Sea surface circulation observed by SAR in the Baltic Sea using the synergy between Sentinel-1 and TanDEM-X

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Introduction - Doppler centroid

- **Goal**: Investigate the potential of spaceborne SAR to monitor the Baltic Sea in/out flow through the Danish straits
- Doppler centroid estimation
  - Along-track interferometry (ATI), e.g. TanDEM-X, SEASTAR
  - Doppler centroid anomaly (DCA), e.g. Envisat, Sentinel-1
- The two methods estimate the SAR Doppler centroid

$$f_{DC} = \frac{1}{2\pi}\frac{\phi_{ATI}}{\tau} = \frac{k_e}{\pi}V_r$$

- V_r : Radial velocity (RVL) of the satellite relative to moving ocean surface
- $V_r = V_h \cdot sin(\theta)$, assumes negligible vertical velocity

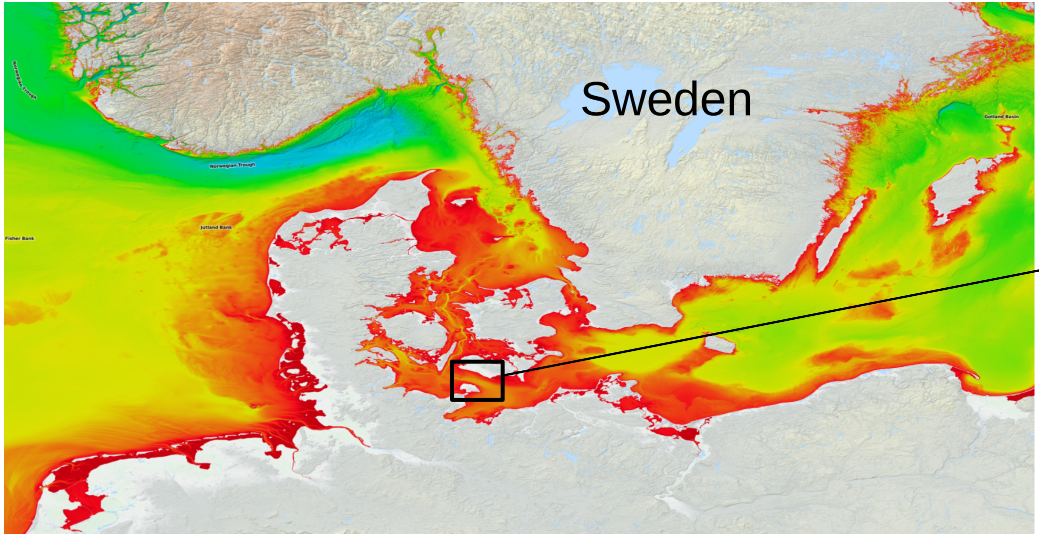
Introduction - Doppler centroid

- Different sources of motion

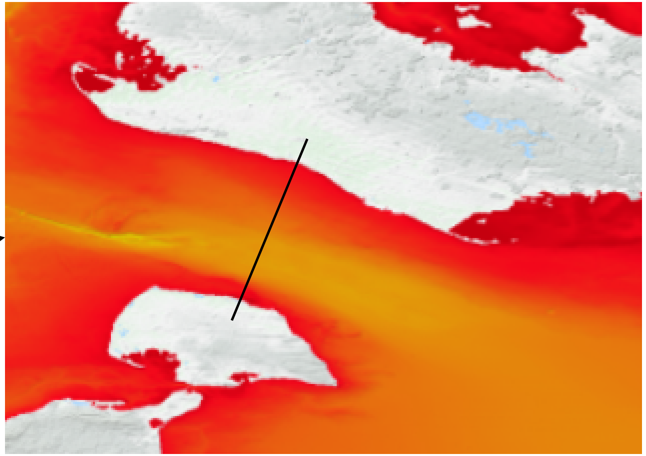
$$f_{DC} = f_{geom} + f_{phys} + f_{error}$$

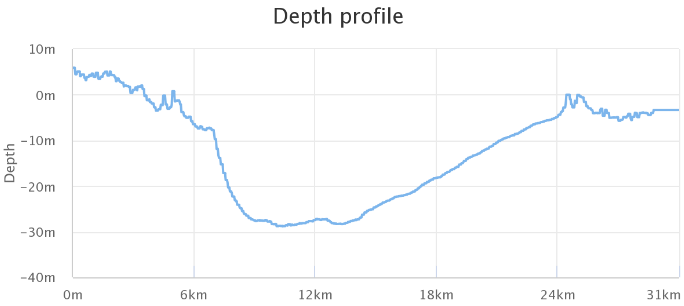
- f_{geom}: Due to satellite velocity relative to solid rotating Earth
  - requires accurate orbital/attitude parameters
- f_{phys}: Due to ocean surface currents and waves
- Precision requirement: ΔV_h= 0.1 m/s requires Δf_{DC}=3.7 Hz, (X-band), Δf_{DC}=2.08 Hz (C-band) at θ=35^o
- Usually Doppler calibration is needed = estimation of f_{error}
  - requires a reference (in height and velocity)

