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TAKING THE PULSE
OF OUR PLANET FROM SPACE

Response of GNSS reflected signals to wave spectra across cyclones

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- On GNSS-Reflectometry (GNSS-R)
- Question
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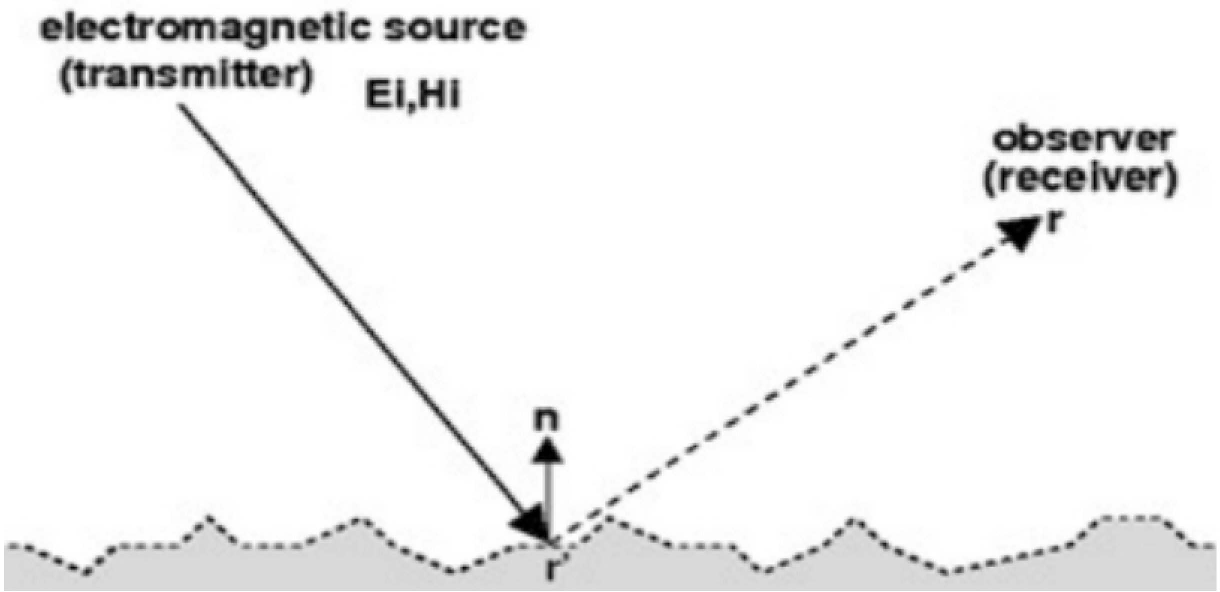
- Case study: GNSS-R Data
- Case stuty: 2D Wave Model
- Preliminary results

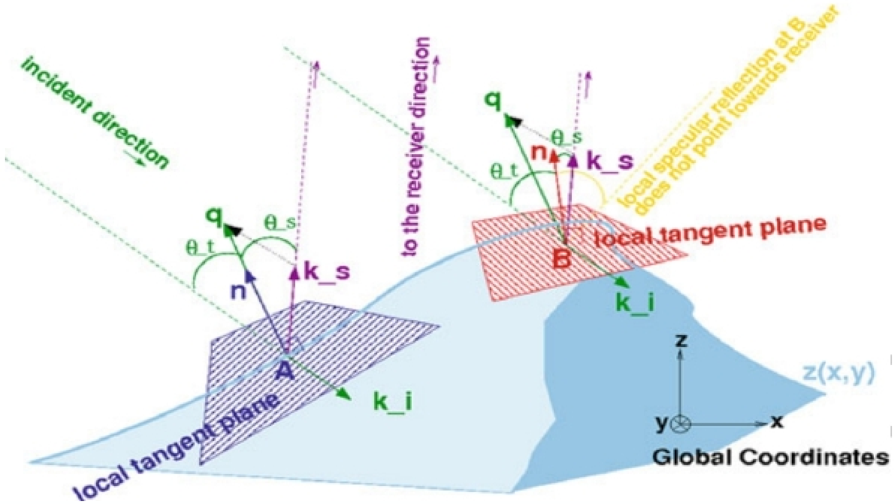
GNSS-R

- Reflectometry using satellite navigation signals (GNSS-R): bistatic forward scattering at L-band (λ_{EM}~19 cm)

