The SARLAKES Project will develop an innovative, powerful and flexible tool for the accurate estimation of water dynamics in medium/large-size lakes through the exploitation of Synthetic Aperture Radar (SAR) products

SpatiAlly Resolved veLocity and wAves from SAR images in laKES

CosmoSkyMed SAR observations of wind and water surface velocity over the Garda Lake. Preliminary results from the SARLAKES project

M. Amadori, M. Bresciani, **G. De Carolis**, G. Fornaro, C. Giardino, S. Verde, V. Zamparelli IREA–CNR

L. Giovannini, S. Piccolroaz, M. Toffolon University of Trento, I

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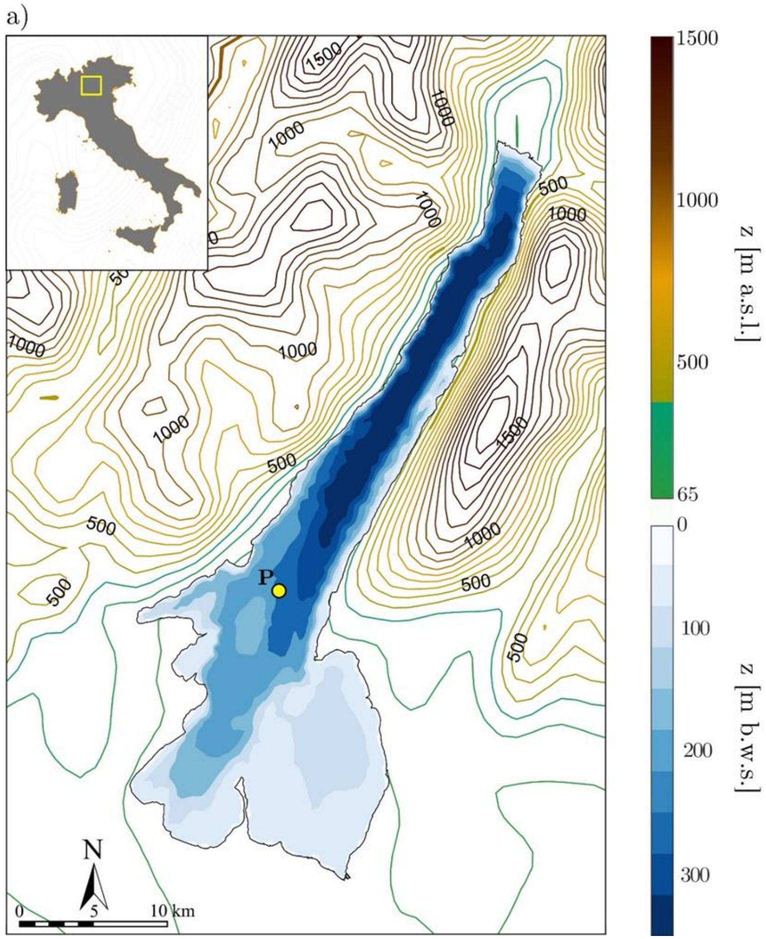
Why SAR imaging for lakes?