Study area



Fehmarn Belt



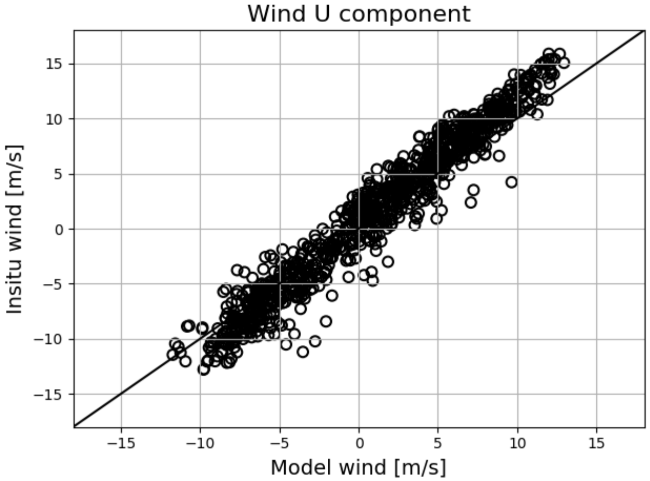


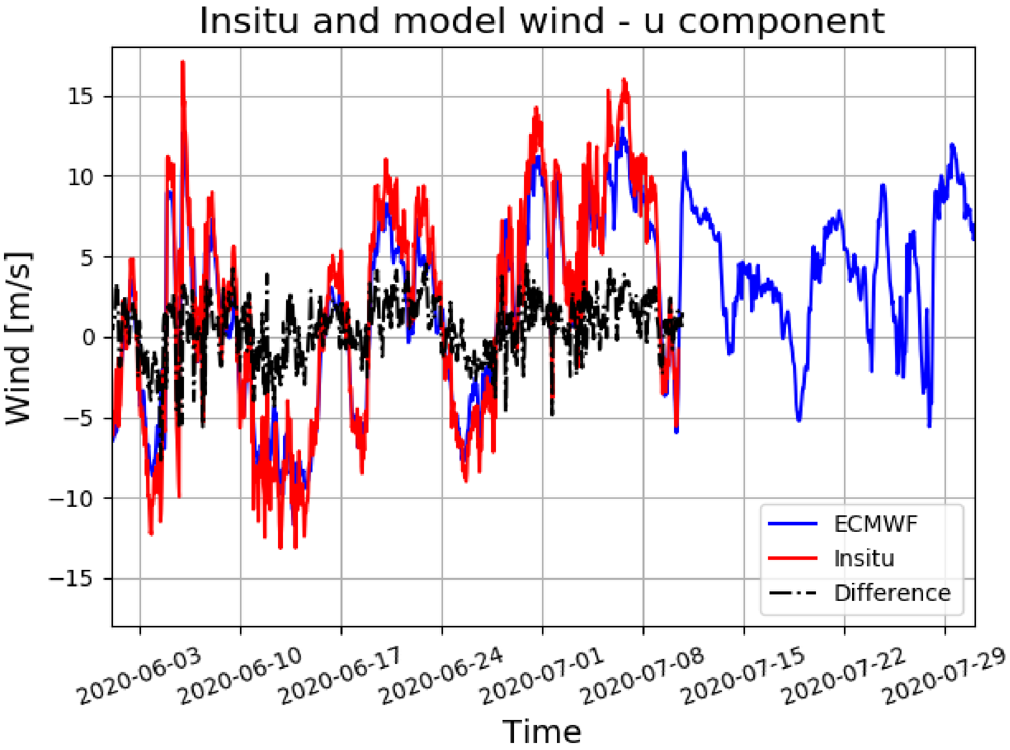
Data

- Satellite data
  - Sentinel-1A & B, OCN products (ESA), 21 images
  - TanDEM-X SLC, images (DLR), 8 images
- In situ data, moored buoy (BSH)
  - Wind speed and direction at + 10 m
  - Current speed and direction at -10 m
- Reanalysis data (ECMWF)
  - ERA5, wind speed and direction at 10 m
- Ocean model data (Copernicus)
  - Nemo-Nordic, model current
  - BALTICSEA_ANALYSIS_FORECAST_PHY_003 _006, surface layer 1 m thick

Insitu vs ERA5 wind

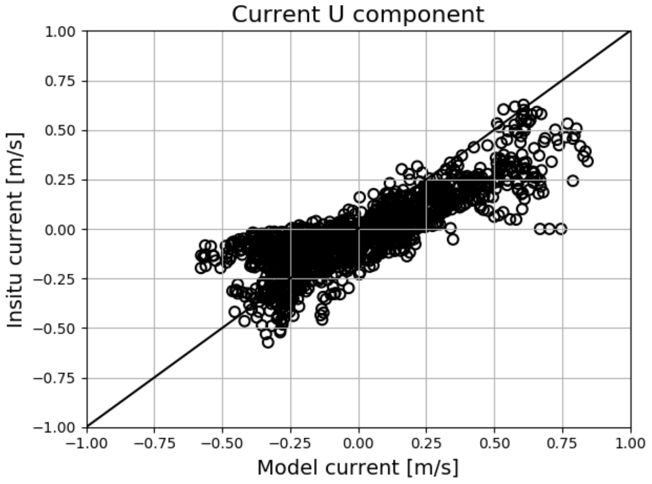
- Insitu wind covers only June
- MAE = 1.59 m/s
- Max inst. diff upto 6 m/s