GNSS satellite

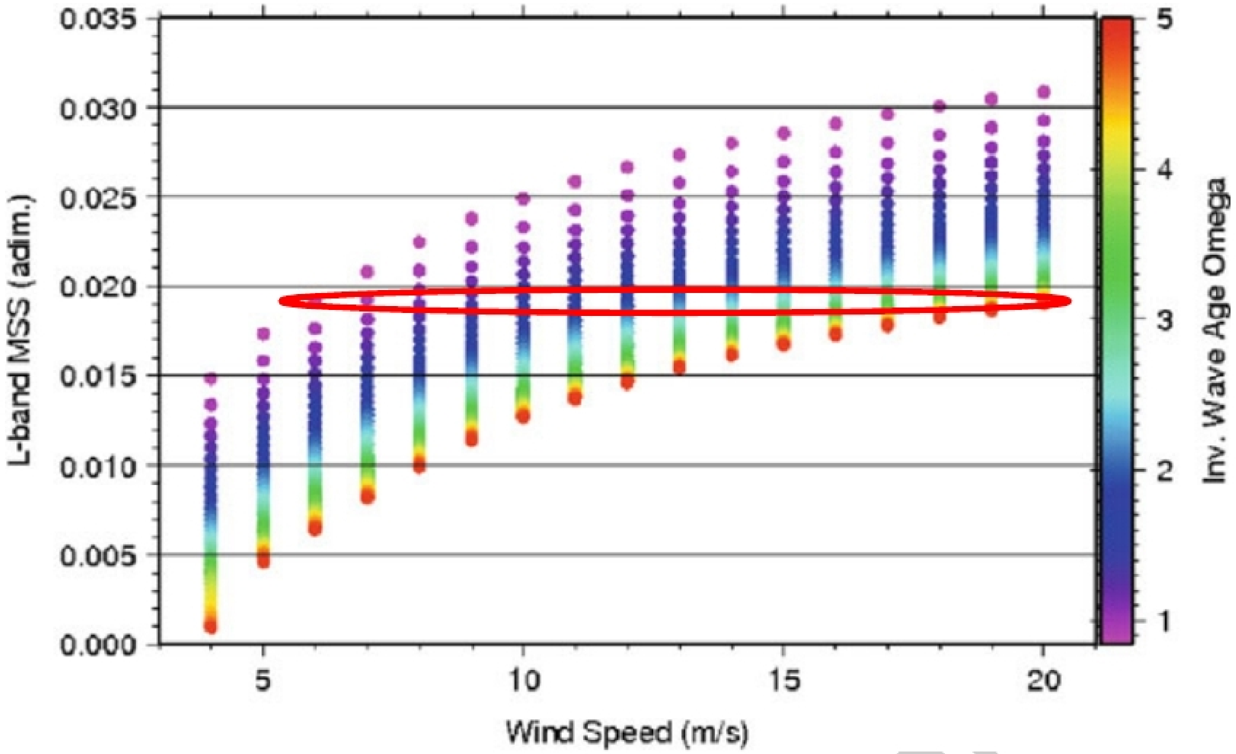


GNSS-R signals are **sensitive to L-band filtered surface roughness** ($\lambda_{sea} \geq 3\,\lambda_{GNSS}$ ~ 0.6m).



GNSS-R

- The statistics of this filtered roughness, through **mean squared slopes (mss),** depend on **combination** of different variables: wind, fetch, waves age, swell...



Using Elfouhaily et al., 1997 spectrum

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Question

- In tropical cyclones, **complex wave structure**: different wave trains of different fetches/ages juxtapose, non-linear effects…
- Does it make sense to **‘invert’** the observables into one of the combined variables (e.g. wind speed)?

QUESTION:
How to use GNSS-R observables around tropical cyclones?

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Suggested answer

- Here we suggest to **avoid 'inversion' schemes** (GNSS-R depends on several variables).

Instead, perhaps the **assimilation of the 'observable'** into complex wave models could get the most of them

Note that the 'observable' is not an oceanographic variable

Suggested answer

- To assimilate an observable, such as σ_0, into numerical models, the observable must be expressed as a **forward operator of the state variables x** of the model. $\sigma^0_{mod} = H[\vec{x}]$
- A variational approach to data assimilation then consists of minimization of a cost function J:

$$J(\vec{x}) = \frac{1}{2}(\vec{x}-\vec{x}_B)^T \underbrace{B^{-1}}_{\text{Covariance of the numerical ocean model}} (\vec{x}-\vec{x}_B) + \frac{1}{2}(\sigma^0_{obs}-\sigma^0_{mod}(\vec{x}))^T(\underbrace{E}_{\text{Covariance of the observations}}+\underbrace{F}_{\text{Covariance of the forward operator H[x]}})^{-1}(\sigma^0_{obs}-\sigma^0_{mod}(\vec{x}))$$

The approach corrects anomalies not originally captured in the numerical model: pre-fit residuals or (O-B).

Certain degree of agreement required for the approach to converge.

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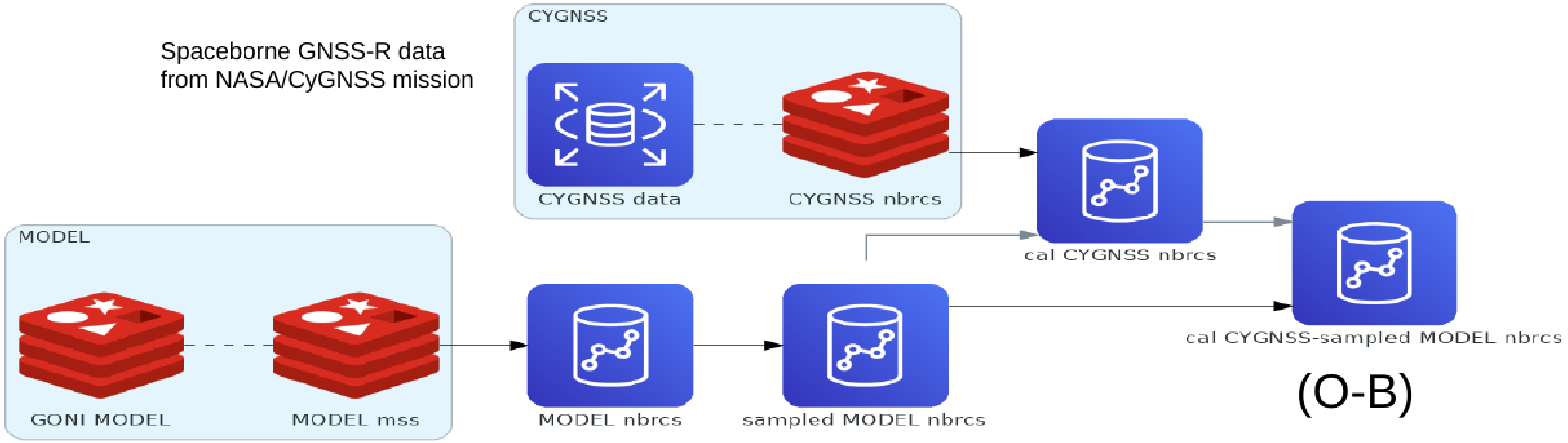
Methodology

- The goal of this initial exercise is to check whether spaceborne GNSS-R observables, σ_0, across TC are sufficiently close to the equivalent σ_0, estimated by a complex wave model.
- This is the first and required condition for future assimilation of σ_0 in such type of models.
- A case example is presented: Goni typhoon.