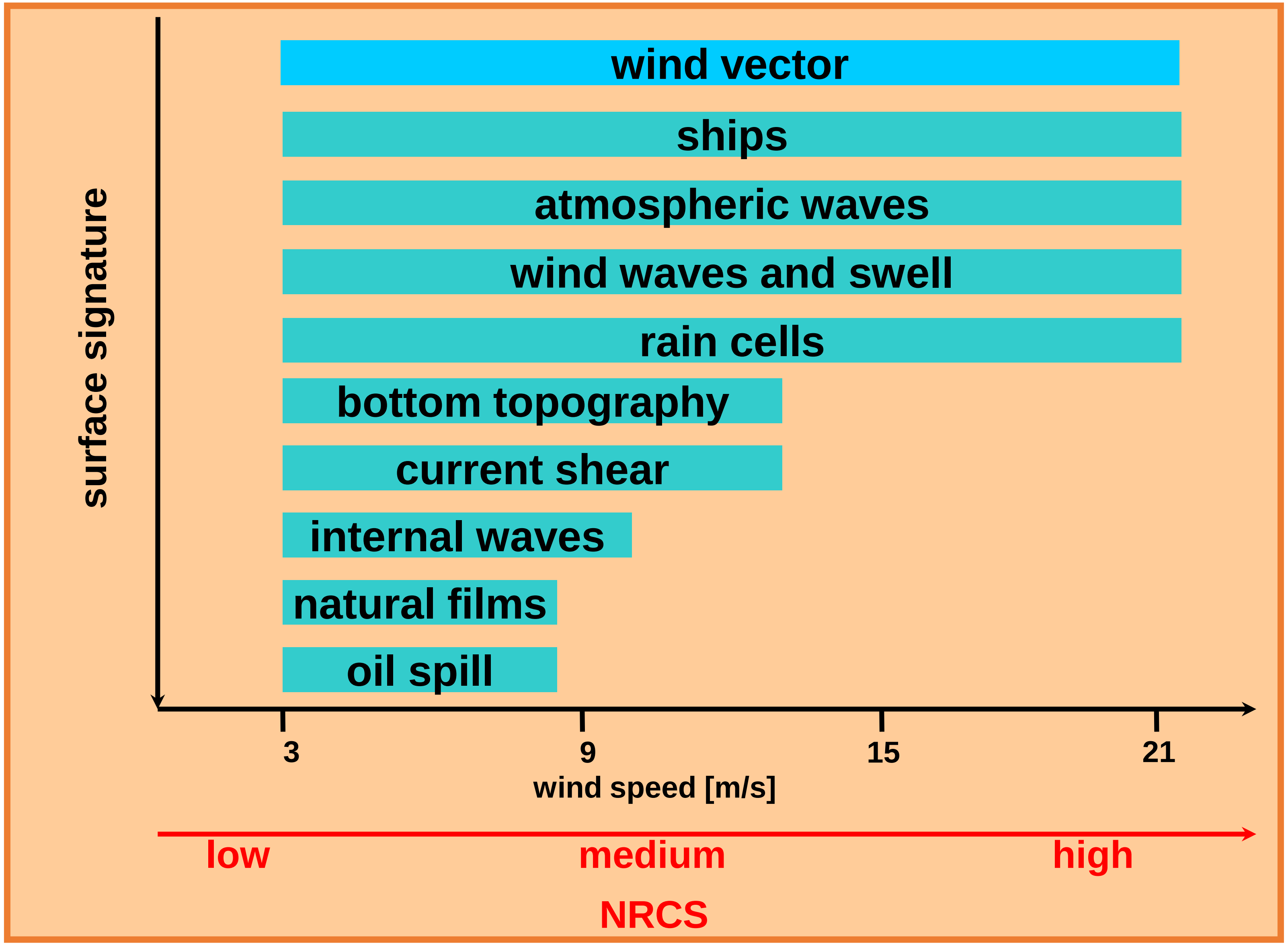
Aim: *to develop an innovative, powerful and flexible tool for the accurate estimation of water dynamics in medium/large-size lakes through the exploitation of Synthetic Aperture Radar (SAR) products*

- SAR is an all-time, all-weather microwave active imaging usually employed to monitor marine environment but rarely exploited to monitor the internal waters such as lakes
- SAR has the capability to sense the near-surface wind field, the surface currents and wind-generated waves
- SAR data in combination to satellite optical imaging and in-situ measurements gathered with traditional instrumentation
- Atmospheric and circulation models in support to SAR image analysis

