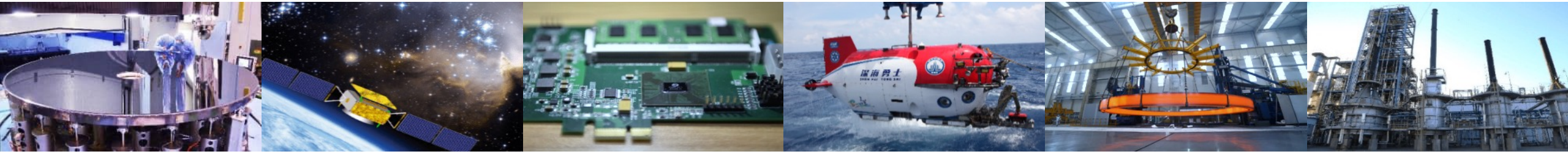
Assessment of Wind-Wave Induced Doppler Velocity Using Sentinel-1 and Coastal HF Radar in the Northwestern Mediterranean

Shilei Wang (National Space Science Center (NSSC), CAS, Beijing, China)
Marcos Portabella (Institute of Marine Sciences (ICM-CSIC), Barcelona, Spain)
Xiaolong Dong (National Space Science Center (NSSC), CAS, Beijing, China)

May 2026



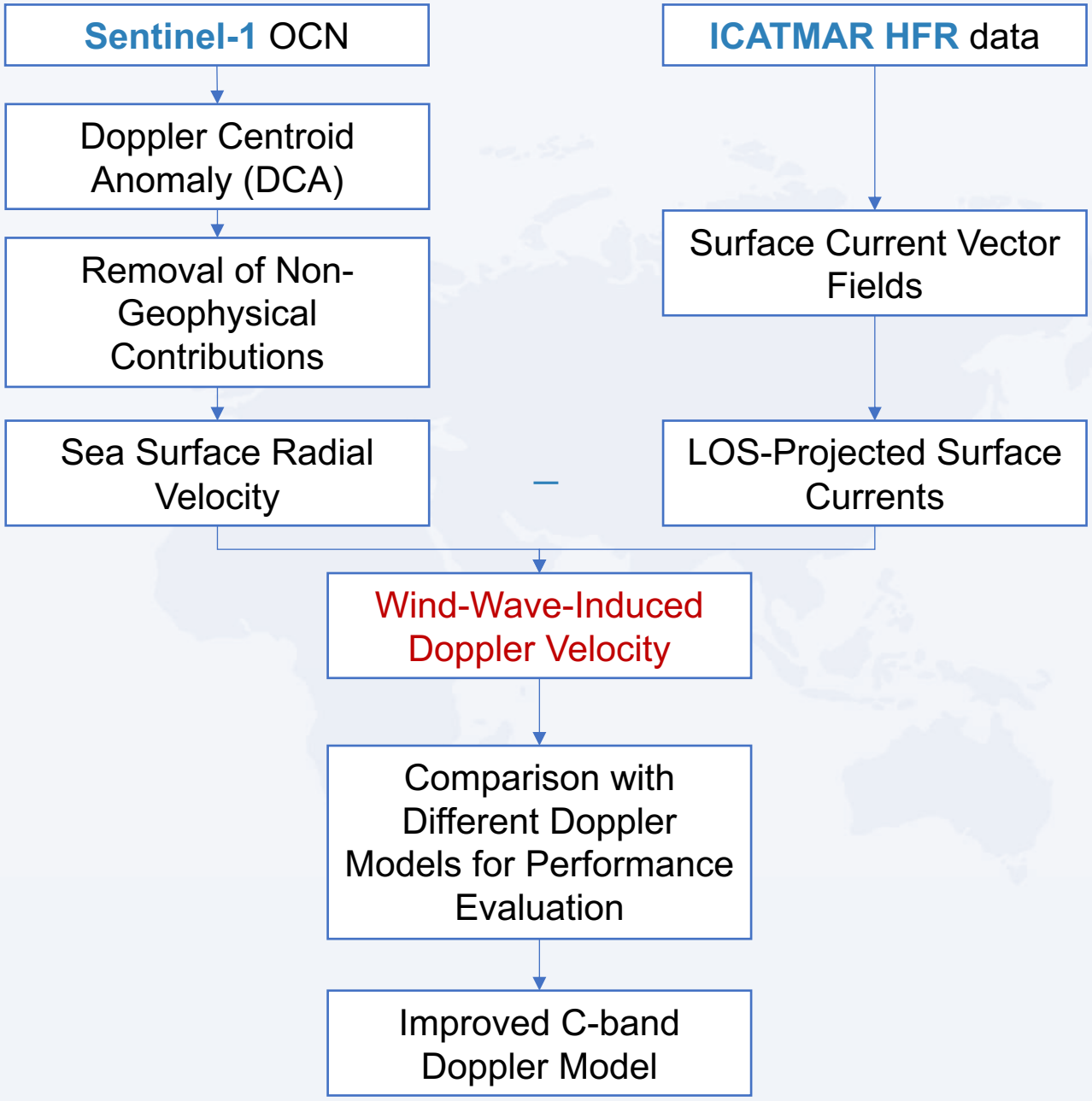
Why Wind-Wave Doppler Matters?