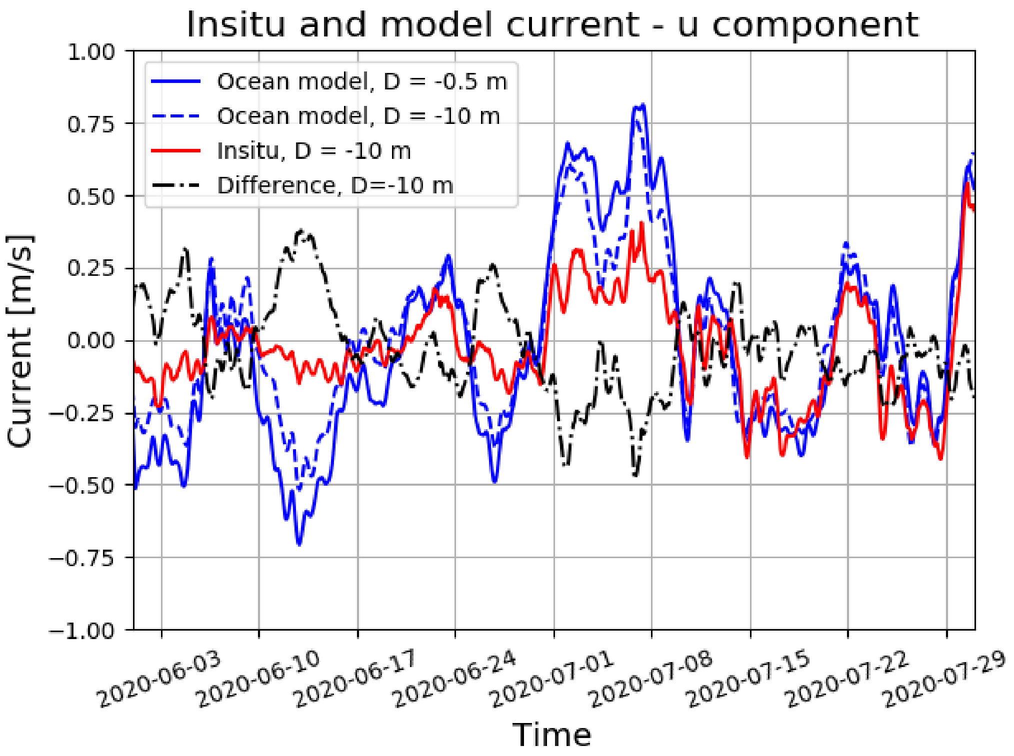




Insitu vs Model current

- Insitu current is at -10 m
- MAE = 0.16 m/s
- Max inst. difference 0.75 m/s

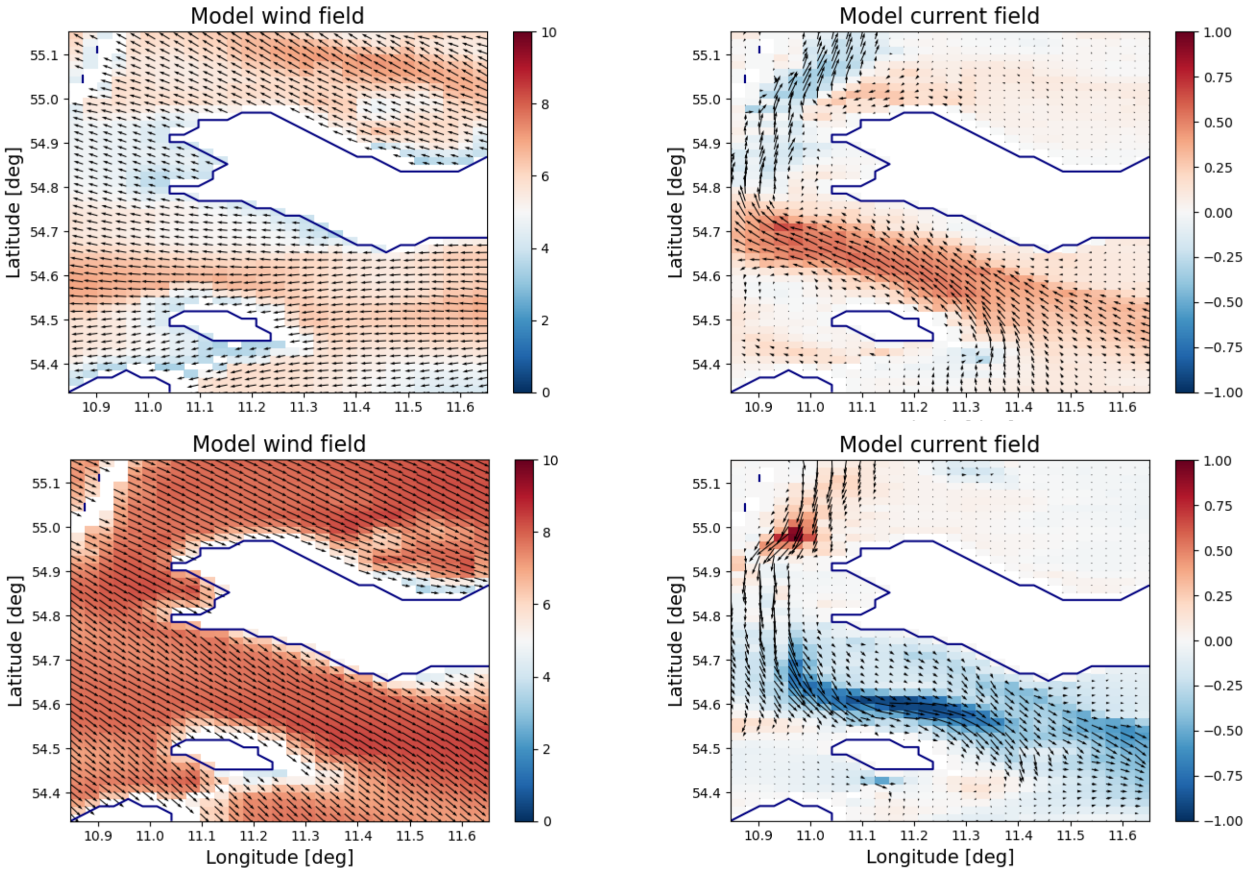




Examples - Model wind and current

2020-06-26

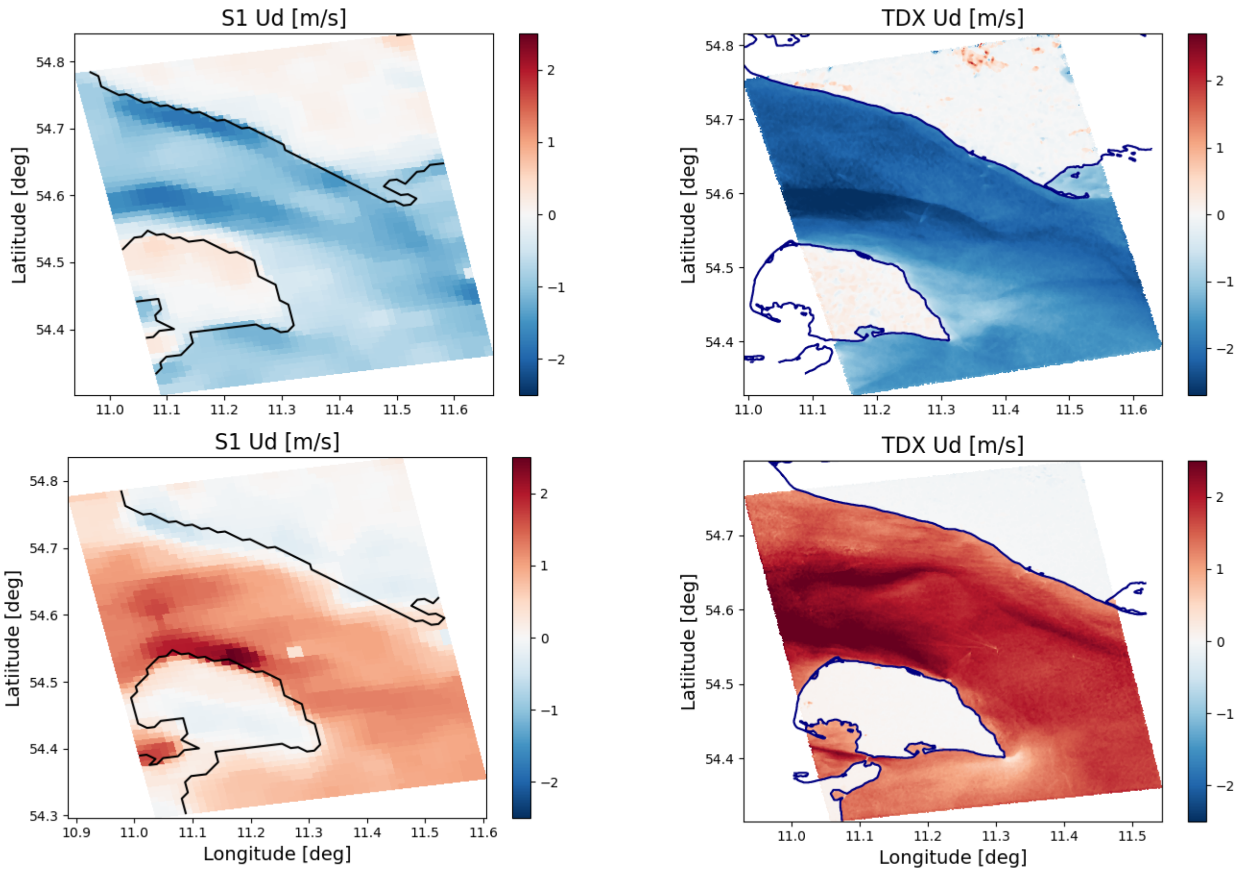
2020-07-08



Examples - SAR Doppler velocity

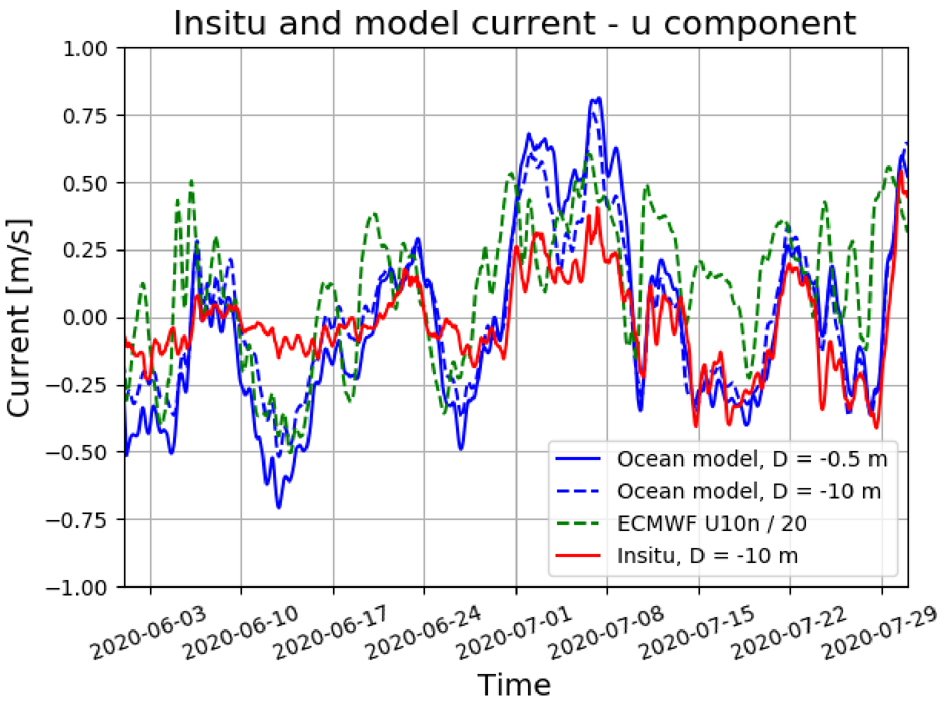
2020-06-26

2020-07-08



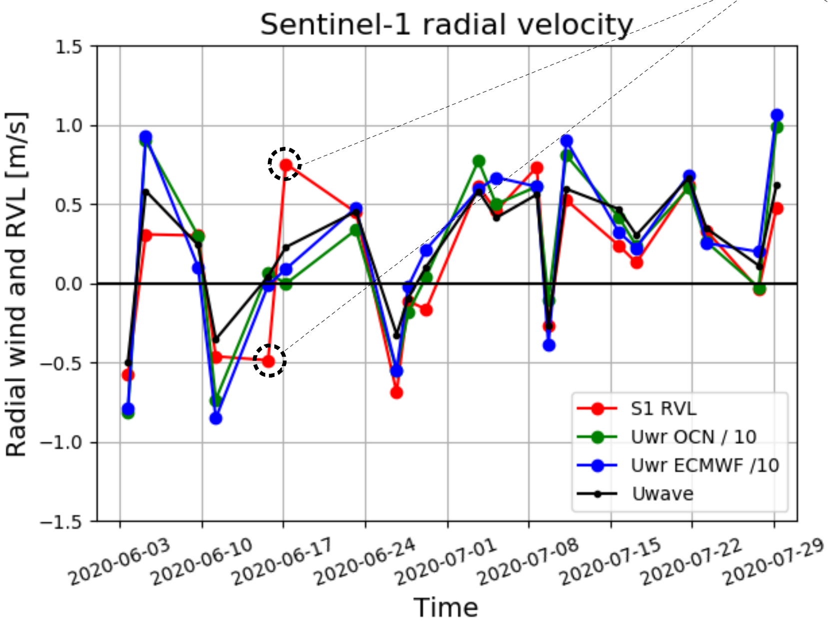