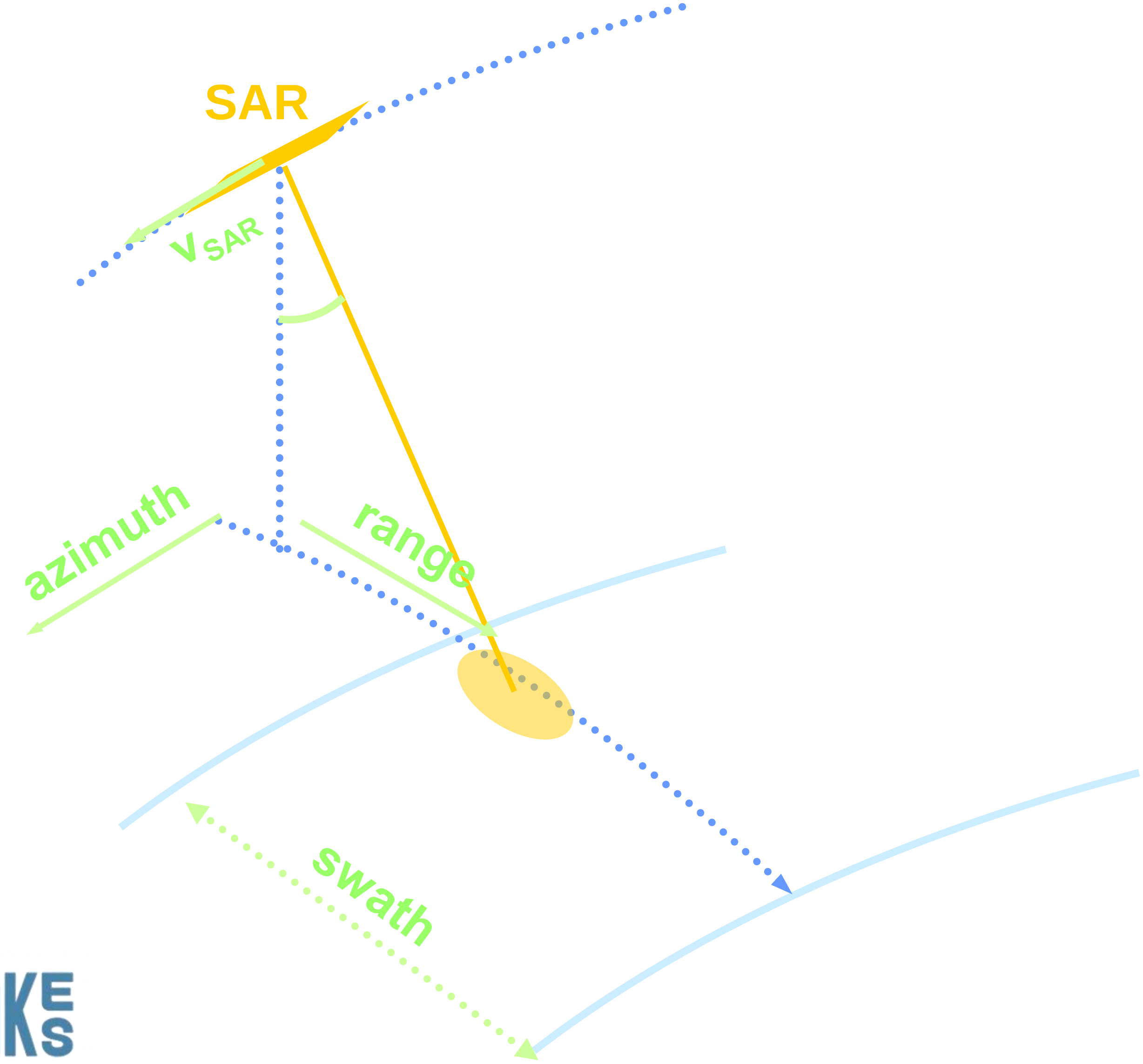
AREA OF INTEREST



What can be seen by SAR



Principle of Synthetic Aperture Radars



Principle in range:
- scanning with speed of light

Principle in azimuth:
- scanning with flight velocity plus synthetic aperture

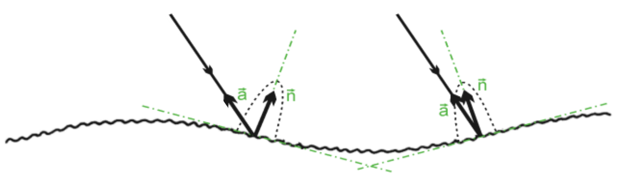
Coherent imaging:
- Complex-valued pixel amplitude and phase information

