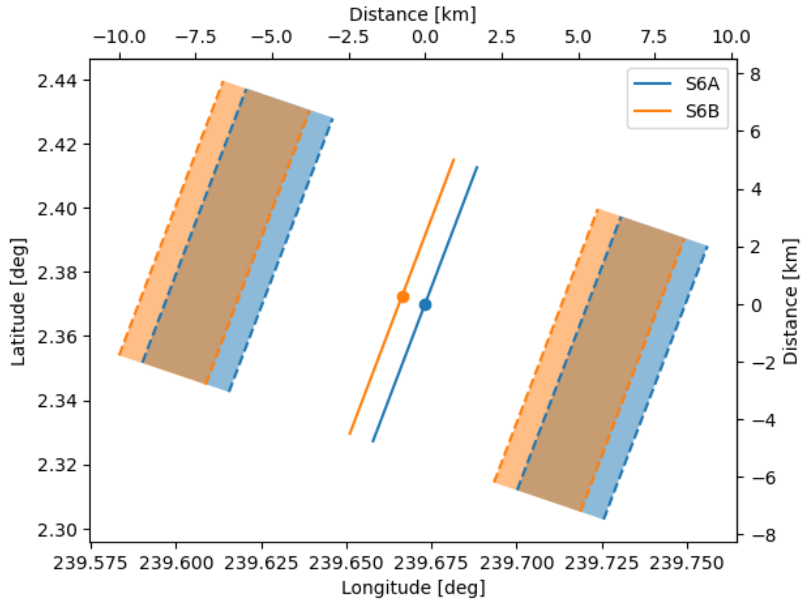


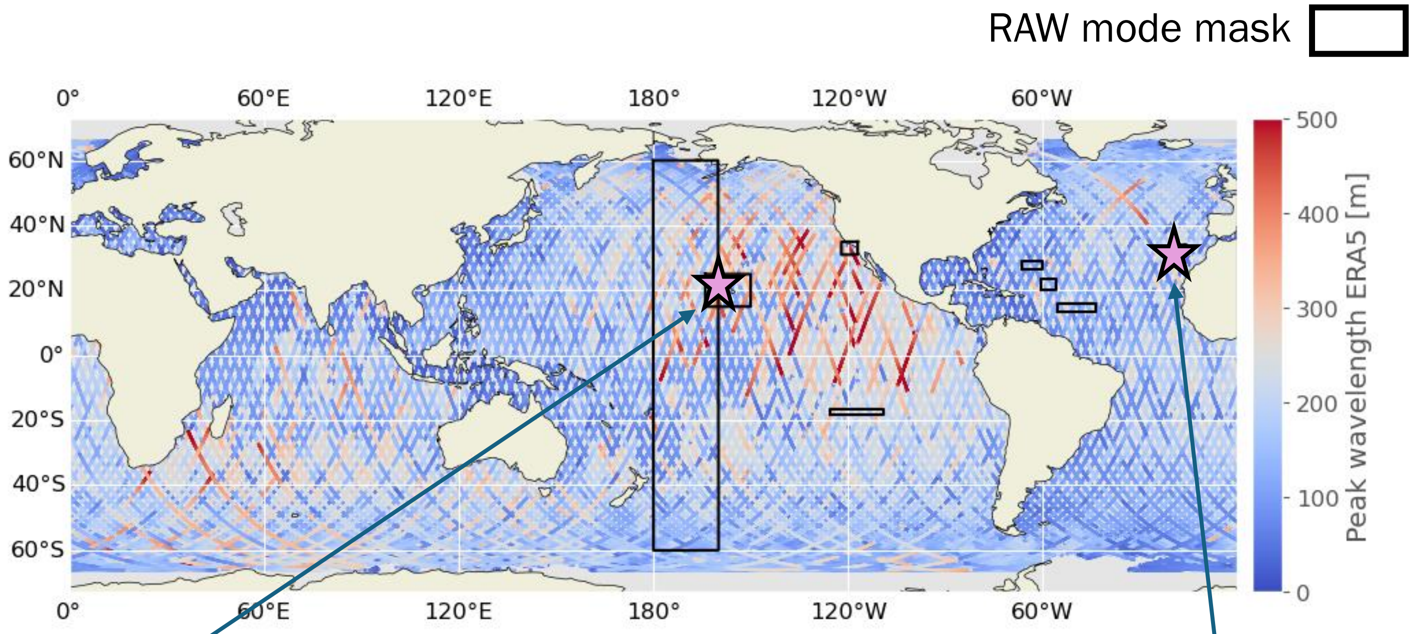
Storm product: Propagation toward the South, consistent with swell propagation after a storm

When the swell is along-track, the left-right ambiguity coalesces and the true partition can be found

Tandem phase: collocating data

We co-locate the two missions data and compute their time and cross-track difference at favorable sea.





Hawaï (21° 28’ N, 154° 27’ W), 30/01/2026 16:56
260 m cross-track difference
$\Delta t = 31$ s

Madeira (32° 59’ N, 17° 22’ W), 30/01/2026 07:30
235 m cross-track difference
$\Delta t = 31$ s

S6B: RAW data mask

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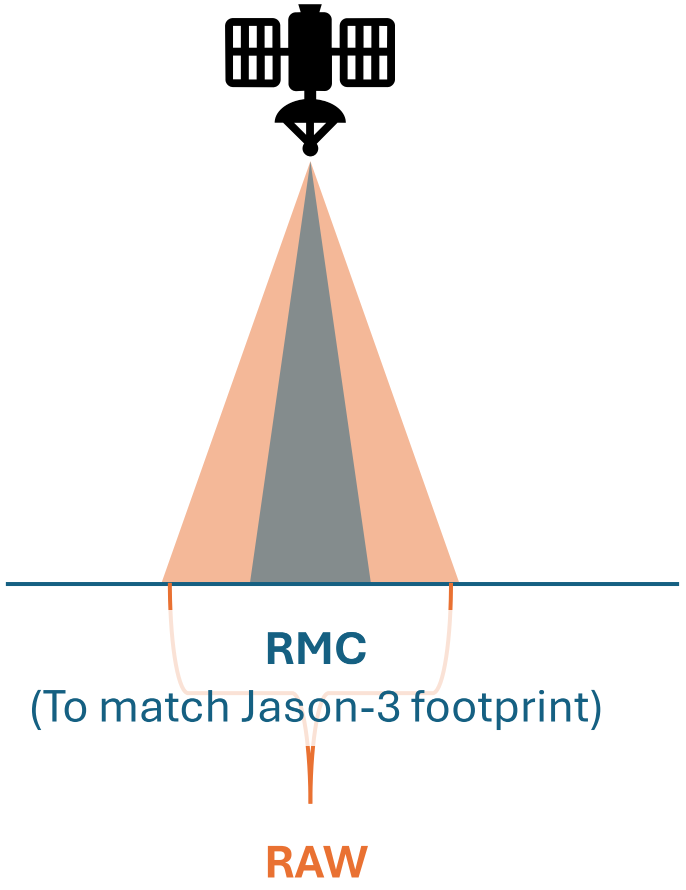
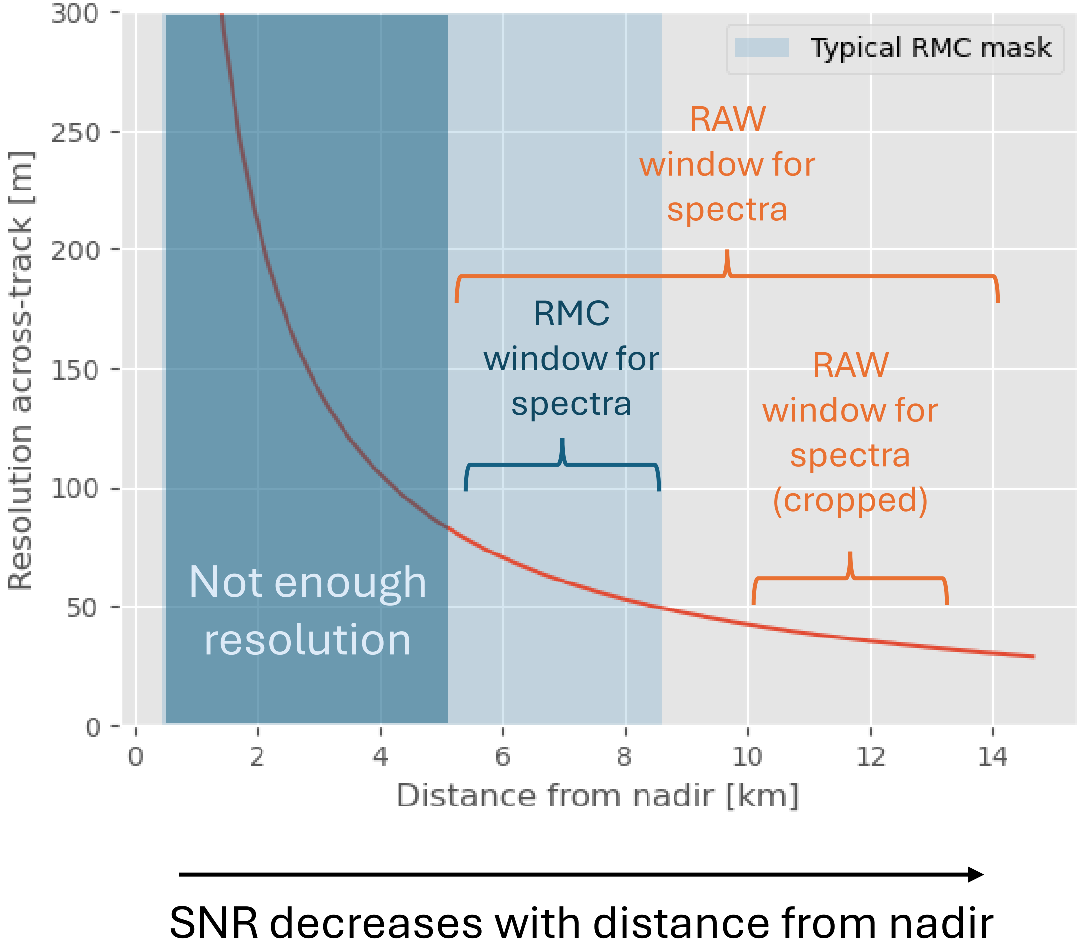
The RAW data increases the cross-track window, improves the cross-track resolution and decreases the range cut-off due to the larger incidence angle.