Wind and current variability

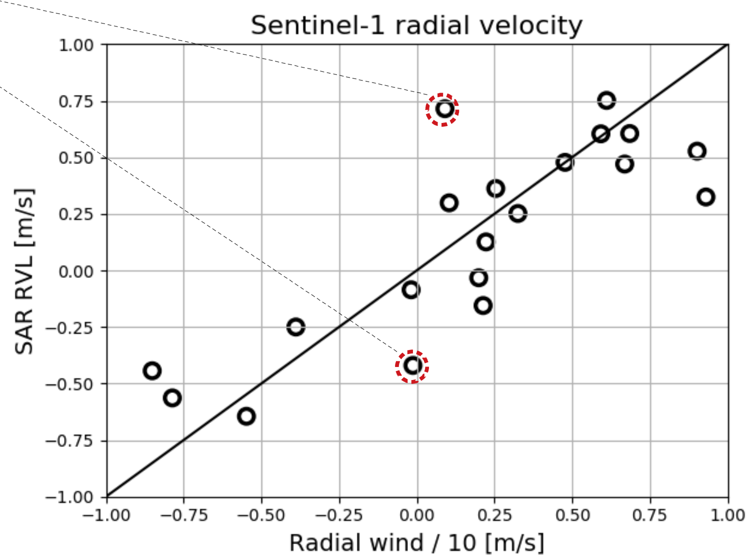
- High temporal variability of both wind and current
- Small current magnitude < 0.3 m/s



Results - Sentinel-1 RVL - before wave bias correction

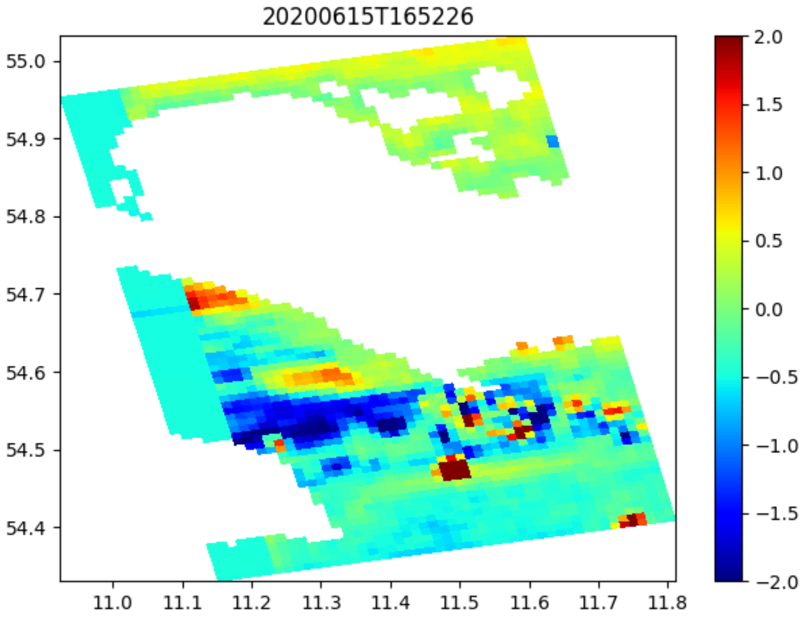
- High correlation between SAR DC and radial wind (R=0.82)
  - Doppler velocity dominated by wind
- 2020-06-15 and 2020-06-17, <u>low wind</u> (< 0.25 m/s), low SNR