SARLAKES

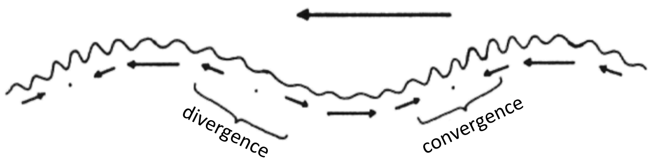
SAR imaging of water surfaces

- SAR transmits e.m. waves that are scattered by resonant interaction with the rough water surface;
- The water surface is simultaneously modulated by wind, waves, current, all together altering the spatial distribution of capillary waves:
- As a result, **wind speed, waves and currents can be retrieved by SAR imaging**

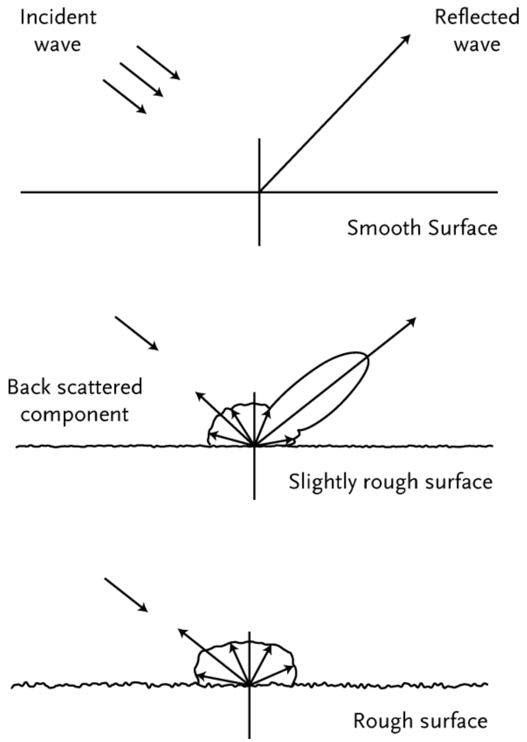
Tilt Modulation