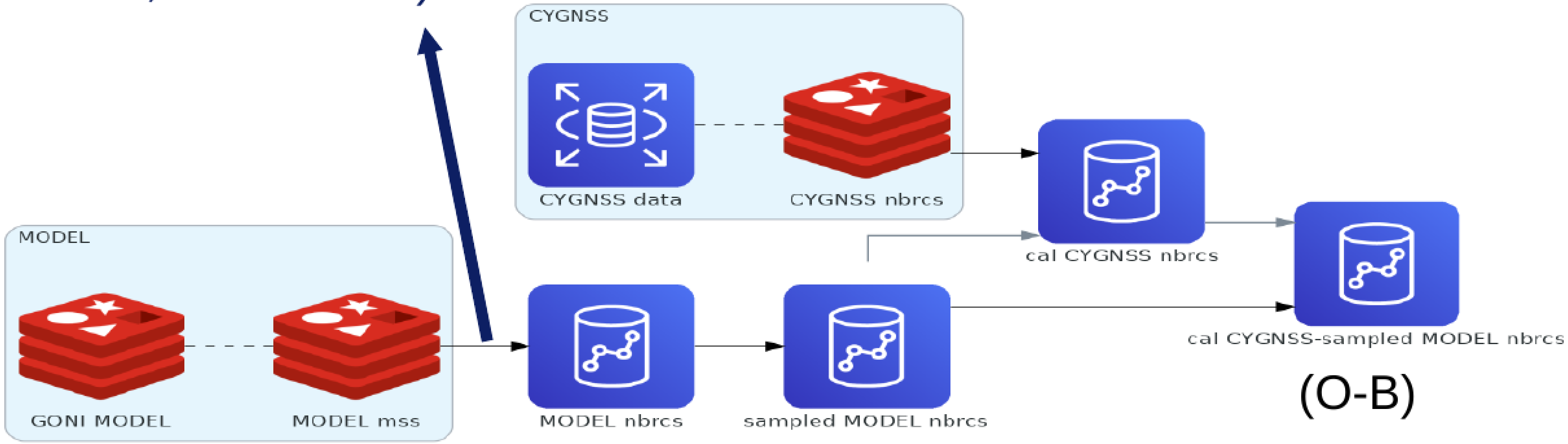
Spaceborne GNSS-R data from NASA/CyGNSS mission

Two-dimensional parametric model for wave development under a varying wind field

Methodology

- Why not assimilating GNSS-R measured mss?

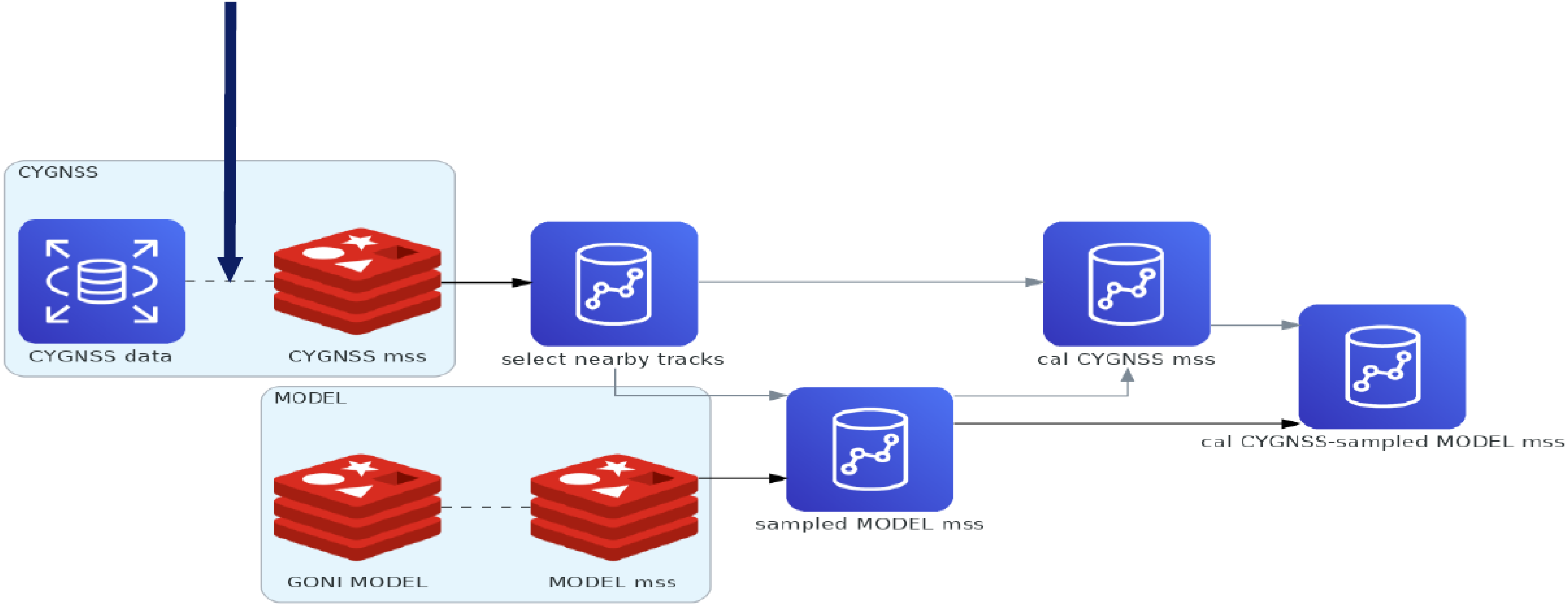
PDF(slopes): the model has all required information (e.g., Gram-Charlier, binormal, Gaussian...)