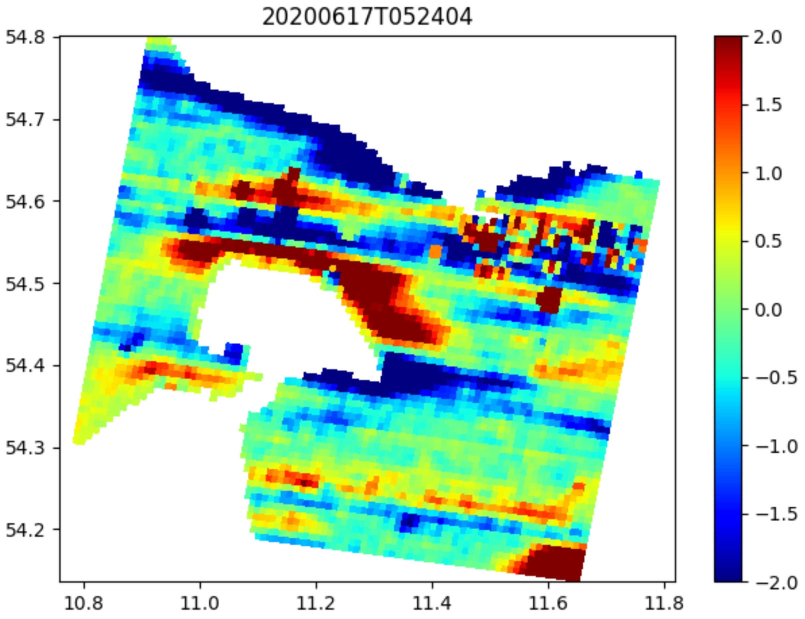




Low wind cases - Noisy DC

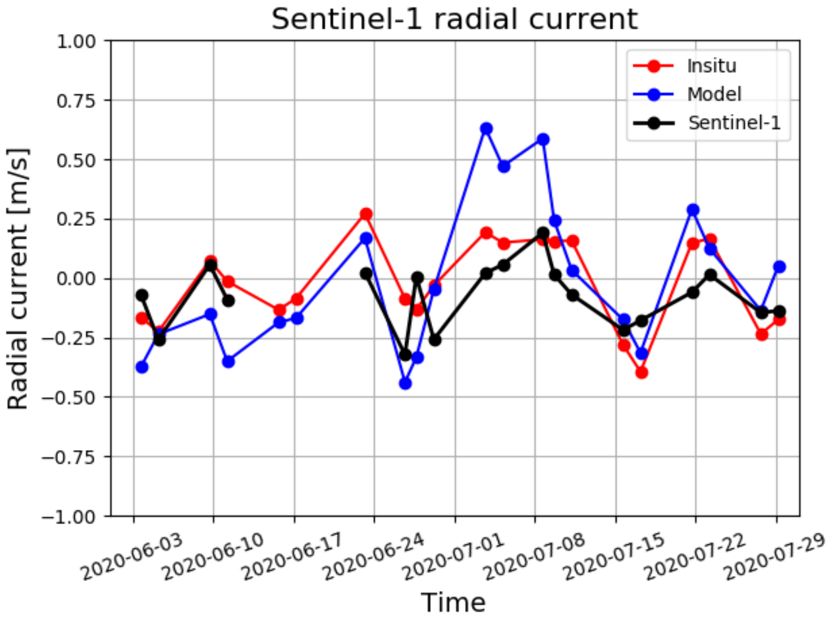
- 2020-06-15 and 2020-06-17, wind speed < 0.25 m/s, very low SNR

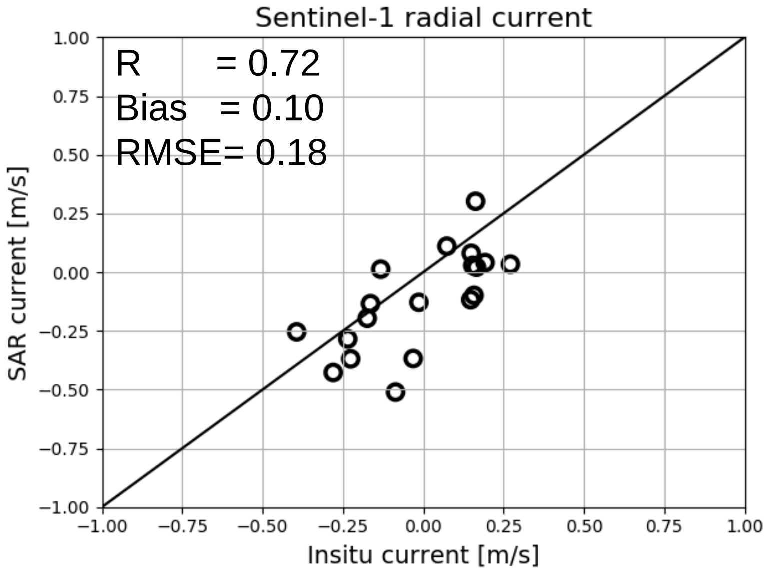




Results - Sentinel-1 - after wave bias correction

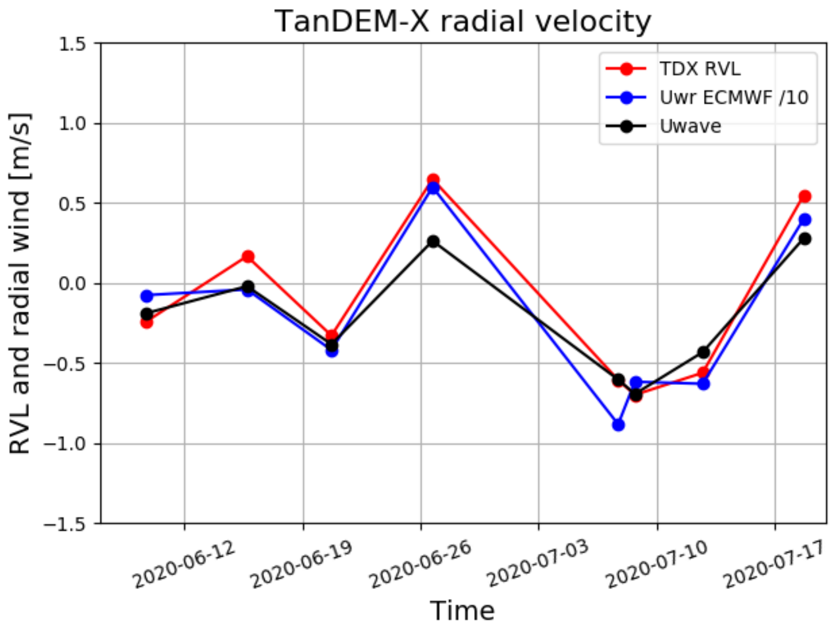
- Sentinel-1 derived ”current”, after removing the wave bias