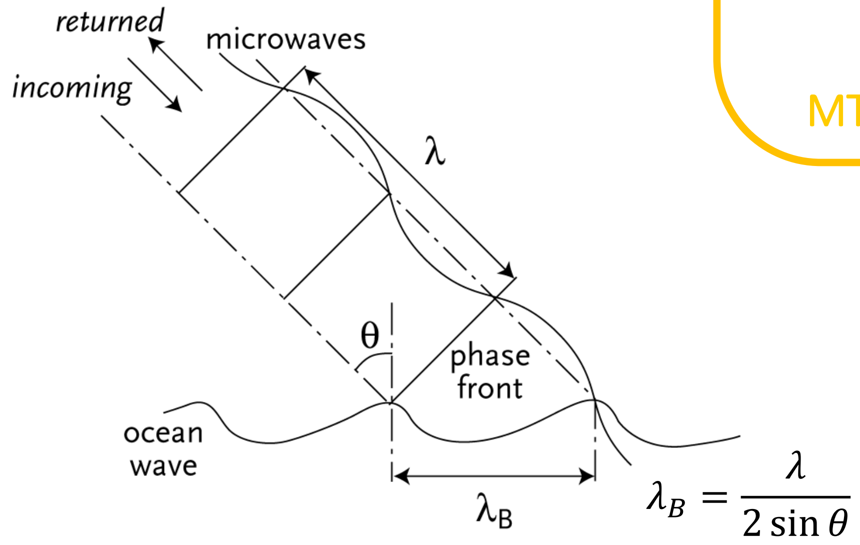


Hydrodynamic Modulation



$MTF_{RAR} = MTF_{Tilt} + MTF_{Hydr}$



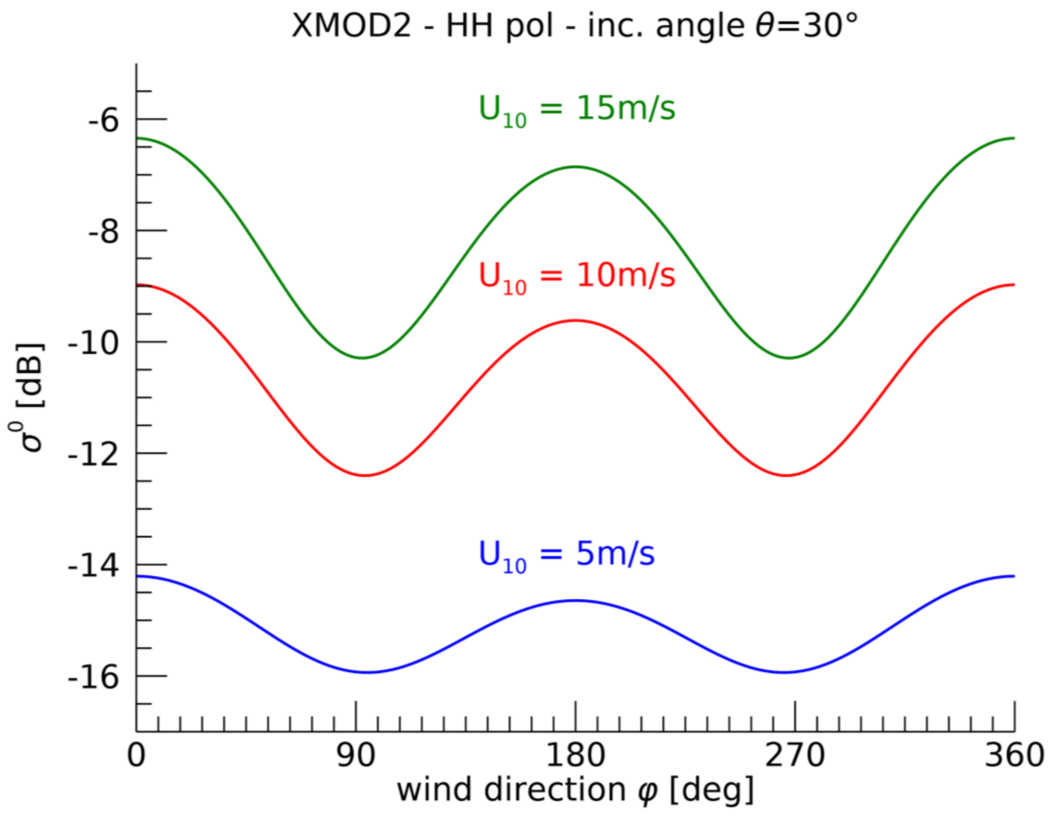


Bragg scattering: e.m. resonance with capillary waves λ_B

$$\sigma^0 \approx B_0[1 + B_1 \cos\varphi + B_2 \cos 2\,\varphi]^n$$

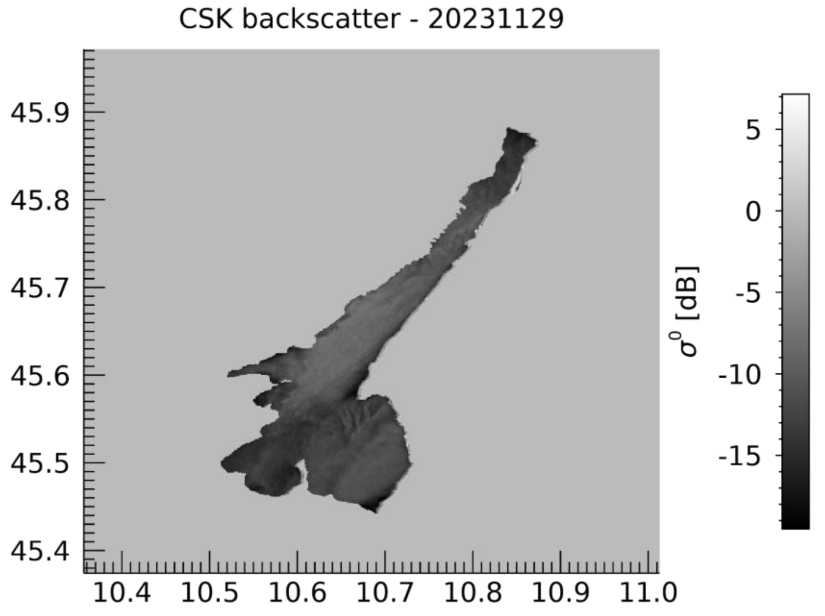
SAR sensitivity to the wind vector

$$\sigma^0 \approx B_0[1 + B_1 \cos\varphi + B_2 \cos 2\,\varphi]^n$$



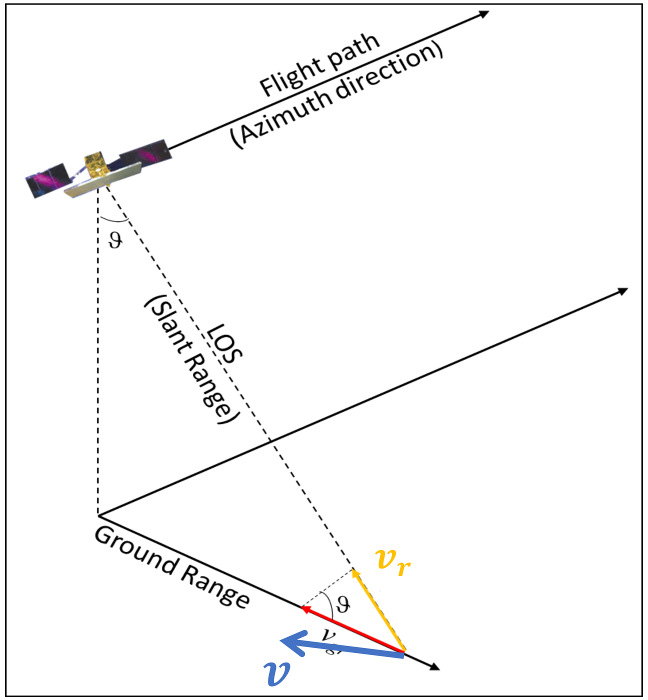
Geophysical Model Function