(O-B)

Methodology

PDF(slopes): assumed by the ‘data provider’ in the inversion procedure → Gaussian



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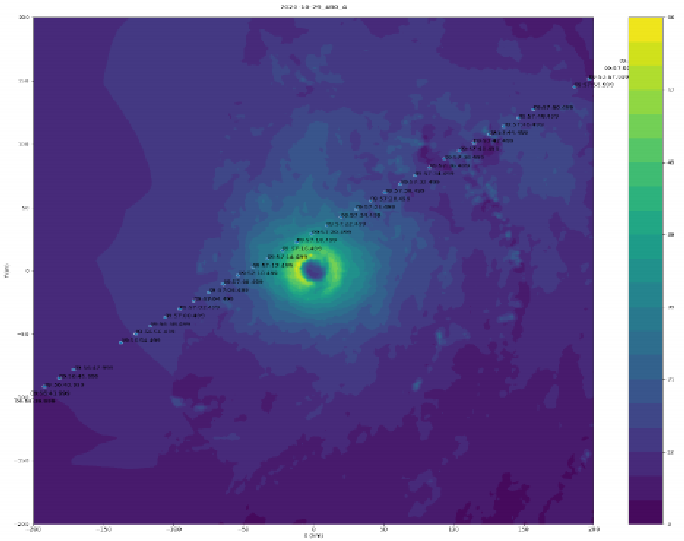
Case study: GNSS-R data

- Case study for Goni Typhoon 2020-10-29
- **GNSS-R data**:
  - Level 1b NBRCS (σ_0) NASA/CyGNSS
  - 3 tracks crossing Goni on 2020-10-29/30

2020-10-29_480_4



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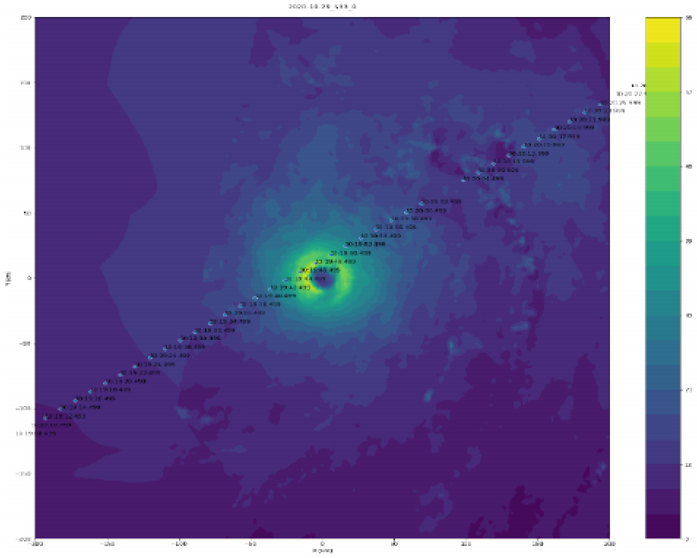

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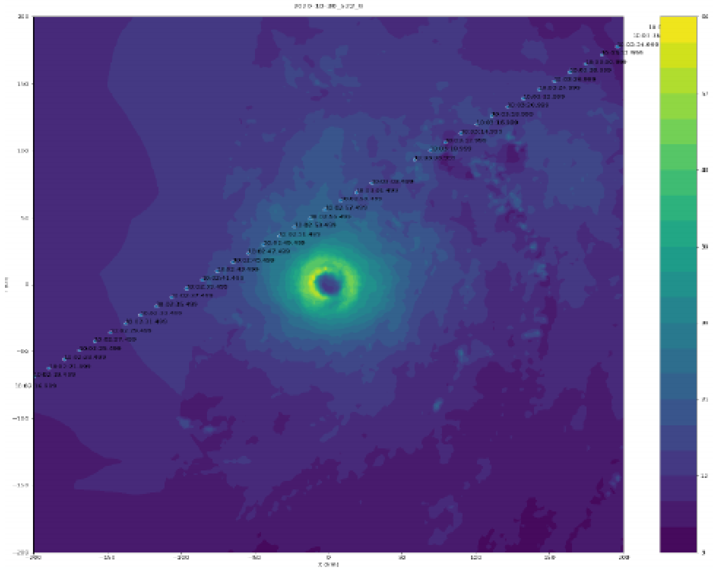

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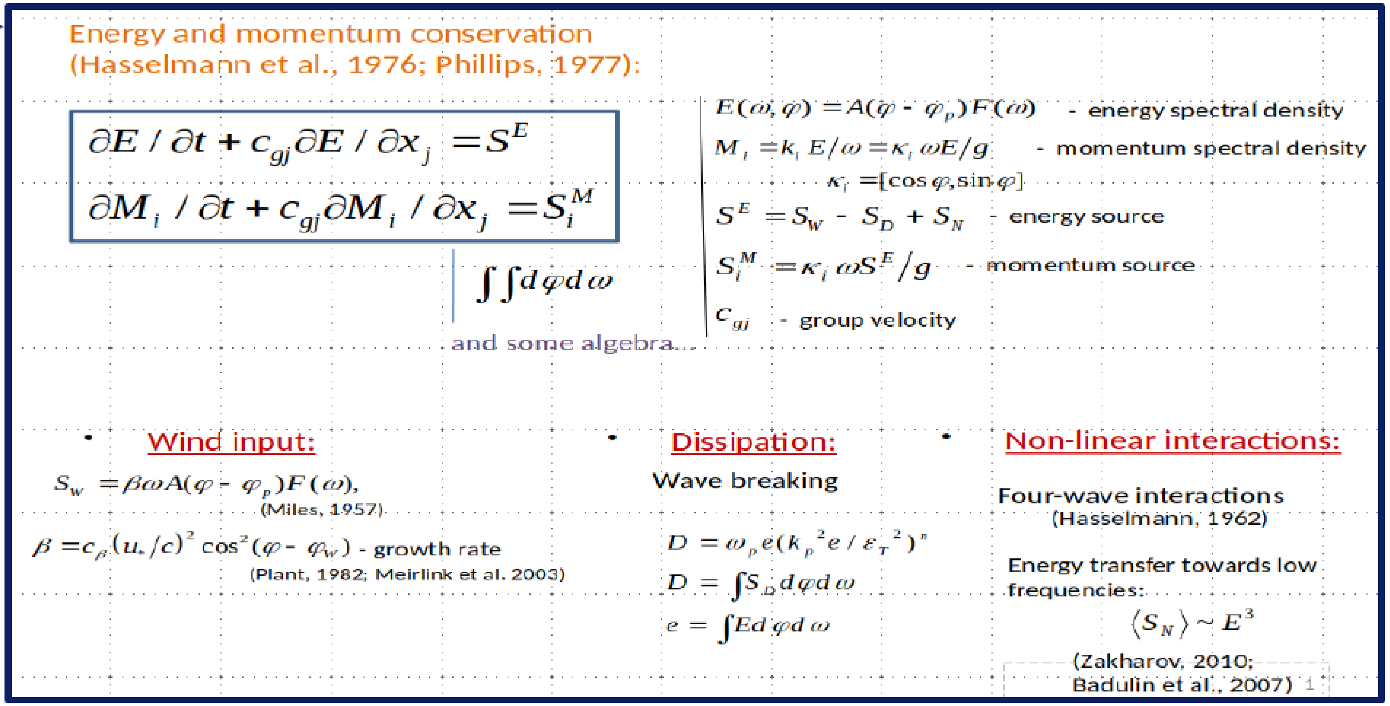
Case study: 2D wave model