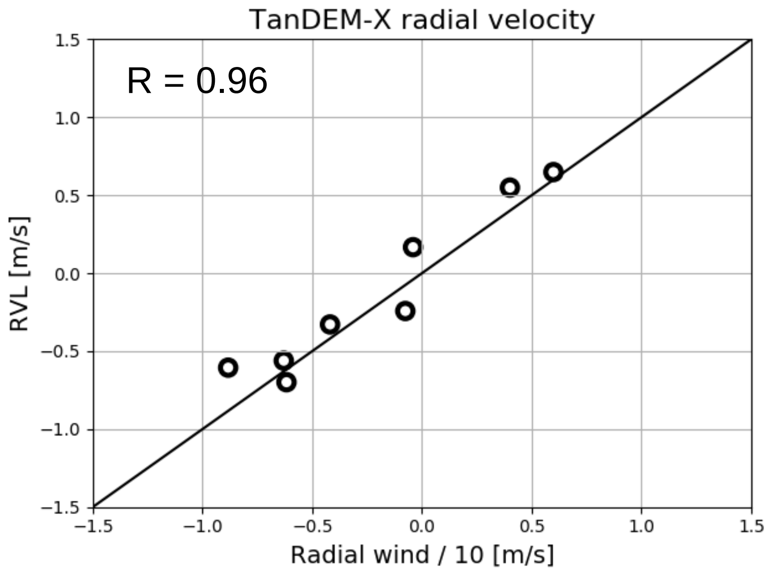




Results - TanDEM-X RVL

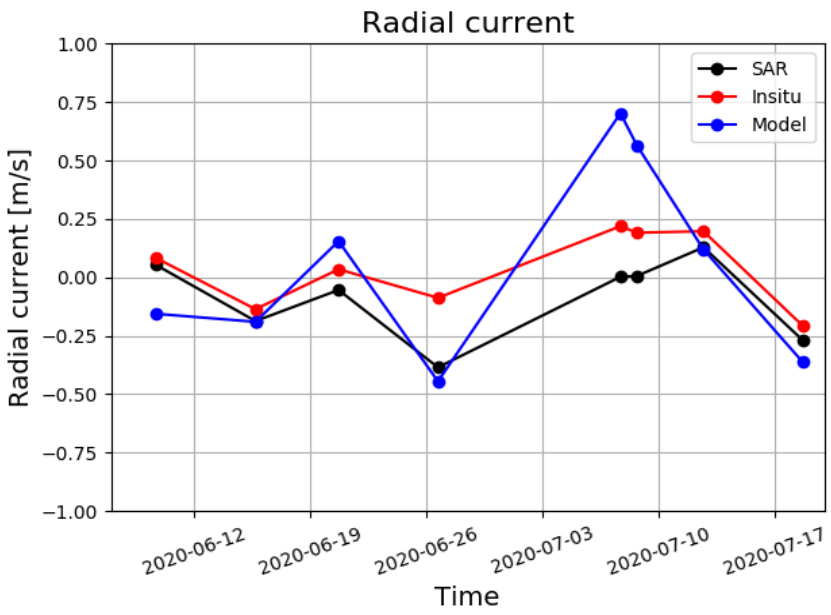
- Similar to Sentinel-1: High correlation between RVL and radial wind
    - Doppler velocity dominated by wind

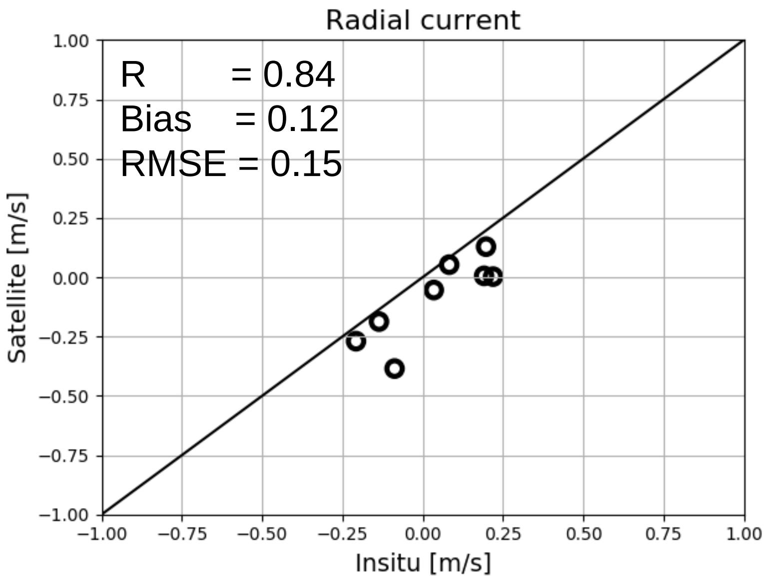




Results - TanDEMX after wave bias correction

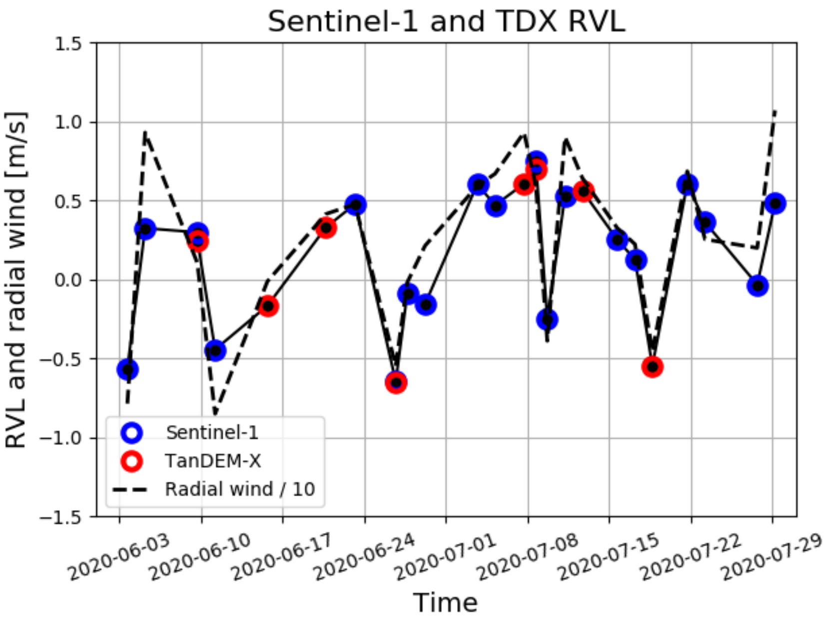
- Sentinel-1 derived ”current”, after removing the wave bias