- SAR Doppler velocity contains both ocean current and wind-wave contributions
- Wind-wave induced Doppler velocity can significantly bias current retrieval
- Quantitative assessment using real observations is still limited

$$V_{dop} = V_{current} + V_{wind-wave}$$

HF radar currents are used as independent reference observations.

2. Datasets and Methodology

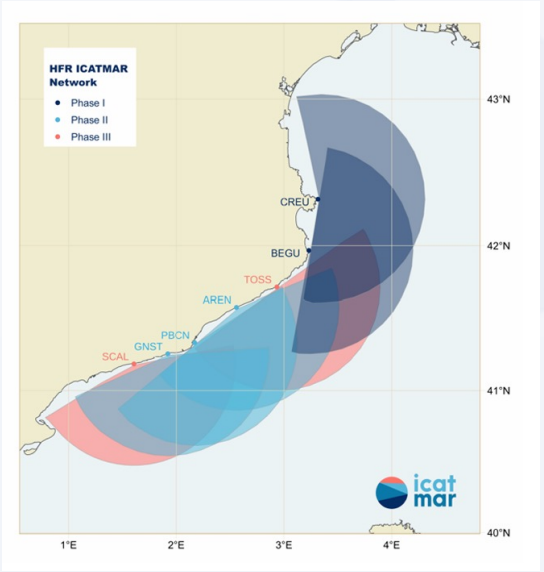


Study Area: Northwestern Mediterranean, coastal area of Catalonia (1°E–4°E, 40°N–43°N)

Study Period: April 2023 – October 2025

Datasets:

- SAR: Sentinel-1 Level-2 OCN product (1 km)
- Model Wind and Wave Data: ERA5 (25 km)
- Coastal HF Radar: ICATMAR HFR (3 km)



3. Removal of Non-Geophysical Contributions in SAR Doppler Velocity

In Sentinel-1 Level-2 OCN product, the Doppler centroid frequency f_{Dc} contains

$$f_{Dc} = f_{geom} + f_{Dca}$$

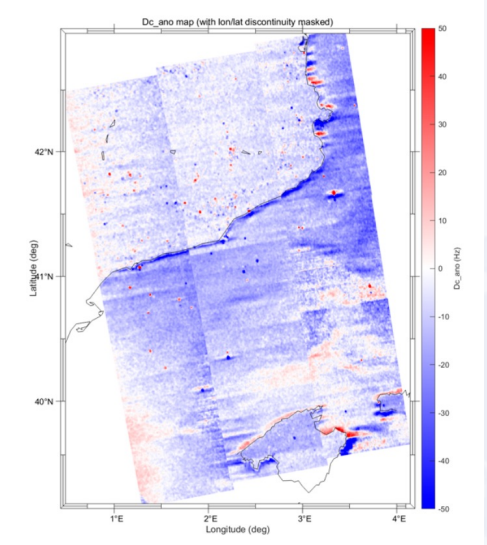
f_{geom} : *Geometric Doppler frequency, determined by the satellite orbital velocity, platform attitude, and imaging geometry.*
f_{Dca} : *Doppler centroid anomaly, representing the combined effects of non-geophysical error sources and ocean dynamic processes.*