S6B: RAW data mask

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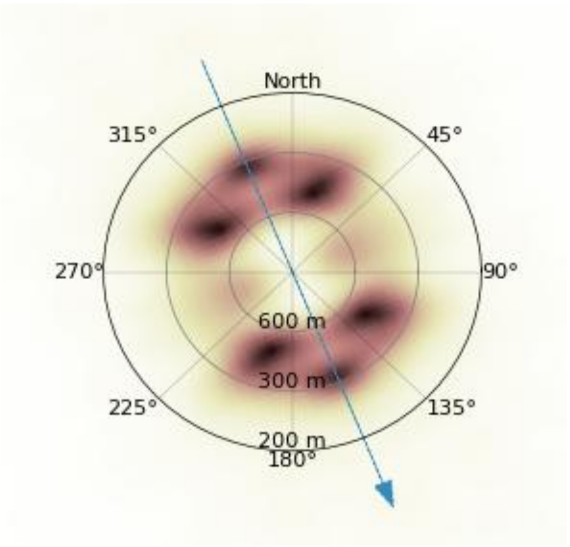
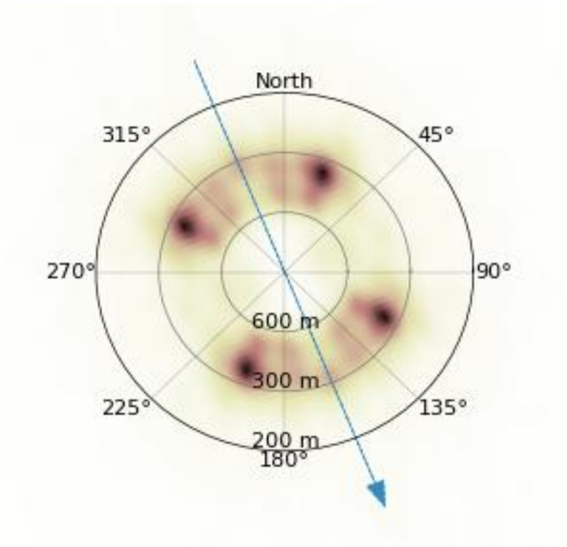
Illustration of the improvement due to RAW: thanks to the increased window (center) or just the increased resolution and incidence angle (right)

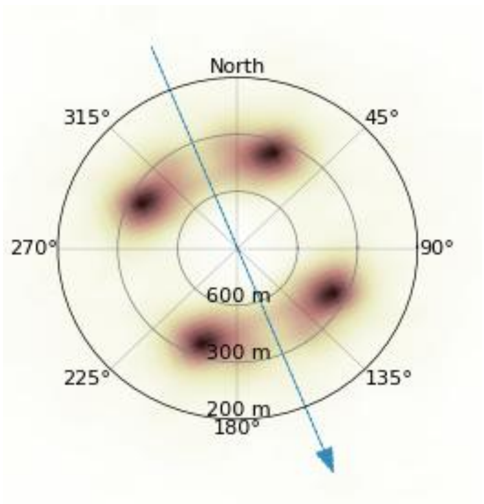
S6B (RMC)

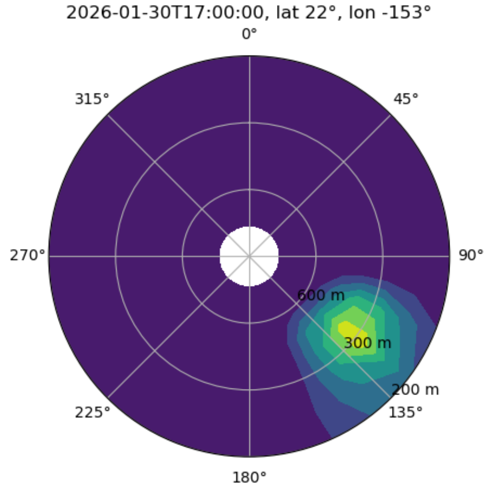


S6B (RAW)



S6B (RAW) cropped window





ERA5

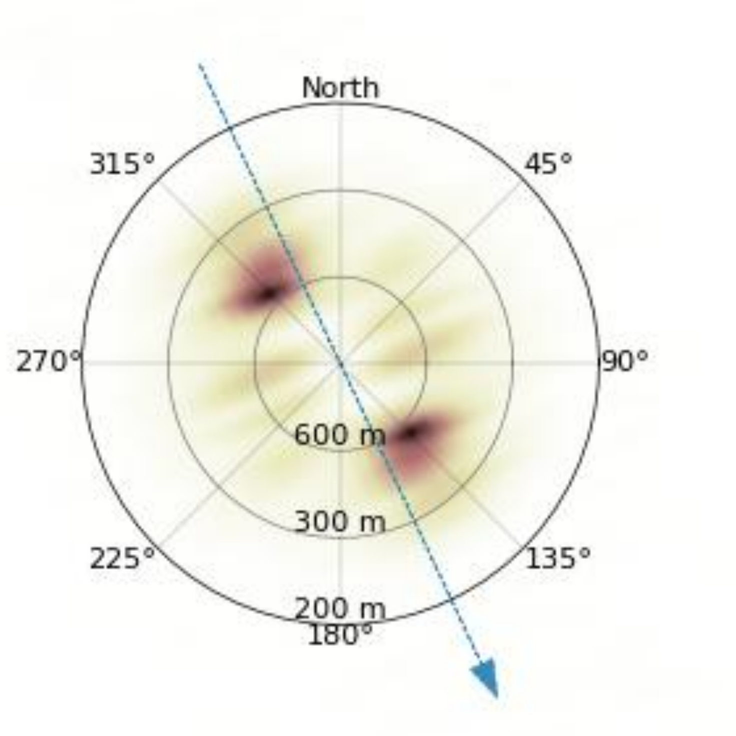
S6B, Hawaï (22° 0’ N, 153° 40’ W), 30/01/2026 16:56

S6B: RAW data mask

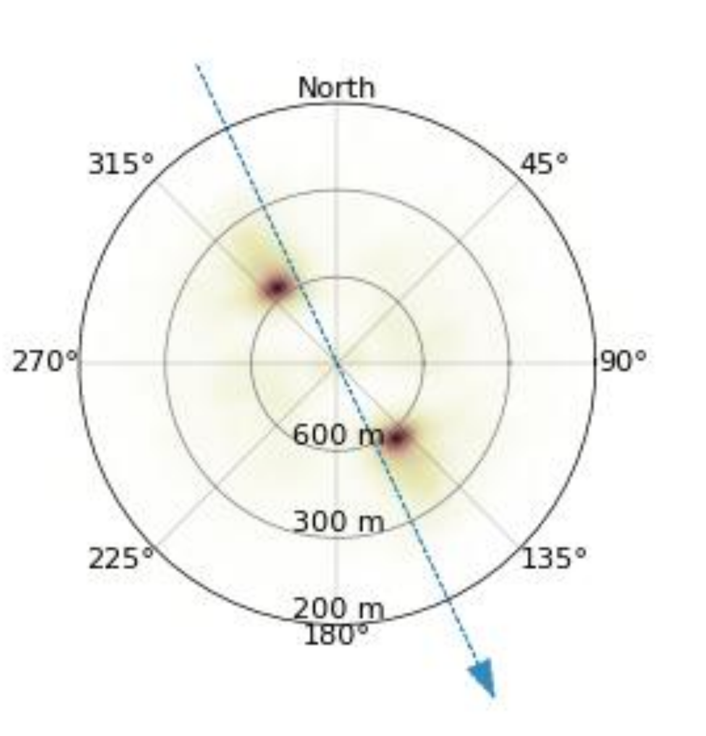
OSTST **2026**

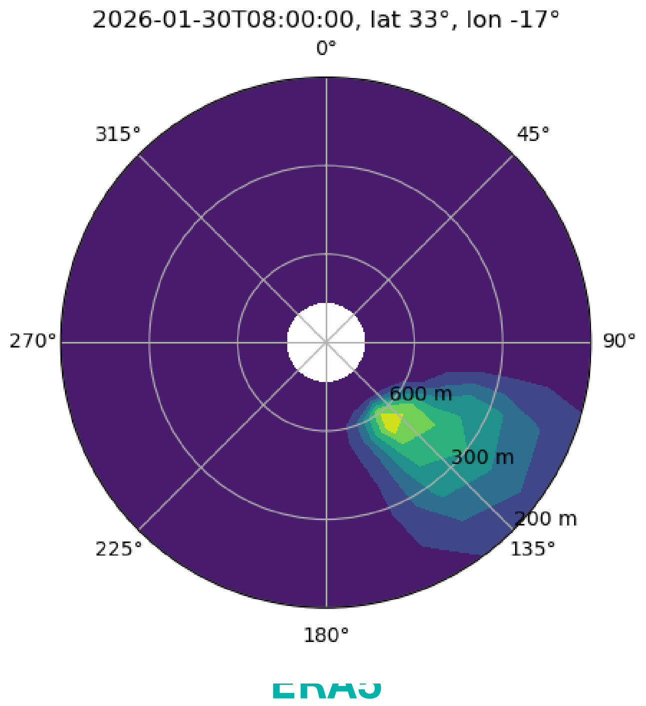
Illustration of the improvement due to RAW: even for along-track spectra, the improvement is significant!