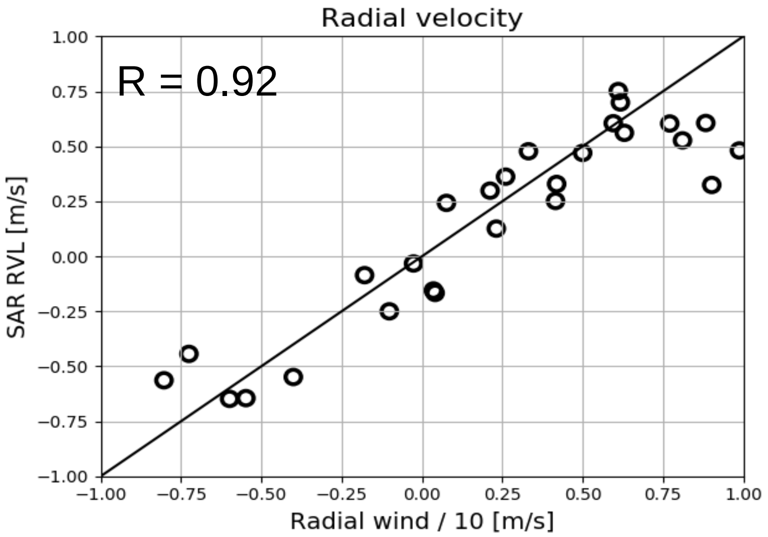




Results - Combination of Sentinel-1 and TanDEM-X

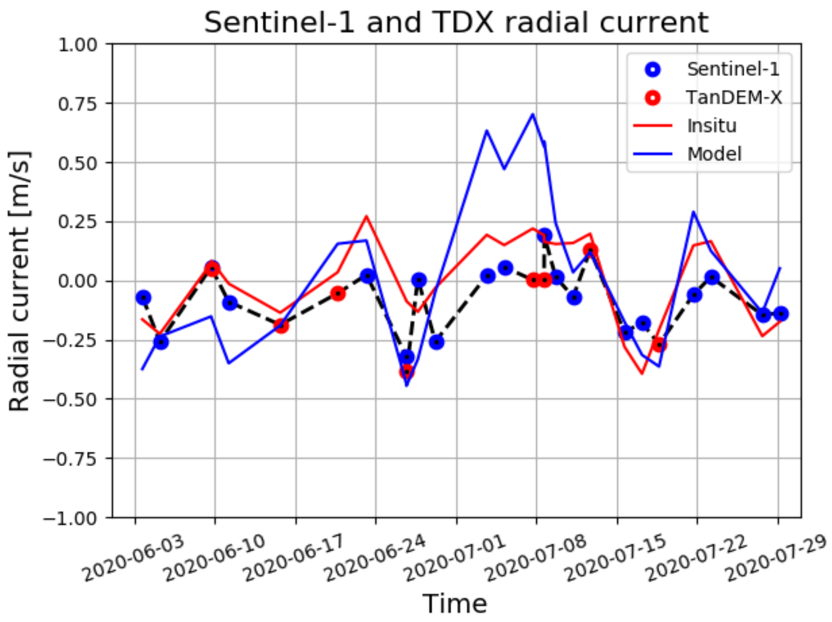
- RVL vs radial wind speed (wave contribution)