$$f_{Dca} = f_{non-geoph} + f_{cur} + f_{ww}$$

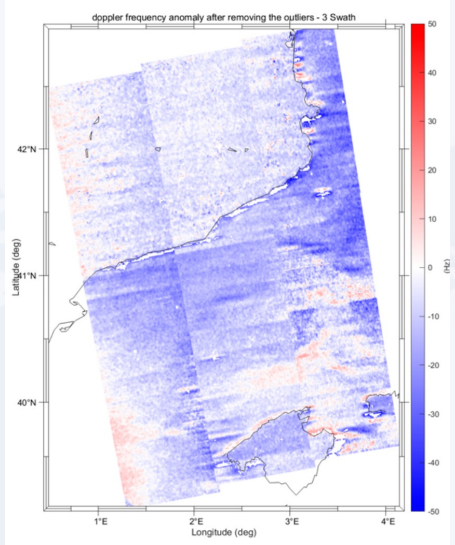
$f_{non-geoph}$: *Non − geophysical error term (e.g., antenna mispointing, scalloping, platform attitude variations, …)*
f_{cur} : *the contribution caused by ocean surface currents.*
f_{ww}: *Wind − wave modulation term*

$$U_D = -\frac{\pi f}{k_e \sin\theta}$$

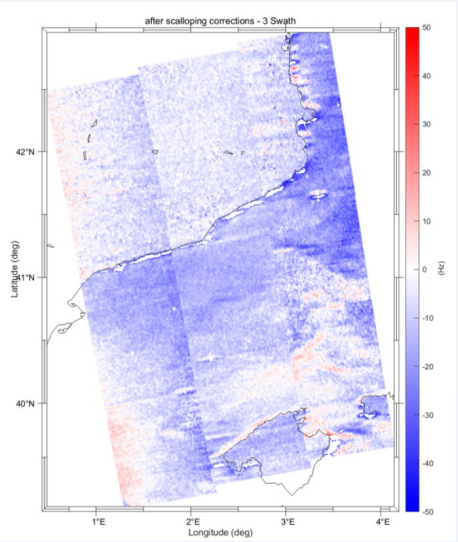
U_D: *Sea Surface Radial Velocity*
f : *Doppler centroid anomaly after non-geophysical correction.*
k_e: *wavenumber*
θ: *incidence angel*



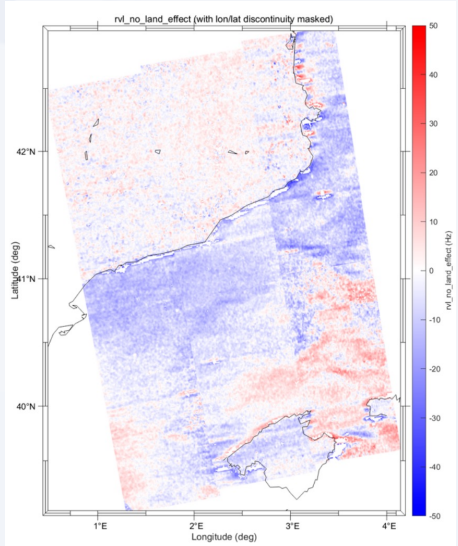
f_{Dca}



After 3σ outlier removal



After scalloping correction



After electronic antenna pointing error correction

4. Existing C-band Doppler Model and Evaluation

Sentinel-1 Sea Surface Radial Velocity

ICATMAR HFR LOS-Projected Surface Currents

Wind-Wave-Induced Doppler Velocity

Empirical C-band Doppler Model

$$f_{ww} = CDOP(\theta, U_{10}, \phi^{re}_{wind})$$

Mouche et al., *IEEE TGRS*, 2012.

CDOP-Yn: Improved Doppler Model with Machine Learning and Wave Parameters

$$f_{ww} = CDOP\text{-}Y_1(\theta, U_{10}, \phi^{re}_{wind})$$

$$f_{ww} = CDOP\text{-}Y_2(\theta, U_{10}, \phi^{re}_{wind}, H_s, T_{mwp}, \phi^{re}_{mwd})$$

$$f_{ww} = CDOP\text{-}Y_3(\theta, U_{10}, \phi^{re}_{wind}, H_{shww}, H_{shts}, T_{mpww}, T_{mpts}, \phi^{re}_{mdww}, \phi^{re}_{mdts})$$

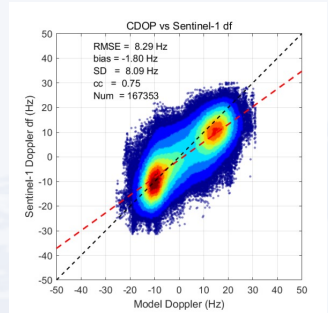
$$f_{ww} = CDOP\text{-}Y_4(\theta, U_{10}, \phi^{re}_{wind}, H_s, H_{shww}, H_{shts}, T_{mwp}, T_{mpww}, T_{mpts}, \phi^{re}_{mwd}, \phi^{re}_{mdww}, \phi^{re}_{mdts})$$