S6B (RMC)



S6B (RAW)



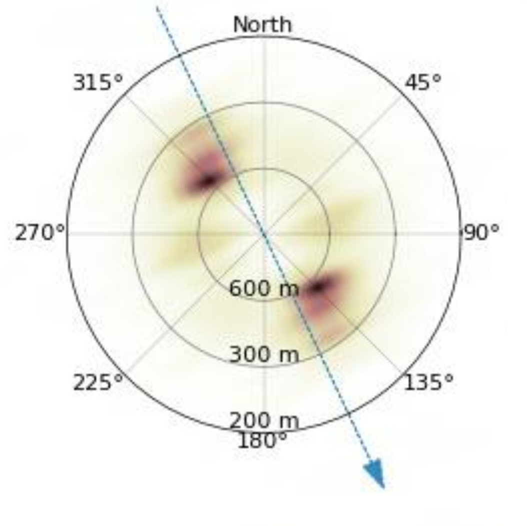


S6B, Madeira (32° 42’ N, 17° 11’ W), 30/01/2026 07:30

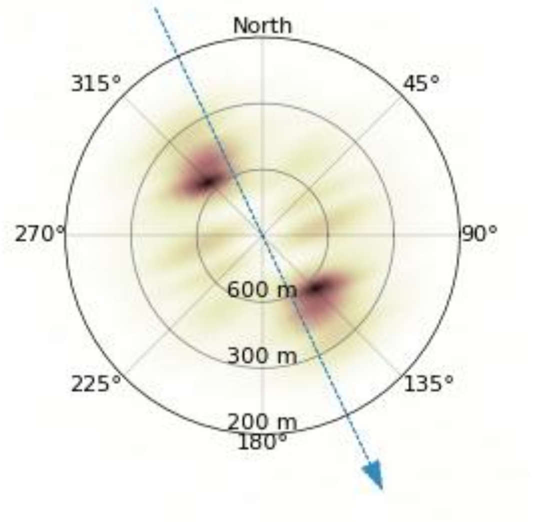
Tandem phase: comparing spectra

The spectra look qualitatively consistent, and the peak wavelengths and directions are within ~50 meters and ~20 degrees.

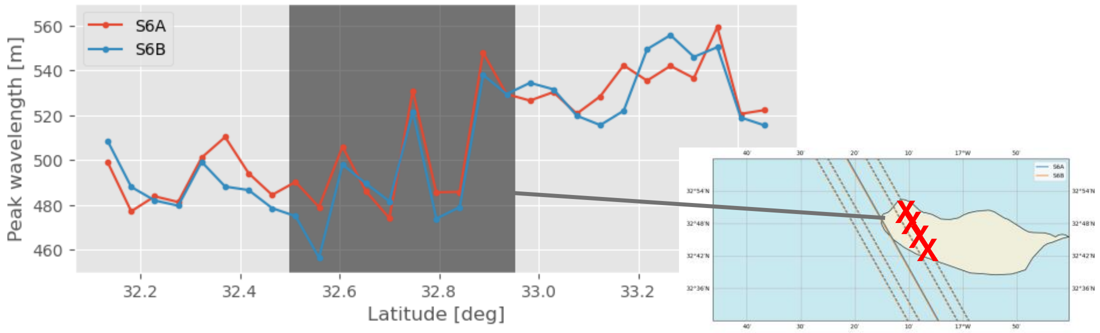
Madeira (32° 59’ N, 17° 22’ W), 30/01/2026 07:30



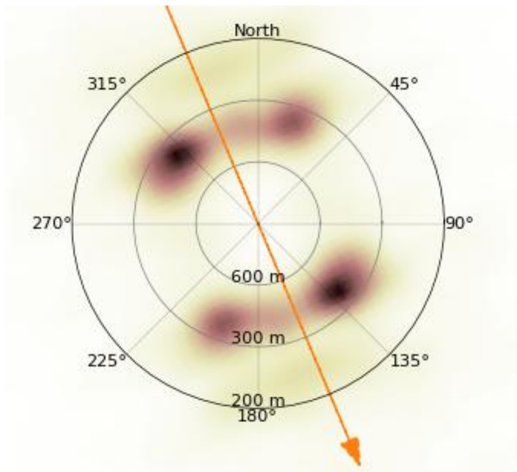
S6A



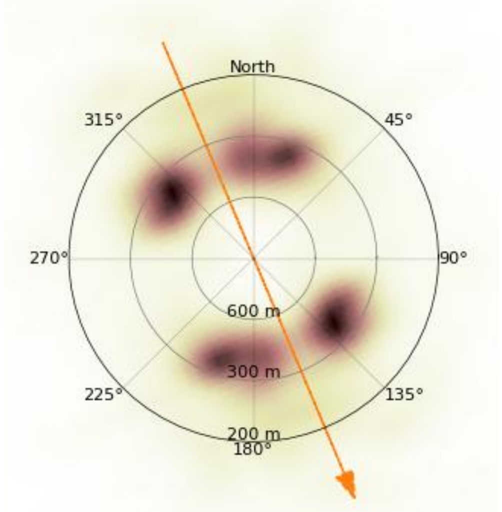
S6B



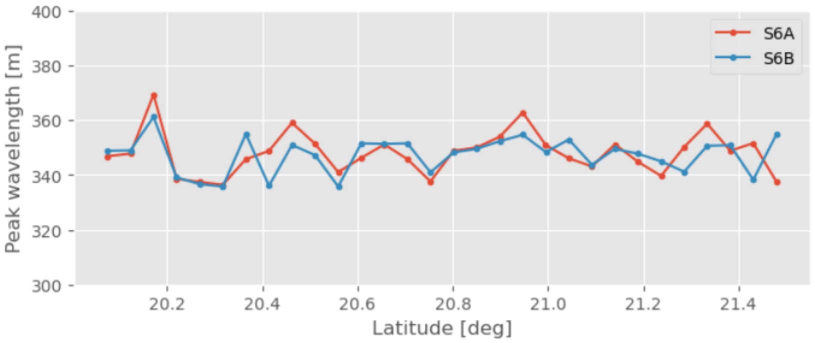
Hawaï (21° 6’N, 152° 52’W), 30/01/2026 16:56