$$\sigma^0 = \mathrm{XMOD2}(U_{10}, \varphi, \theta, p, \lambda)$$



Ill-posed inversion problem

SAR sensitivity to water surface velocity

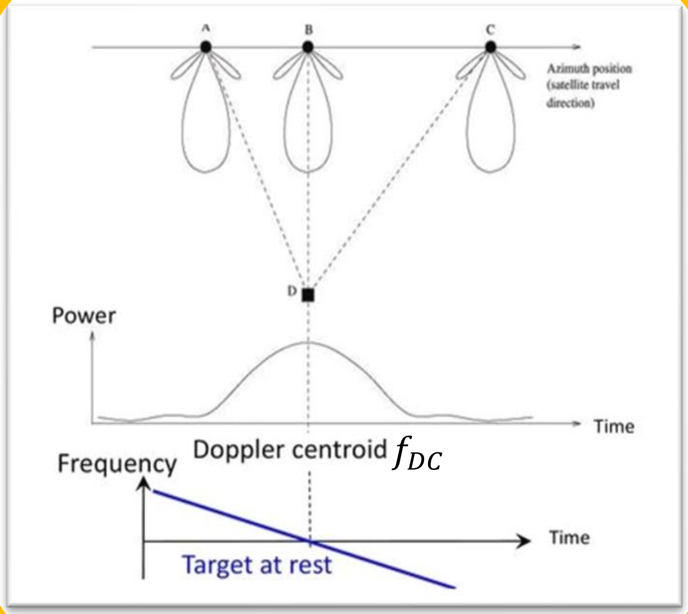


- SAR can sense currents through the Doppler centroid frequency shift of the imaged region:

$$\Delta f_{DCA} = \frac{2}{\lambda} v_r(x,r),$$

where

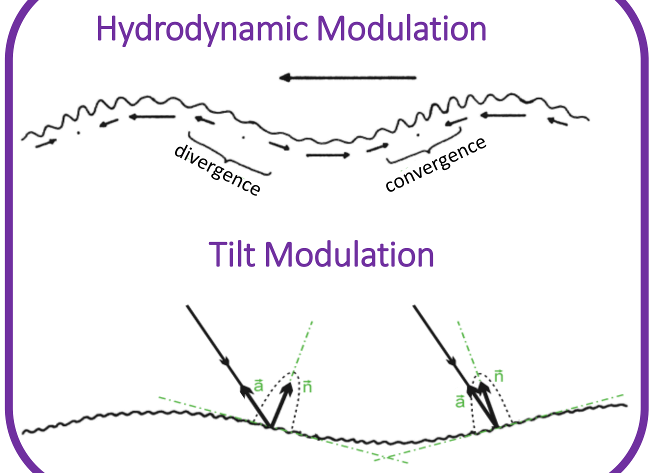
- v_r is the slant range component of the ground range component of the surface velocity vector v