Two-dimensional parametric model for wave development under varying wind field

(Kudryavtsev, Yurovskaya & Chapron, 2021)

- The system describes the development of surface waves under a varying wind field in both space and time, and the evolution of swell propagation in the absence of wind forcing.
- Input: 2D wind field at 1 km resolution from Sentinel-1 SAR images (provided by IFREMER).
- Governing Equations: →



Energy and momentum conservation (Hasselmann et al., 1976; Phillips, 1977):

$$\partial E / \partial t + c_{gj} \partial E / \partial x_j = S^E$$

$$\partial M_i / \partial t + c_{gj} \partial M_i / \partial x_j = S_i^M$$

$$\int\int d\varphi d\omega$$

and some algebra...

$E(\omega,\varphi) = A(\varphi - \varphi_p)F(\omega)$ - energy spectral density

$M_i = k_i E/\omega = \kappa_i \omega E/g$ - momentum spectral density

$\kappa_i = [\cos\varphi, \sin\varphi]$

$S^E = S_W - S_D + S_N$ - energy source

$S_i^M = \kappa_i \omega S^E / g$ - momentum source

c_{gj} - group velocity

- Wind input:

$S_W = \beta\omega A(\varphi - \varphi_p)F(\omega)$,

(Miles, 1957)

$\beta = c_\beta (u_*/c)^2 \cos^2(\varphi - \varphi_W)$ - growth rate

(Plant, 1982; Meirlink et al. 2003)

- Dissipation:

Wave breaking

$D = \omega_p e(k_p{}^2 e / \varepsilon_T{}^2)^n$

$D = \int S_D d\varphi d\omega$

$e = \int E d\varphi d\omega$

- Non-linear interactions:

Four-wave interactions (Hasselmann, 1962)

Energy transfer towards low frequencies:

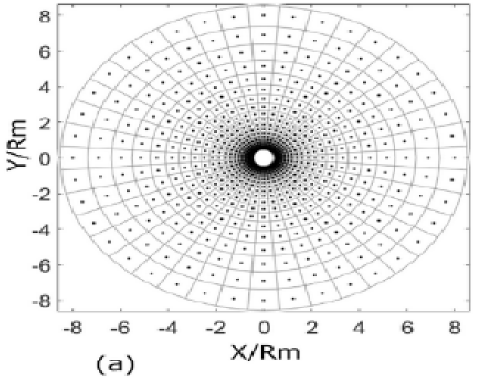
$\langle S_N \rangle \sim E^3$

(Zakharov, 2010; Badulin et al., 2007)

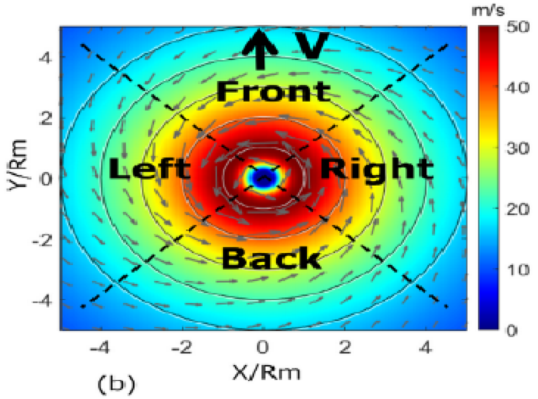
Case study: 2D wave model

- The model is solved in the storm frame of reference.
- Each wave train location and wave parameters (peak frequency, energy and direction) at each moment of time are obtained with the use of 4th order Runge-Kutta scheme.
- Wave-rays visualize how wave trains develop and travel through the TC varying wind field, and how they leave the storm area as swell systems.
- The wave train with maximal wave length/energy in a given grid cell can be treated as the primary wave system. Each grid cell can be considered to analyze multiple wave systems and their time evolution.
- For this exercise: we used the L-band filtered mss, at each grid cell.