S6A



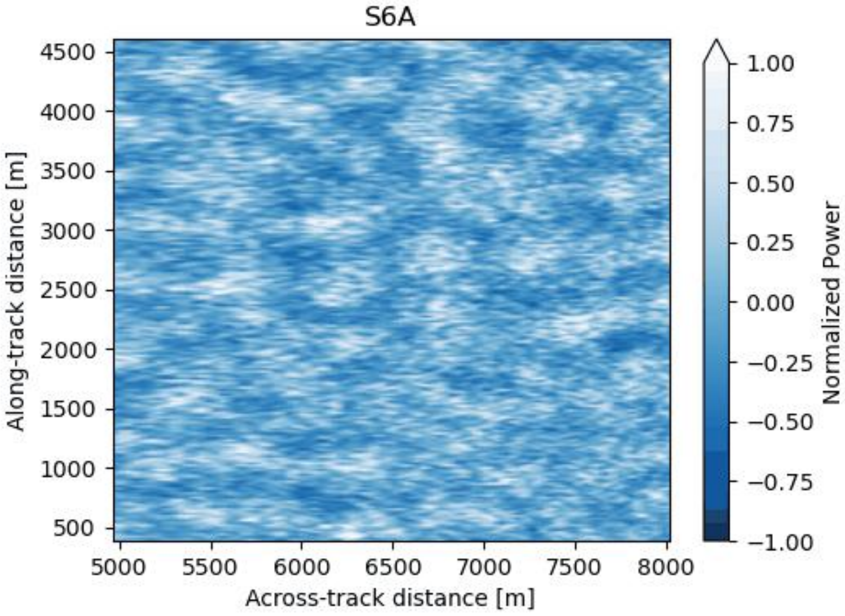
S6B

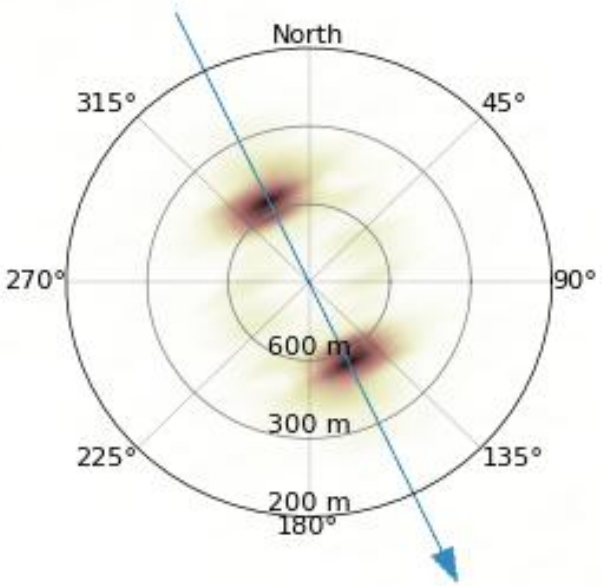


Tandem phase: computing cross-spectra

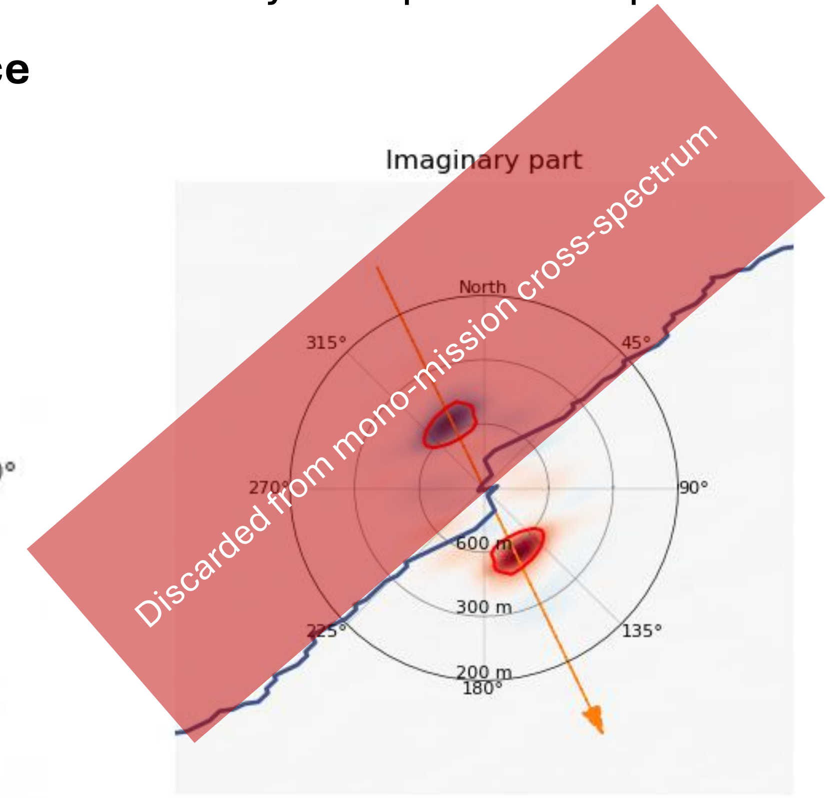
By looking at the same scene with a larger time difference and a small cross-track shift, we can improve the SNR and remove the 180° degree and left-right ambiguity by performing their cross-spectra and study their power and phase.

Tandem phase: 30 seconds difference





S6A – S6B



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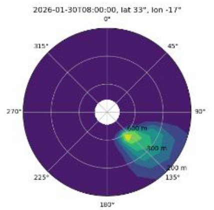


Madeira (32° 59’ N, 17° 22’ W), 30/01/2026 07:30

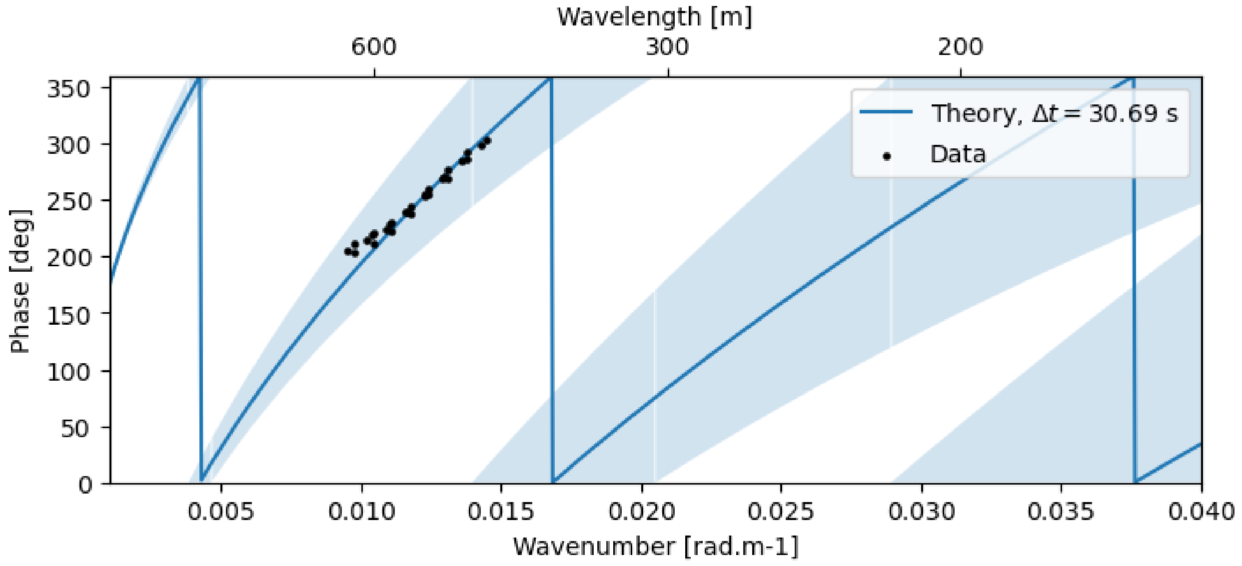
Tandem phase: analyzing the phase

By looking at the same scene with a larger time difference and a small cross-track shift, we can improve the SNR and remove the 180° degree and left-right ambiguity by performing their cross-spectra and study their power and phase.

Perfectly matches the theory: $\boldsymbol{\phi} = \boldsymbol{k}\, \boldsymbol{v_{\phi}}(\boldsymbol{k})\boldsymbol{\Delta t}$
with

$$\Delta t = 31 \text{ s}$$
$$v_{\phi} = \sqrt{g/k}$$

where v_{ϕ} is the phase velocity in deep depth conditions.



For along-track swells, the cross-track shift has no impact.

Tandem phase: analyzing the phase

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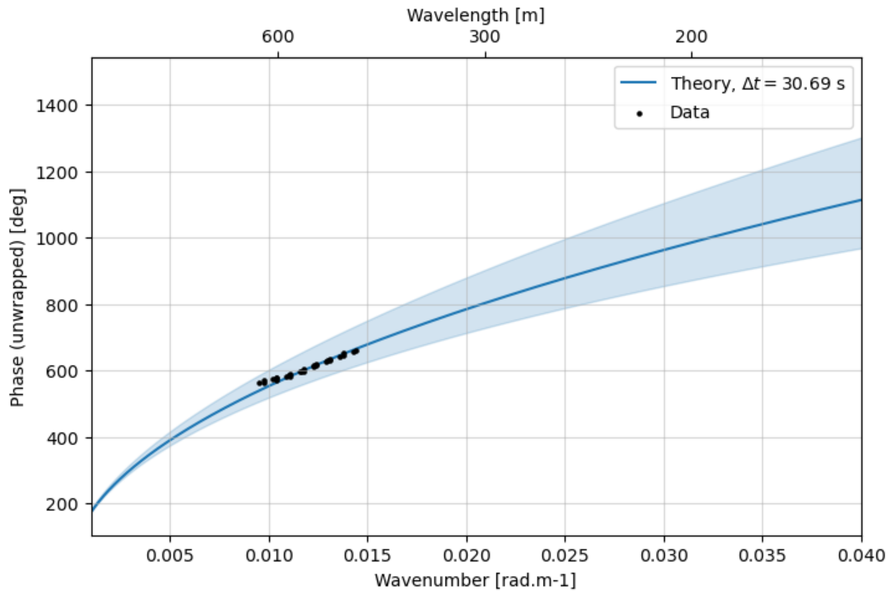
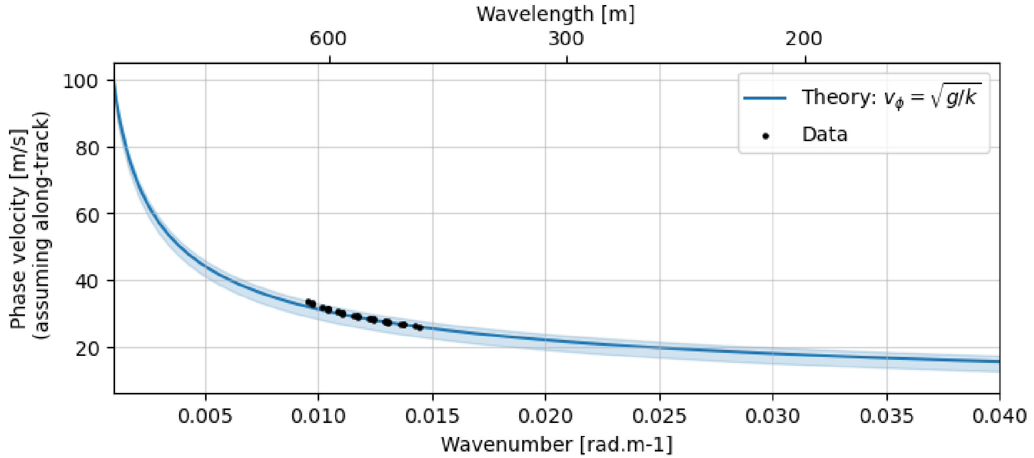
The theory gives $\boldsymbol{\phi = k\, v_\phi(k) \Delta t}$.

Conversely, we can use the phase to compute the swell phase velocity with $\Delta t = 31\, s$:

$$\boldsymbol{v_\phi(k) = \frac{\phi}{k\, \Delta t}}$$

We retrieve the theoretical dispersion relation of gravity waves on the surface of deep water!