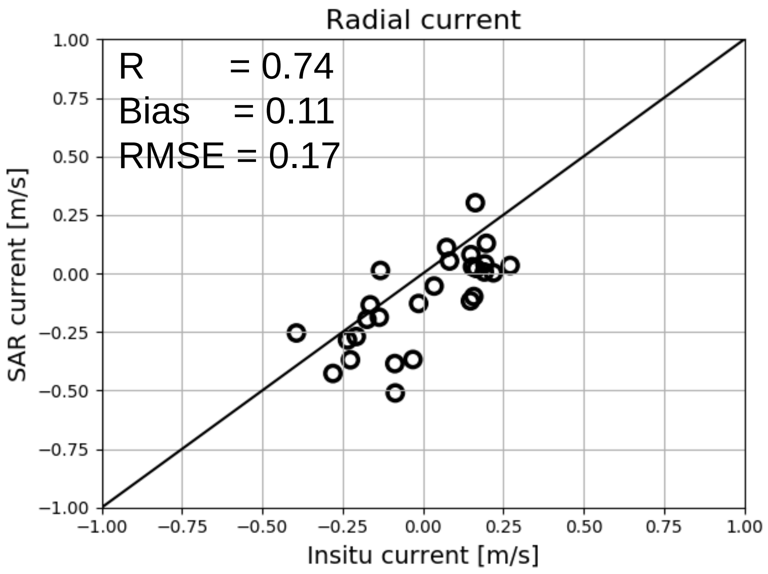




Results - Combination of Sentinel-1 and TanDEM-X

- SAR derived ”current”, after removing the wave bias

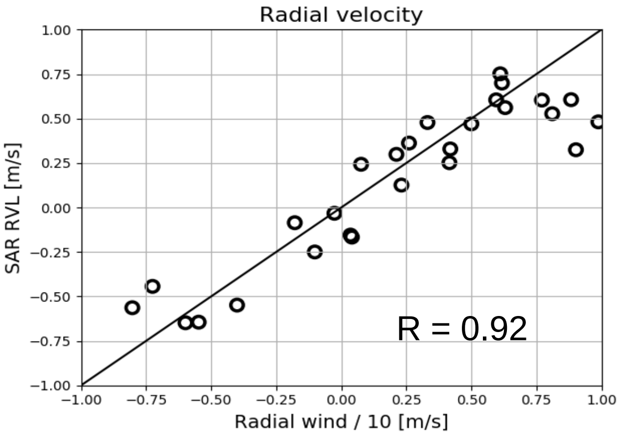




Results - summary

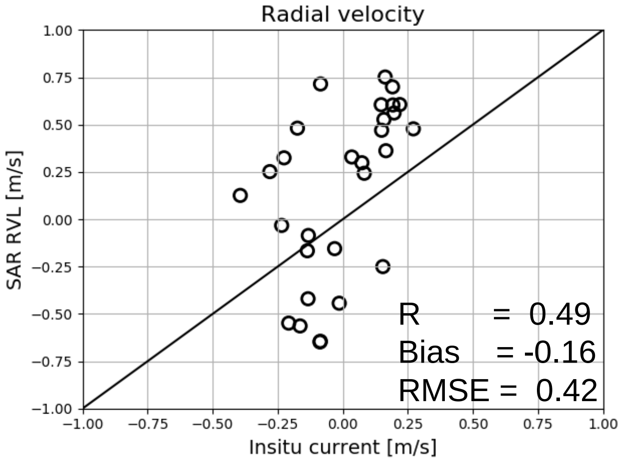
- Calibration and wave bias correction

After calibration



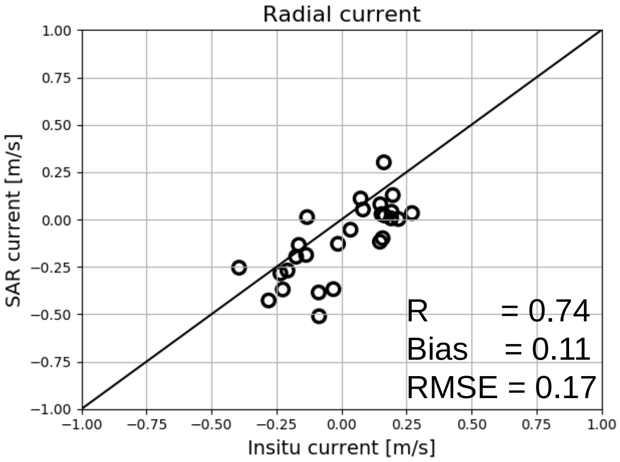
SAR RVL

Before wave bias correction



SAR RVL

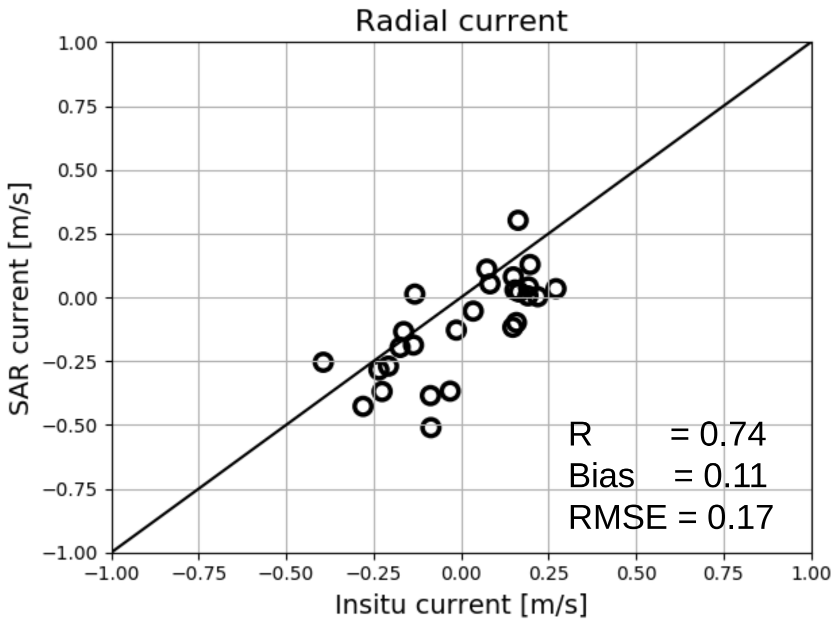
After wave bias correction



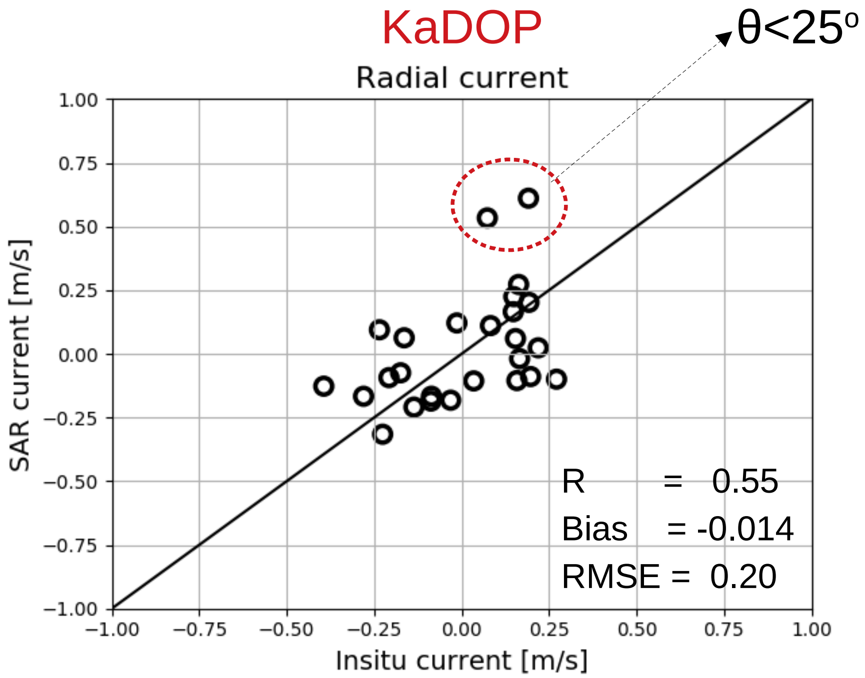
SAR derived ”current”

Differences between Doppler GMFs

CDOP



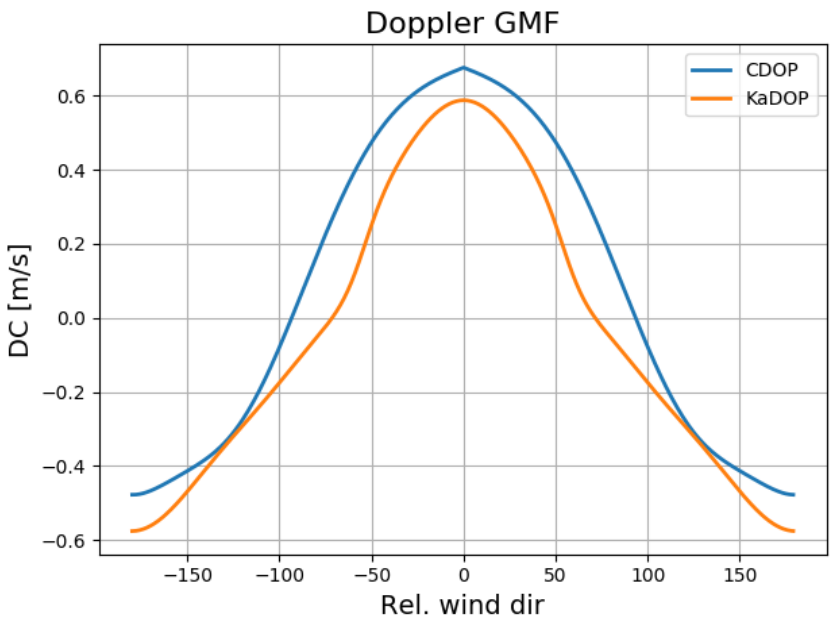
KaDOP



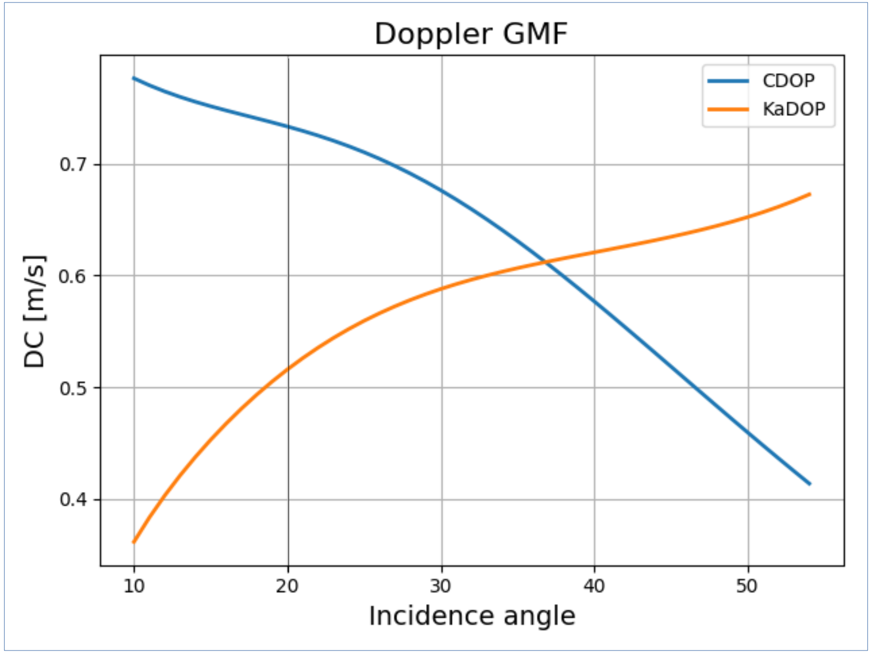
CDOP vs KaDOP

- Opposite variation vs incidence angle!

u10 = 7 m/s, θ = 35 deg



Upwind, u10 = 7 m/s



Conclusions

- Calibrated RVL, high correlation (>0.9) with radial wind speed
- After wave bias correction, good correlation (~0.72) with insitu radial current
- SAR is capable of monitoring the Baltic Sea flow through the Fehmarn Belt
    - Synergy increases temporal sampling
- Sensitivity to wave bias correction and input (wind or waves) to Doppler GMF
    - CDOP and KaDOP GMFs give slightly different results
    - Validity of Doppler models at low (<25) and high (>45) incidence angles
- Extended dataset needed for comprehensive analysis

Looking forward to SEASTAR

- Total current vector instead of radial
- Simultaneous wind and current measurements
- Fast revisit phase