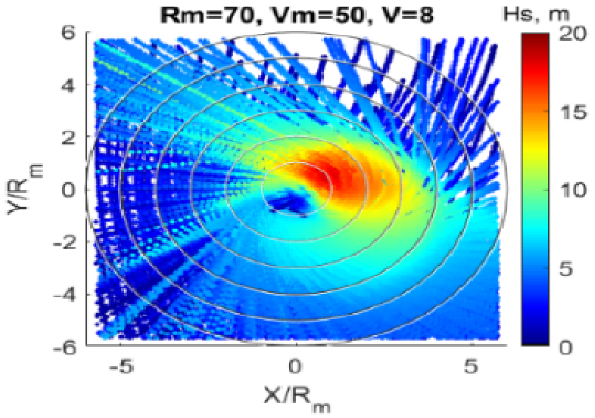
Initial wave train locations



Wind field

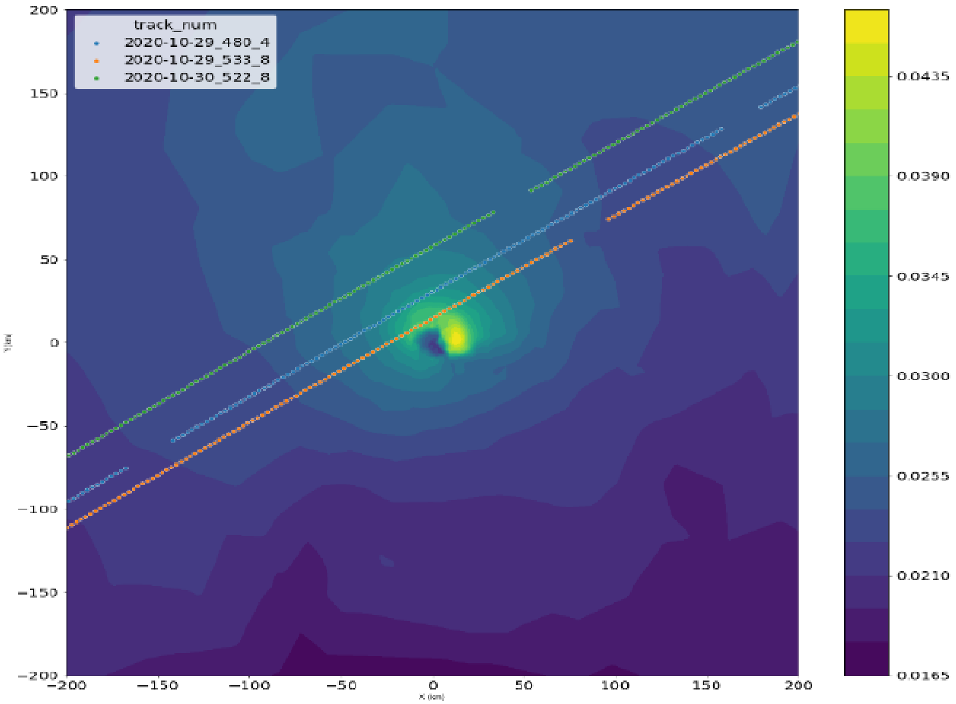


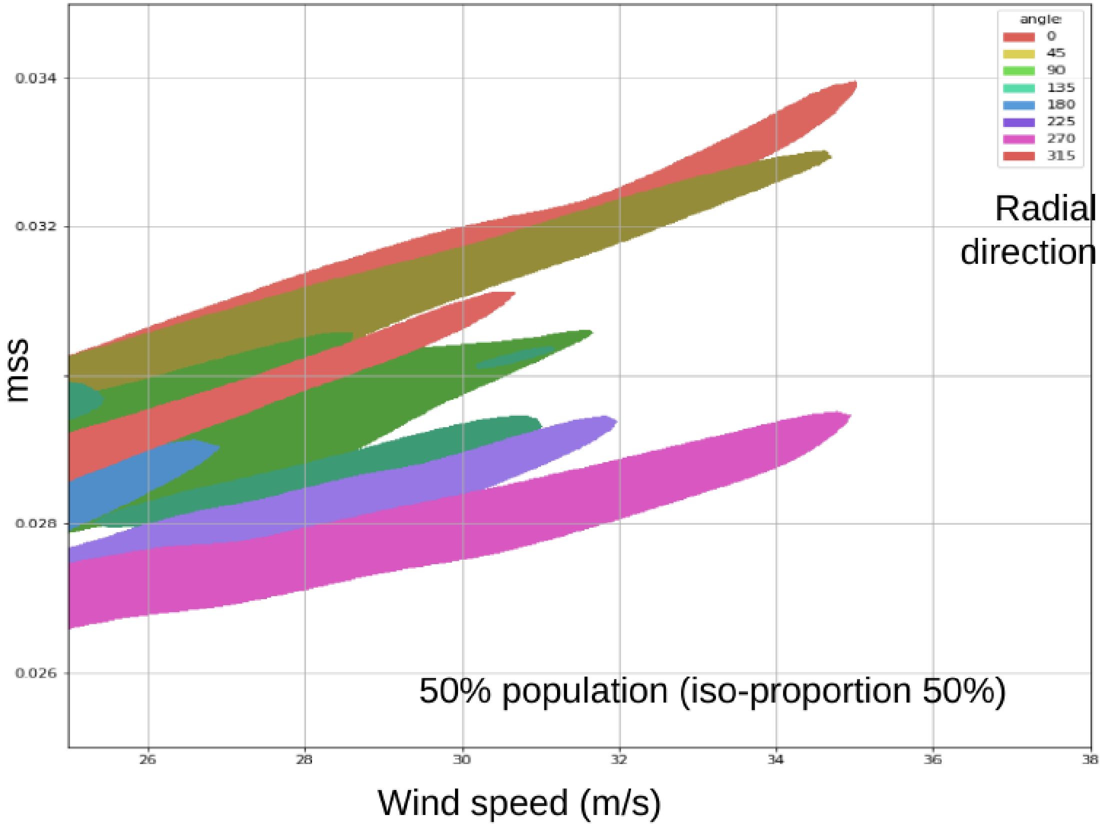
Wave rays after 48 hours



Case study: 2D wave model

Outcome of the L-band mss model around
TC Goni on 2020-10-29
(three CyGNSS tracks overplotted)





Radial direction

50% population (iso-proportion 50%)

Relationship between mss and wind speed given by the model, for high winds around Goni