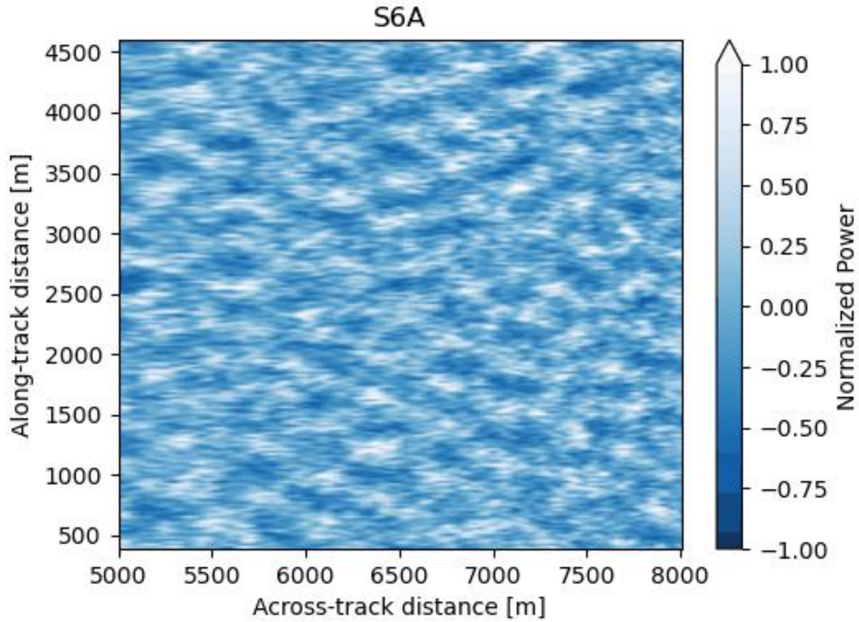


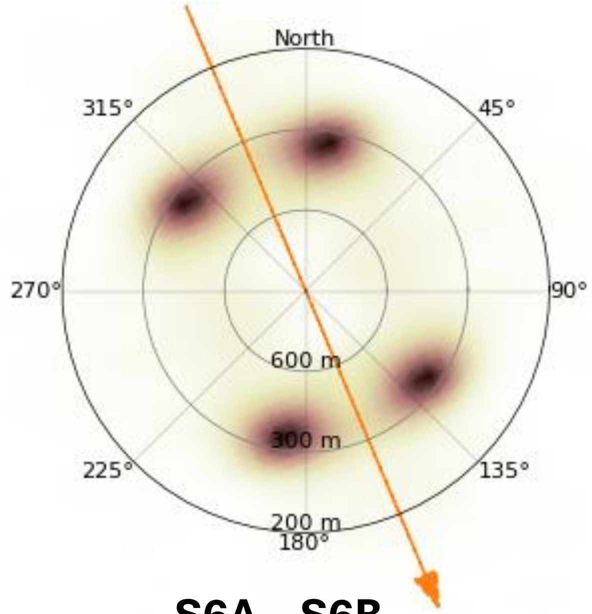


Tandem phase: computing cross-spectra

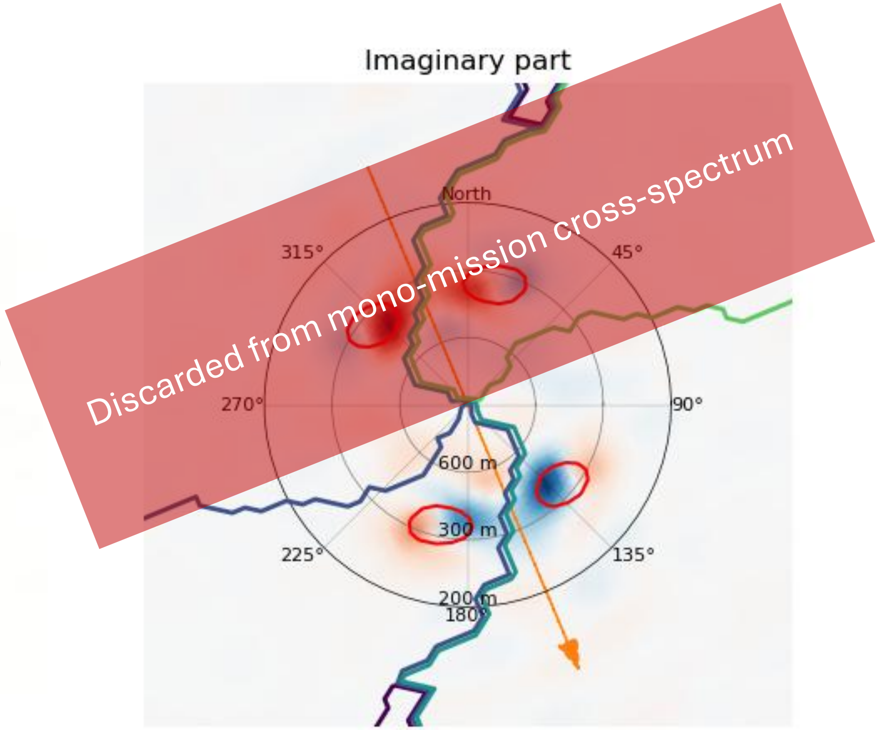
By looking at the same scene with a larger time difference and a small cross-track shift, we can improve the SNR and remove the 180° degree and left-right ambiguity by performing their cross-spectra and study their power and phase.

Tandem phase: 30 seconds difference





S6A – S6B



S6A, Hawaï (21° 28’ N, 154° 27’ W), 30/01/2026 16:56

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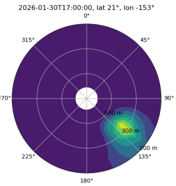


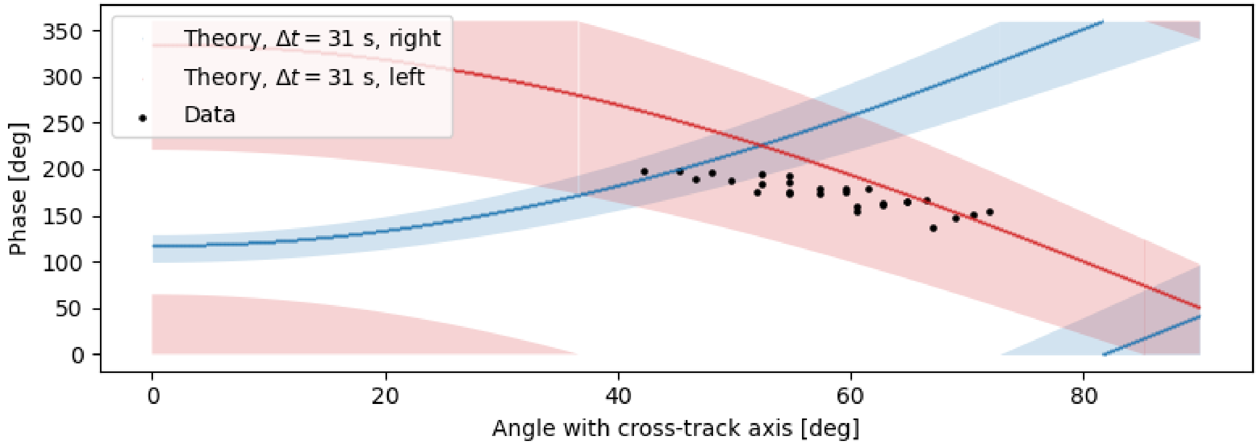
Tandem phase: analyzing the phase

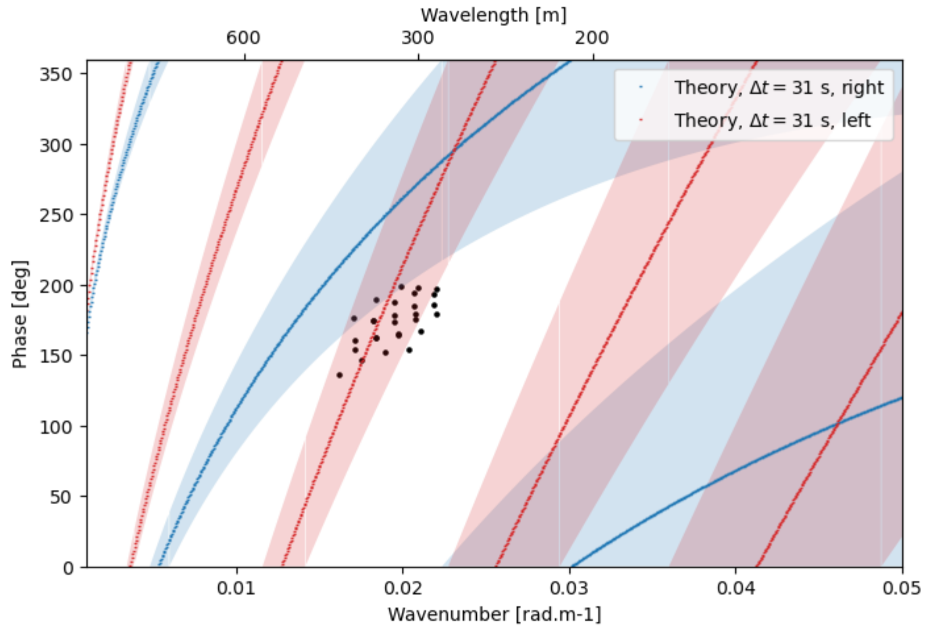
By looking at the same scene with a larger time difference and a small cross-track shift, we can improve the SNR and remove the 180° degree and left-right ambiguity by performing their cross-spectra and study their power and phase.