CDOP-Y1: Wind-only (≈ CDOP)

CDOP-Y2: Wind + total wave parameters

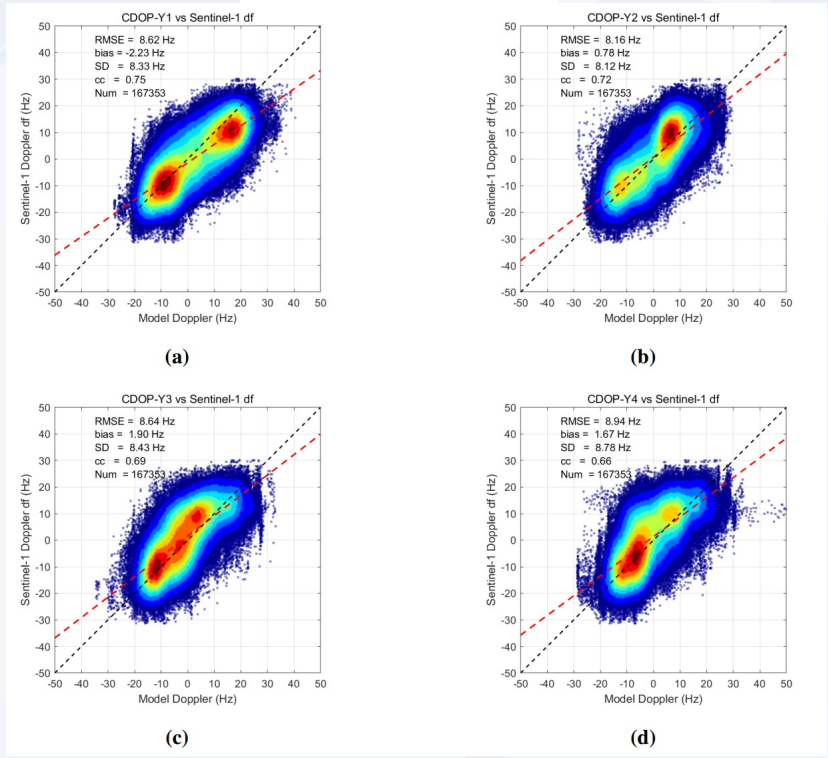
CDOP-Y3: Wind + wind-wave + swell separation

CDOP-Y4: Wind + full wave parameters



X-axis: Model simulations

Y-axis: SAR & HFR-derived results



- **CDOP-Y2 shows the best performance** (RMSE ≈ 8.16 Hz).
- **Higher model complexity does not guarantee better accuracy.**

Reference: Yang Z, Wang J, Liu L, et al. Estimating effects of wind and waves on the Doppler centroid frequency shift for the SAR retrieval of ocean currents[J]. *Remote Sensing of Environment*, 2024, 311: 114312.

5. Improved C-band Doppler Model

A linear correction model is developed to reduce systematic bias:

$$f_{ww}^{obs} = a\, f_{ww}^{model} + b$$

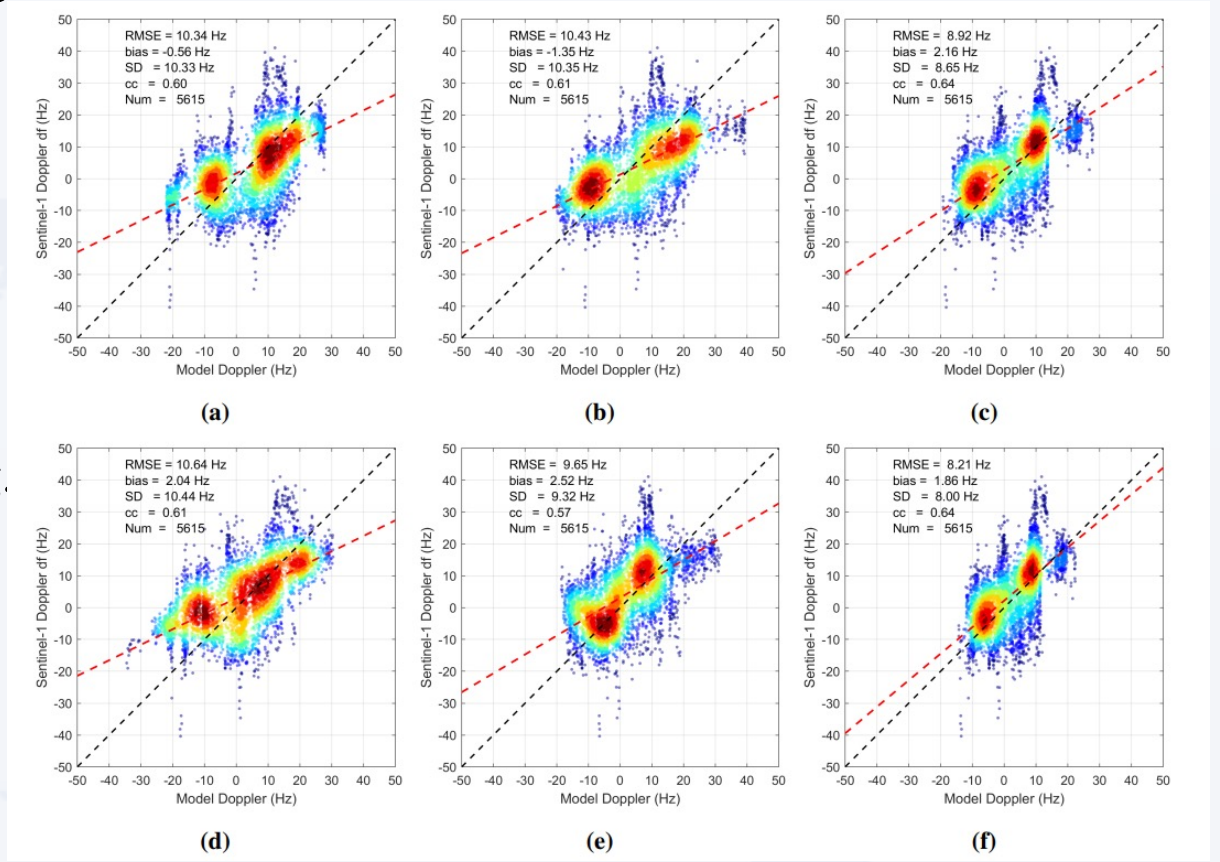
f_{ww}^{model} : $model - derived\ wind - wave\ Doppler\ frequency$

f_{ww}^{obs} : $observed\ wind - wave\ Doppler\ frequency$

Parameters a and b are estimated using least squares fitting.

$$f_{ww}^{mod} = 0.7781\, f_{ww}^{CDOP-Y2} + 0.6822$$

Validation: using an independent dataset (November 2025)



Comparison of different Doppler models on an independent validation dataset: (a) CDOP; (b) CDOP-Y1; (c) CDOP-Y2; (d) CDOP-Y3; (e) CDOP-Y4; **(f) Improved model**

The improved model achieves the lowest RMSE (~8.21 Hz).

6. Summary & outlook

- Sentinel-1 Doppler centroid anomaly contains significant wind-wave-induced contributions over the northwestern Mediterranean.
- Existing empirical C-band Doppler models (CDOP and variants) show limitations in coastal conditions, with systematic biases in wind-wave contributions.
- The best performance is achieved by CDOP-Y2 and the improved model, both yielding the lowest RMSE.
- Model complexity does not necessarily lead to better performance.
- Future activities
  - Use scatterometer winds as reference (HY-2B & S-1 in 6am/pm orbit)
  - Perform similar analysis in other coastal regions
  - Use of other in situ ocean current data

7. Future: CFOSAT-NG and Ocean wind and wave satellite

CFOSAT (The China France Oceanography SATtellite)

China: SCAT-NG　Doppler Scatterometer, DOPS

France: SWIM-NG

DOPS is based on OSCOM, operated in Ka + Ku band.

- Ocean current (5 km, 0.1 m/s)
- Ocean wind (5 km, 1.5 m/s)
- Ocean wave (10 km、50-500 m wavelength）

Swath: ≥ 1000 km

Ocean wind and wave satellite

Doppler Scatterometer, DOPS, operated in **Ku** band.

- Ocean current (10-20 km, 0.2 m/s)
- Ocean wind
- Ocean wave
- Swath: ≥ 1000 km