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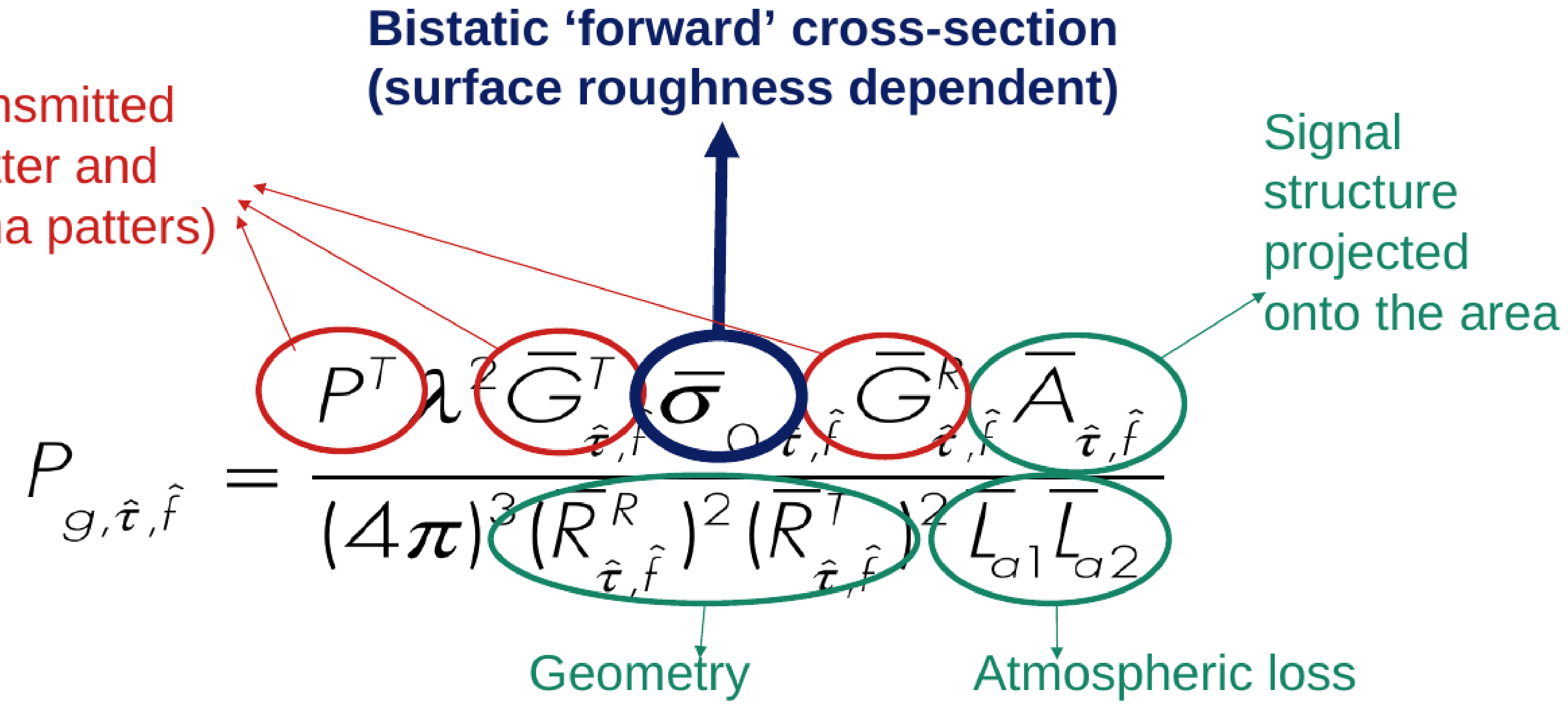
Calibration process

The received GNSS-R power, at a given ‘pixel’, can be modeled as:



Bistatic ‘forward’ cross-section (surface roughness dependent)

Instrument (transmitted power, transmitter and receiver antenna patters)

Signal structure projected onto the area

$$P_{g,\hat{\tau},\hat{f}} = \frac{P^{T}\lambda^{2}\bar{G}^{T}_{\hat{\tau},\hat{f}}\,\bar{\sigma}_{0\,\hat{\tau},\hat{f}}\,\bar{G}^{R}_{\hat{\tau},\hat{f}}\,\bar{A}_{\hat{\tau},\hat{f}}}{(4\pi)^{3}(\bar{R}^{R}_{\hat{\tau},\hat{f}})^{2}(\bar{R}^{T}_{\hat{\tau},\hat{f}})^{2}\bar{L}_{a1}\bar{L}_{a2}}$$

Geometry

Atmospheric loss

Calibration process

From measurements:

$$\bar{\sigma}_{0,DDMA} = \frac{\boxed{P_{g,DDMA}}(4\pi)^3 L_{a1} L_{a2} l}{\boxed{P^T}\lambda^2 \boxed{G^T_{SP} G^R_{SP}} R^{Total}_{SP} A_{DDMA}}$$

Calibration required

Forward operator around the specular point (model):

$$\sigma_0 = \pi|\mathcal{R}|^2 PDF(slope = 0; \{\kappa_s\})$$

Calibration process

From measurements:

$$\bar{\sigma}_{0,\,DDMA} = \frac{\boxed{P_{g,DDMA}}\,(4\pi)^3 L_{a1} L_{a2} l}{\boxed{P^T}\,\lambda^2 \boxed{G^T_{SP} G^R_{SP}}\, R^{Total}_{SP} A_{DDMA}}$$