Theory (with $\Delta t = 31$ s, $\Delta d_{xt} = 260$ m and $v_\phi = \sqrt{g/k}$):

$$\boldsymbol{\phi = k\, v_\phi(k)\Delta t + k\,|\cos\theta|\,\Delta d_{xt}} \textit{ (if left propagation)}$$

$$\boldsymbol{\phi = k\, v_\phi(k)\Delta t - k\,|\cos\theta|\,\Delta d_{xt}} \textit{ (if right propagation)}$$

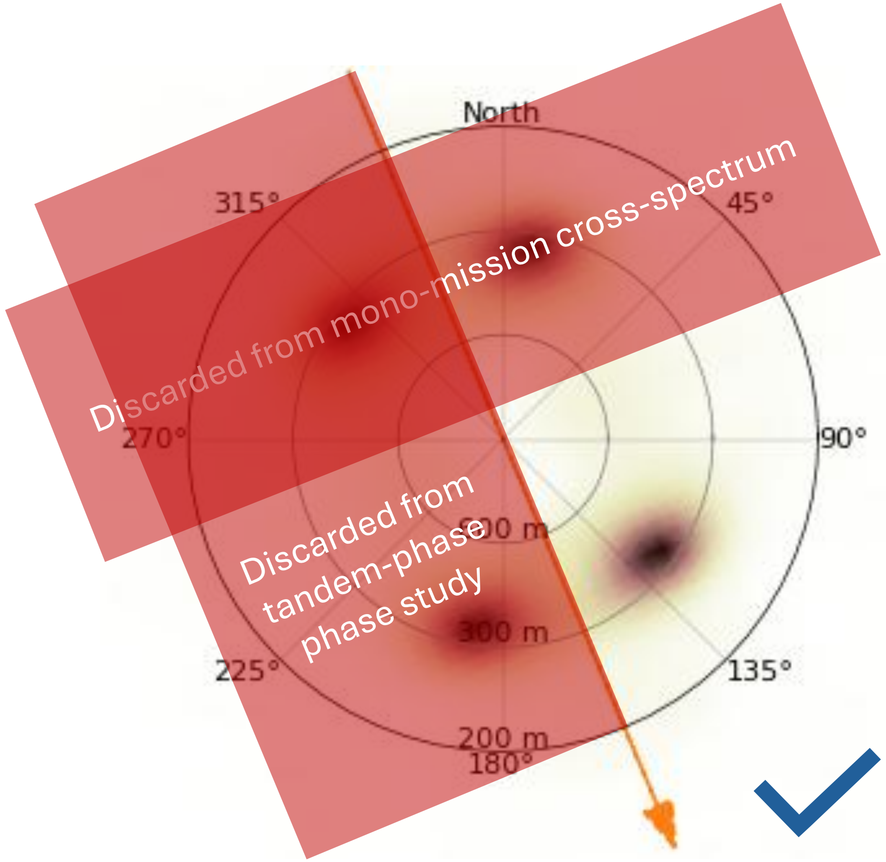




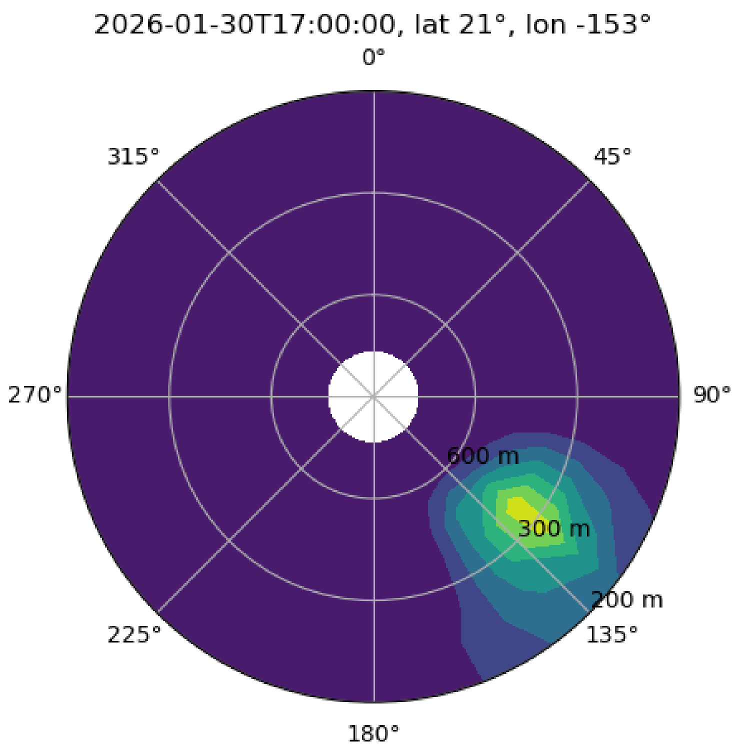
The data shows a better consistency with left propagation.

Tandem phase: analyzing the phase

Using the tandem phase, we effectively remove the left-right ambiguity!



S6A – S6B



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Conclusion: Thank you for your listening!

OSTST 2026

- In low to moderate sea state, the spectral analyses of SAR nadir altimetry radargram modulations and swath altimetry 2D data give a good proxy for the swell spectrum, allowing us to estimate its wavelength and direction (within ambiguities).
  "Noise" becomes information!

- We were able to remove the 180° ambiguity by computing cross-spectra between sublooks, in suitable cases (low wind and SWH).

- The tandem phase provides further validation and a way to remove the left-right ambiguity!

- The RAW mask, by giving access to a larger scene with a finer resolution, improves the spectral characterization.

- 2D directional spectrum can be provided from nadir altimetry offering valuable sea-state information, complementing SAR imagery and supporting new operational and scientific applications. Next generation altimeter missions (S6-NG and S3-NGT) are developing the capability to deliver these data products to meet evolving Copernicus user needs

➔ Contact: lrodet@groupcls.com

➔ Full analysis in Rodet et al. 2026, to be submitted

Supplementary material: Limitation

OSTST **2026**

In all missions, the resolution is also limited by cut-offs in both directions:

- **Along-track**: the vertical velocity spread due to the high velocities of wind waves is blurring the Doppler resolution (Altiparmaki et al. 2024)

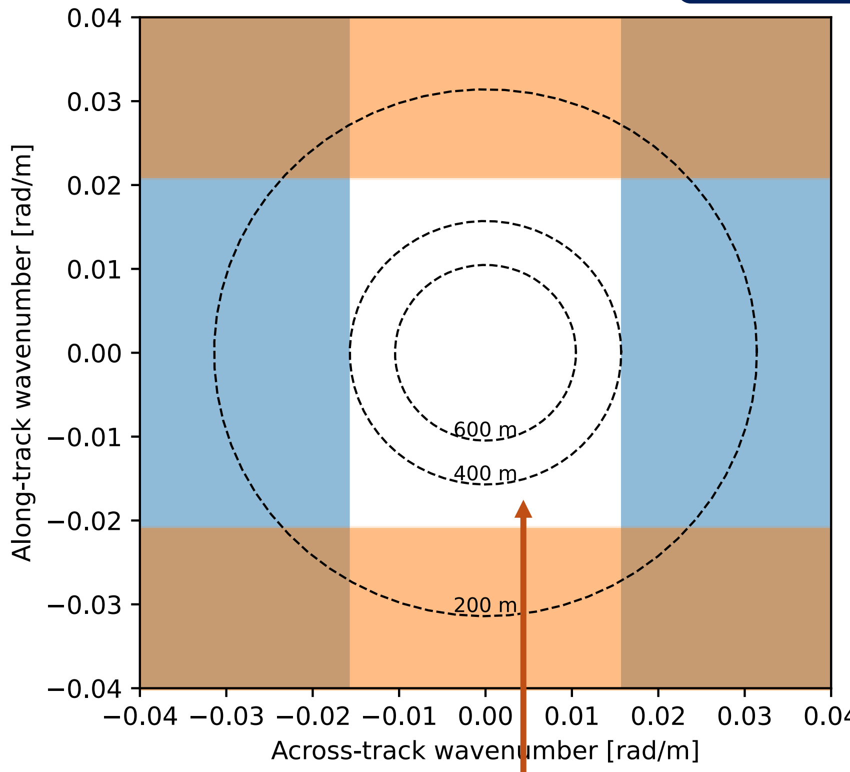
$$\lambda_{c,\mathrm{az}} = \pi \frac{H}{V} \sigma_v \approx 300\ \mathrm{m} \left(\frac{H}{1350\ \mathrm{km}}\right) \left(\frac{V}{7\ \mathrm{km.s^{-1}}}\right)^{-1} \left(\frac{\sigma_v}{0.5\ \mathrm{m.s^{-1}}}\right)$$

where H is the satellite altitude, V its velocity, $\boldsymbol{\sigma_v}$ **the vertical velocity variance**.

- **Across-track**: when the wave slope is greater than the look angle, the overlays and differences in surface areas captured in resolution cells become strongly non-linear

$$\lambda_{c,\mathrm{rg}} = \max\left(\pi \frac{SWH}{4\tan(\theta)}, \frac{c}{2\ \mathrm{B}\sin(\theta)}\right) \approx 400\ m \left(\frac{SWH}{2\ m}\right) \left(\frac{\theta}{0.25°}\right)^{-1}$$

where SWH is the Significant Wave Height, B the frequency bandwidth, c the velocity of light and θ the look angle.