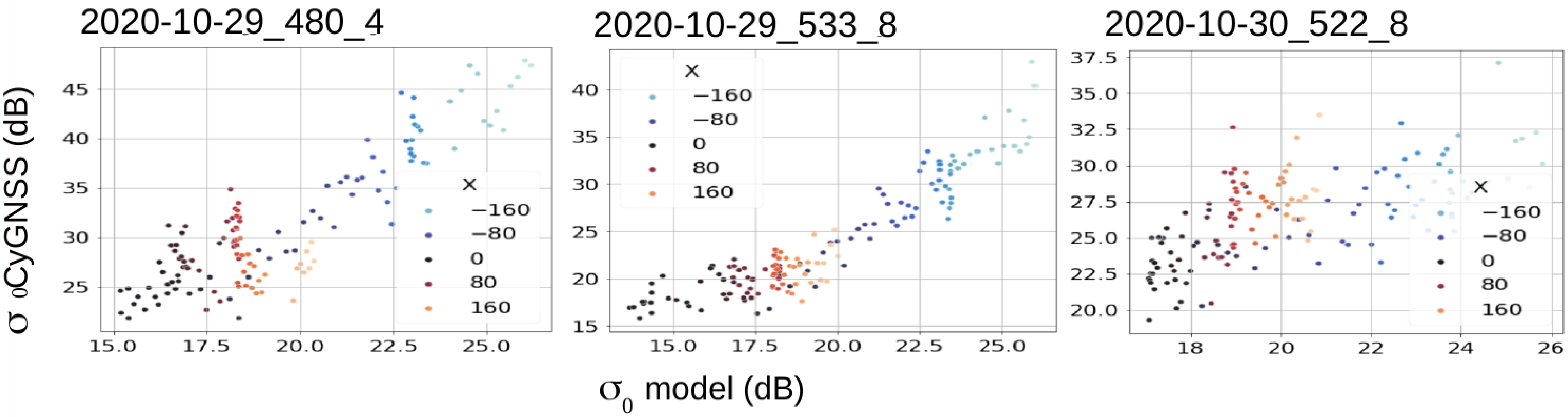
Calibration required

Forward operator around the specular point (model):

$$\sigma_0 = \pi |\mathcal{R}|^2 \underset{\downarrow}{PDF}(slope = 0; \{\kappa_s\})$$

For simplicity, here we used Gaussian with σ^2 = mss
Should be better done, actual slopes' statistics of the model

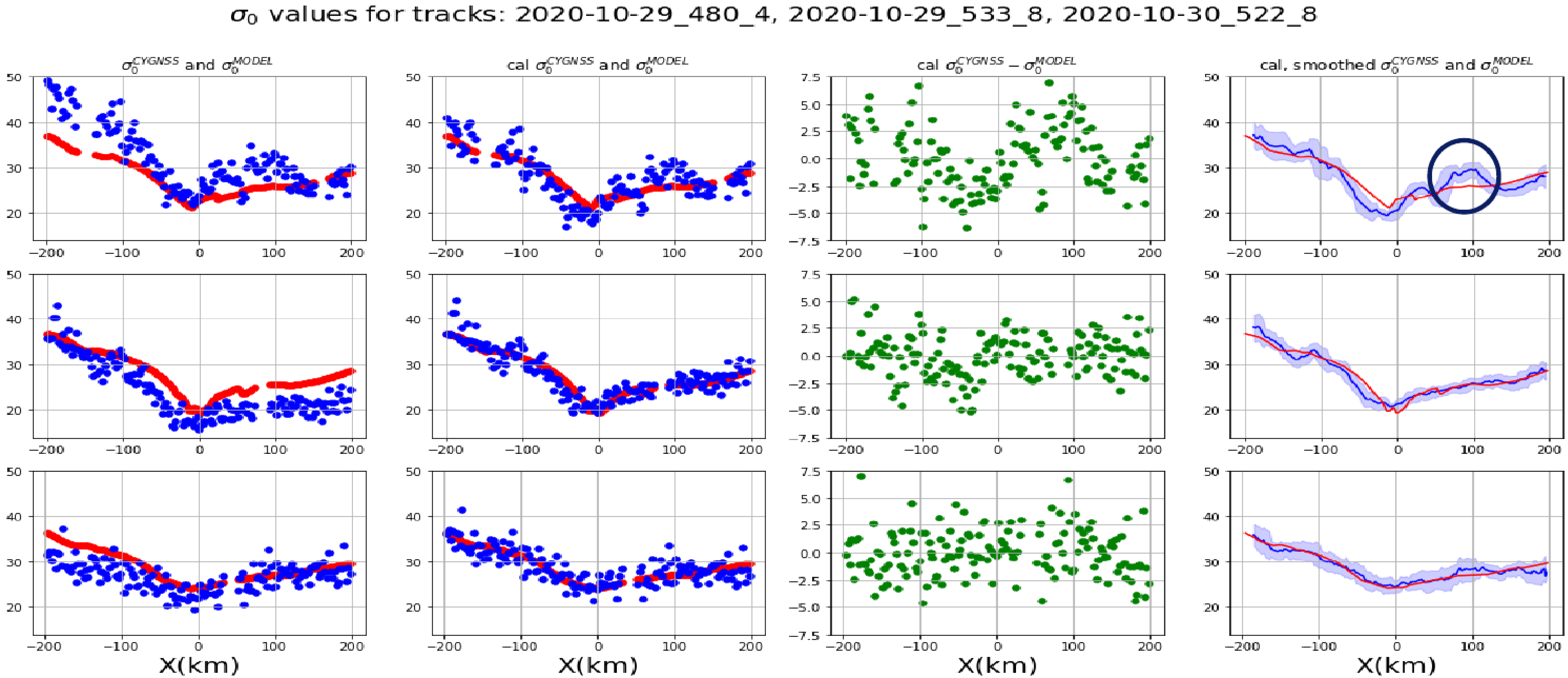
Calibration process



Trackwise (for each track): linear fit and calibration of the CyGNSS σ_0

$$\sigma_0^{cal} = \frac{\sigma_0^{CyGNSS} - a}{b}$$

O-B



0.5 sec sampled data

5 sec smoothing

Summary

- Preliminary studies to assess the potential of spaceborne GNSS-R 'observables' (σ_0) for assimilation into complex wave models acorss TC.
- Assimilation of σ_0 rather than geophysical variables inverted from GNSS-R (wind, mss) is preferred as
  - GNSS-R is sensitive to a combination of variables;
  - assimilation of σ_0 moves all the assumptions at the model-side (thus consistent with and taking advantage of the richness of the model).
- There is the need of calibration of the data, to 'align' it with the model. We suggest trackwise calibration based on linear fit.
- This approach tested on a case study, TC Goni, 2020, 2D wave model [Kudryavtsev, Yurovskaya & Chapron, 2021], initialized with S1 SAR-wind [IFREMER].
- Good agreement between modelled σ_0 and calibrated GNSS-R σ_0.
- Some 'anomalies' detected, where the GNSS-R data could 'correct' the model.