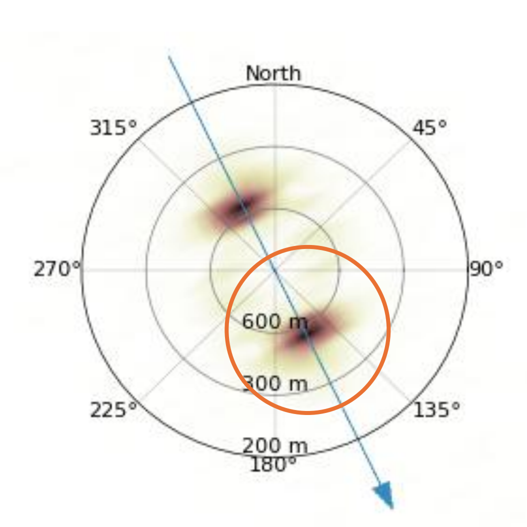


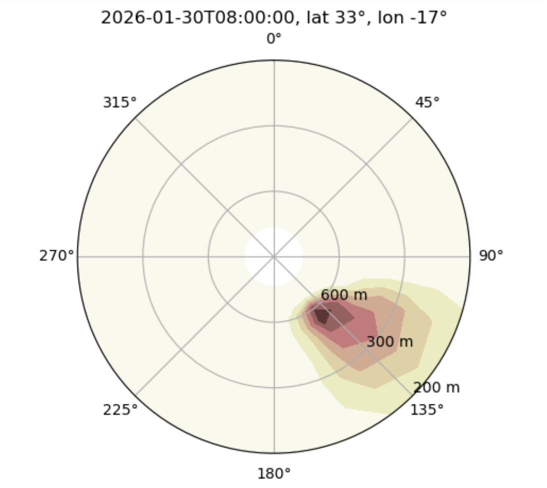
In a typical sea state, only this part of the spectrum is reliable

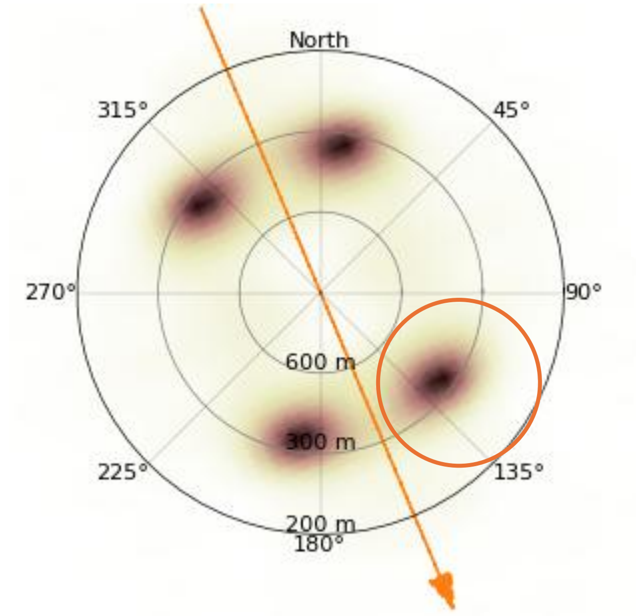
See Ourania Altiparmaki's poster for discussion around azimuth cut-offs in SAR altimetry !

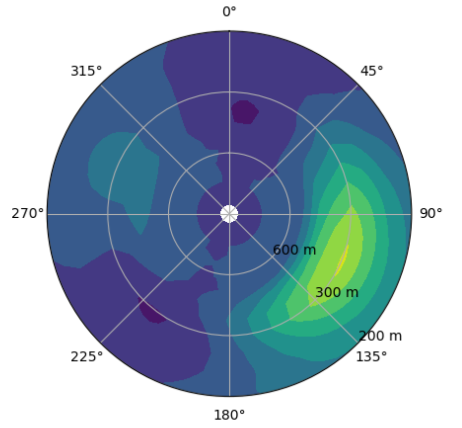
Supplementary material: validation

We compare our results to spectra from ERA5 wave model and NOAA buoys:

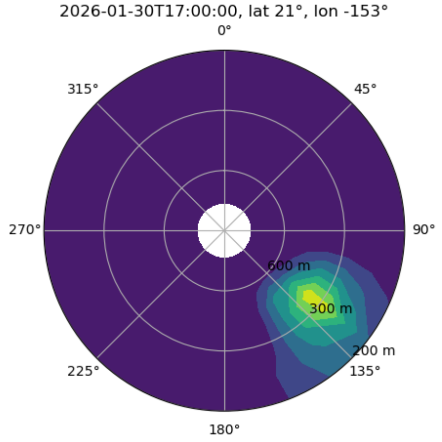








NOAA



ERA5

See our presentations in the 2025 EUMETSAT workshop and 30 year of altimetry symposium for validation with Sentinel-1, Sentinel-3 and CFOSAT crossovers.

Supplementary material: Detection

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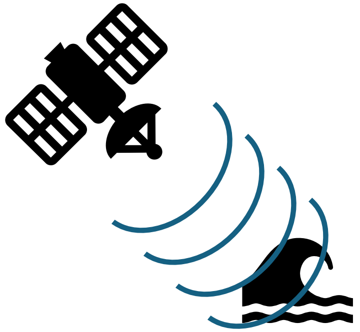
Range

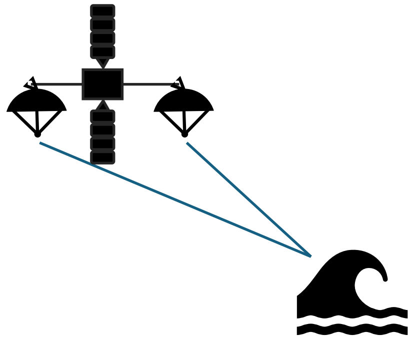


Sentinel-1

Sentinel-3

Sentinel-6

CRYOSAT-2

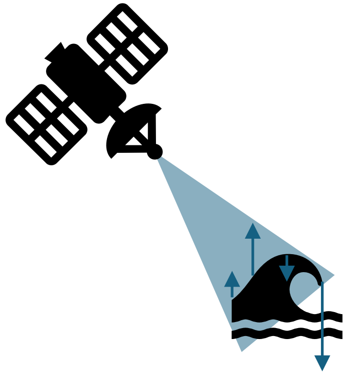


SWOT

S3NG-T

→ Range bunching due to the surfboard effect becomes chaotic when wave slopes are steeper than the incidence angle: cross-track cut-off $\lambda_{c,\mathrm{rg}} \propto SWH/\theta$

Velocity (via Doppler effect)



Sentinel-1

Sentinel-3

Sentinel-6

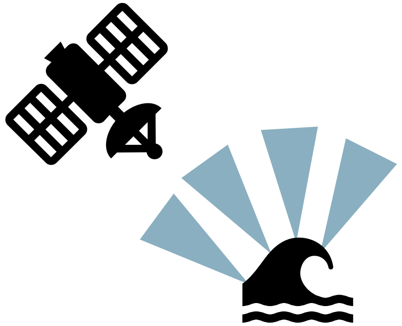
CRYOSAT-2

SWOT

S3NG-T

→ Velocity bunching due to the fast-moving wind waves blurs the azimuth measurement: along-track cut-off $\lambda_{c,\mathrm{az}} \propto H\ \sigma_v$

Tilt



CFOSAT

Sentinel-1

SWOT

S3NG-T

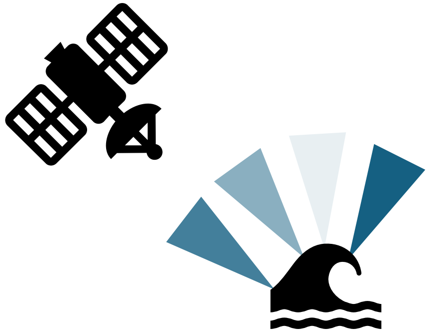
Sentinel-3

Sentinel-6

CRYOSAT-2

second order

Backscatter ("Hydrodynamic") (usually negligible for waves)



Sentinel-1

Sentinel-3

Sentinel-6

CRYOSAT-2

CFOSAT

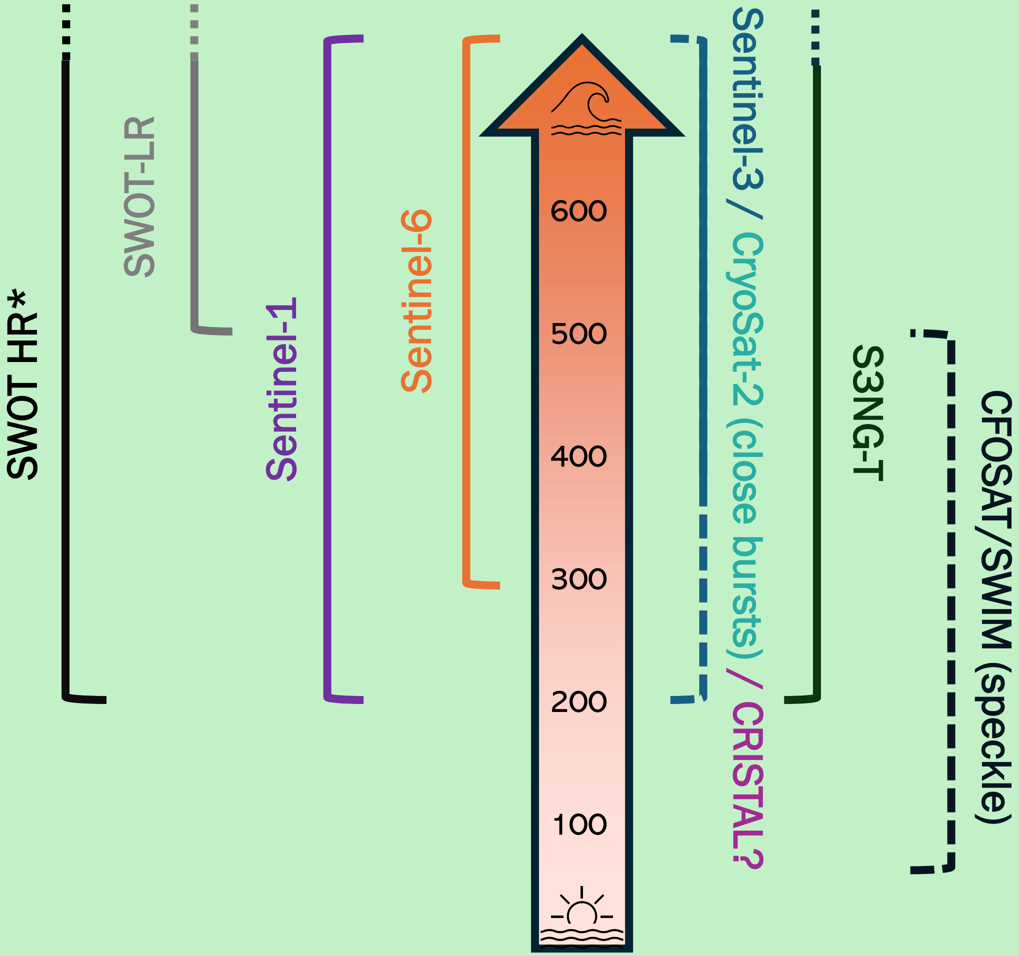
SWOT

S3NG-T

Supplementary material: Comparison

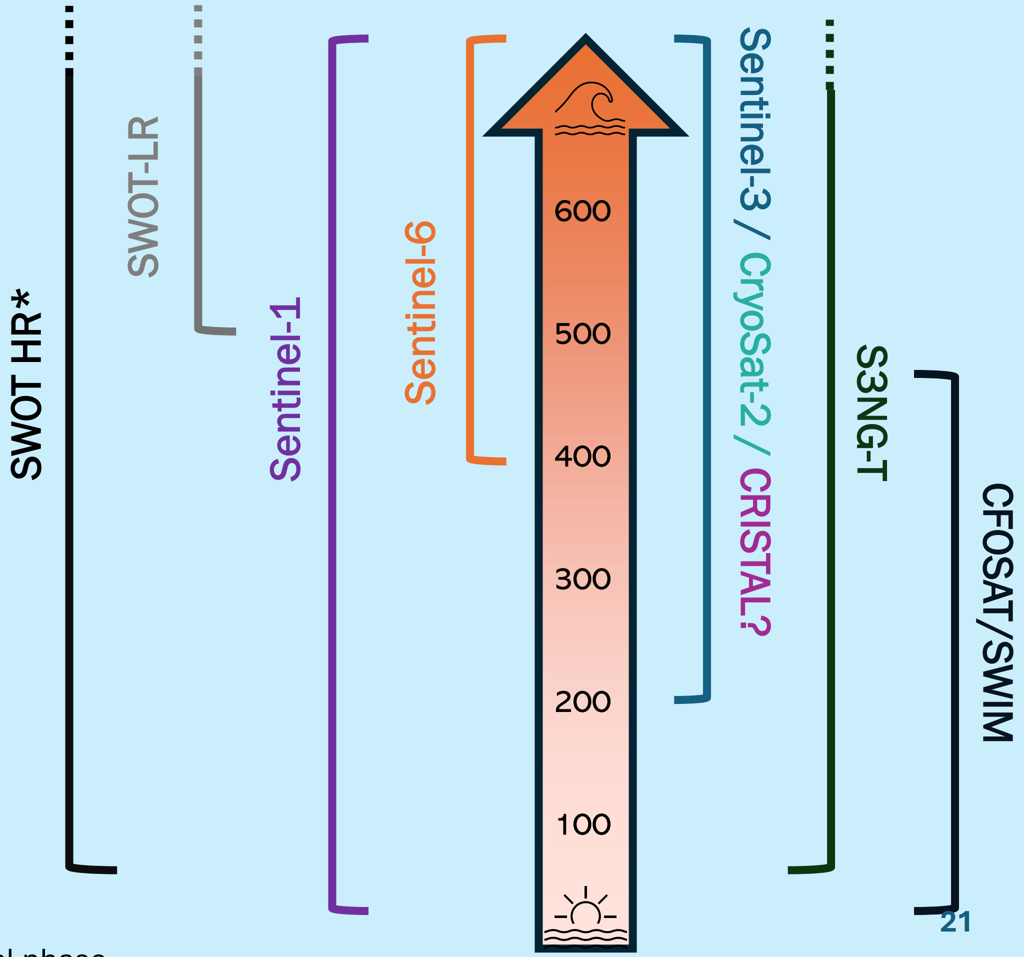
Along-track

Limited by azimuth cut-off due to wave velocities
Mostly impacted by wind and altitude



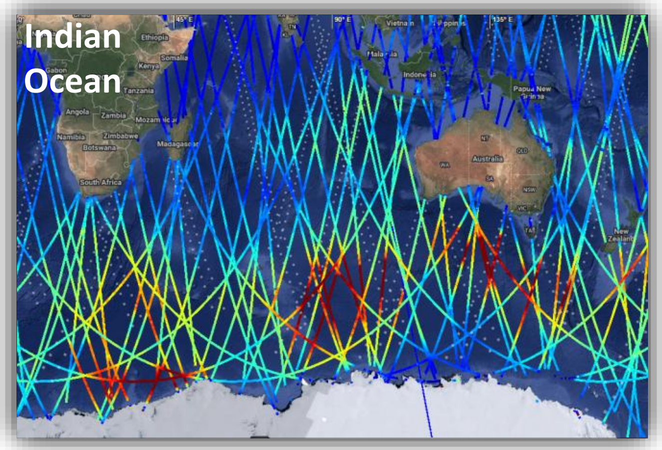
Across-track

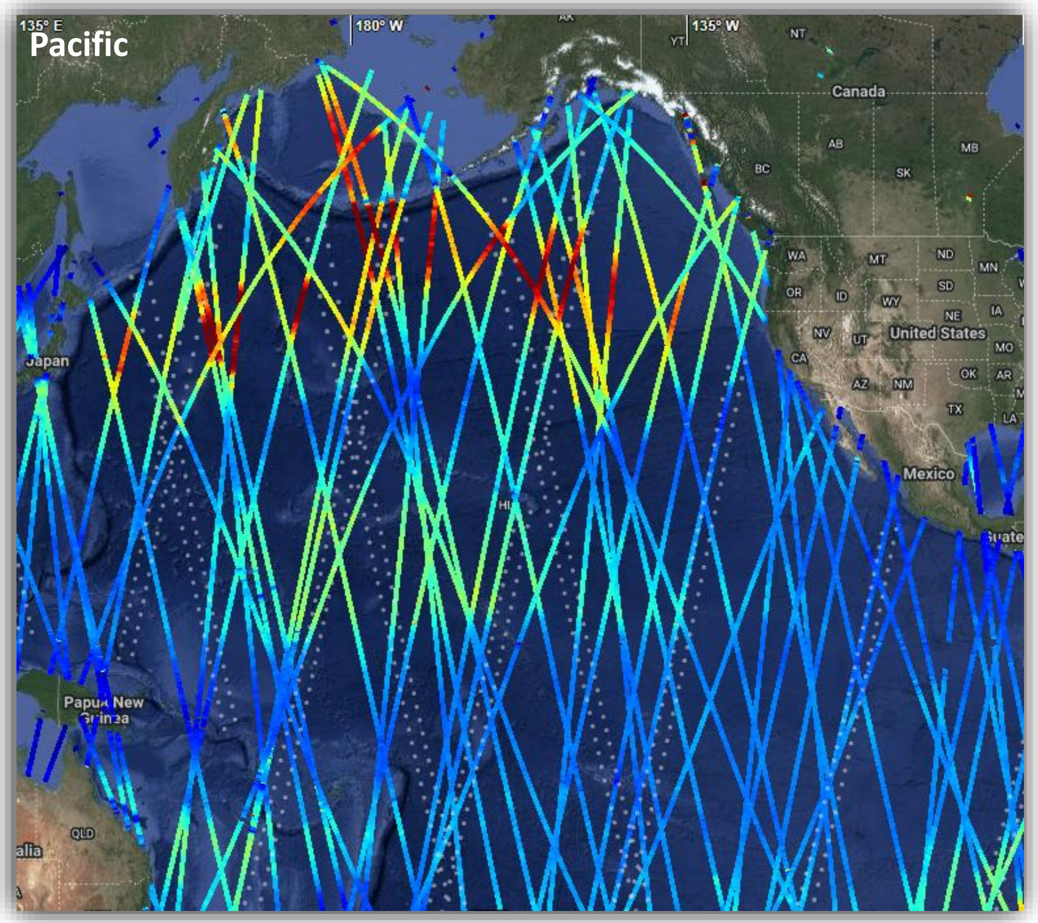
Limited by range cut-off due to wave heights and slopes
Mostly impacted by SWH and incidence angle



*Limited to the calval phase

Supplementary material: Coverage





S1 + CFOSAT + SAR ALTIMETERS

Credit to Ourania Altiparmaki