$$\Delta f_{DCA}(x,r) = f_{DC}(x,r) - f_{GEO}(x,r) - f_{WW}(x,r)$$

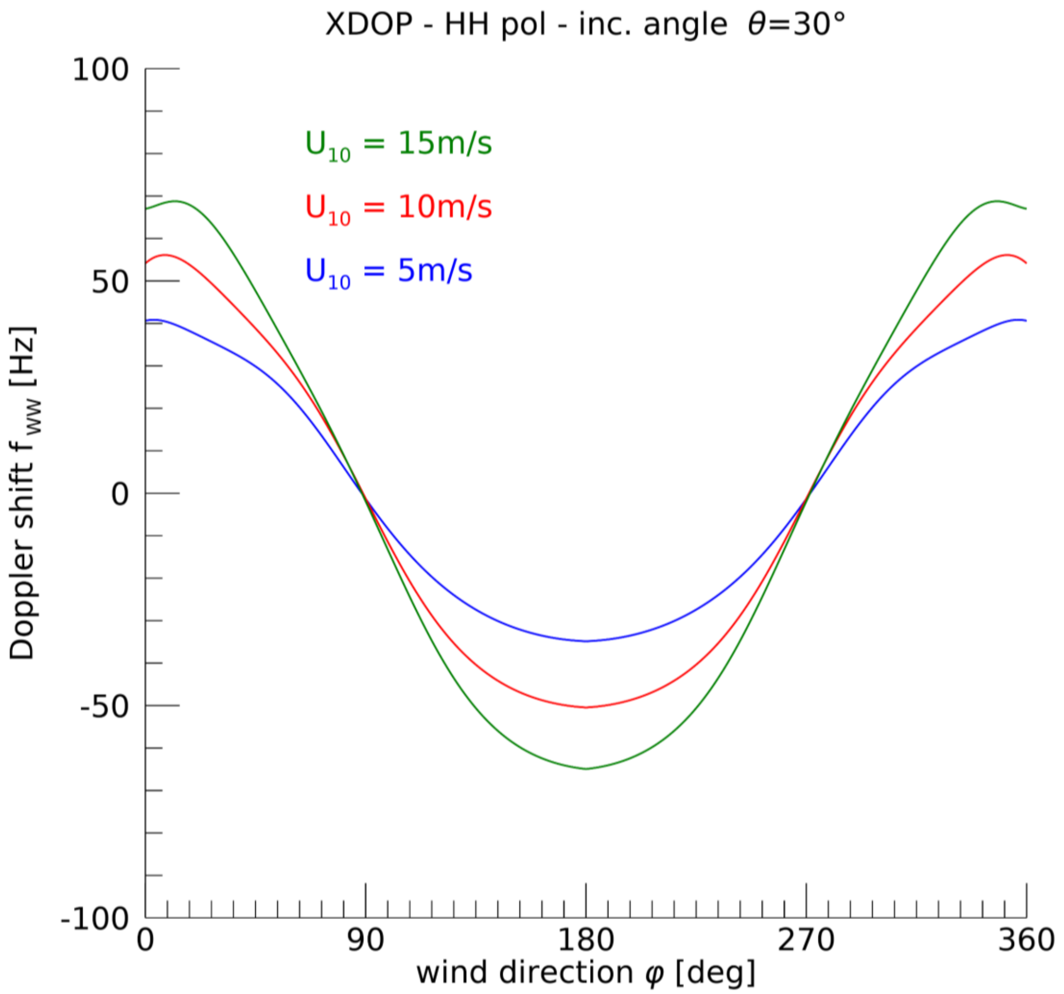
✓ f_{GEO} geometric Doppler shift due to the relative motion between the SAR and the Earth

✓ f_{WW} Doppler shift due to effects of wind and waves
  - long-wave induced surface velocity
  - tilt, hydrodynamic modulations



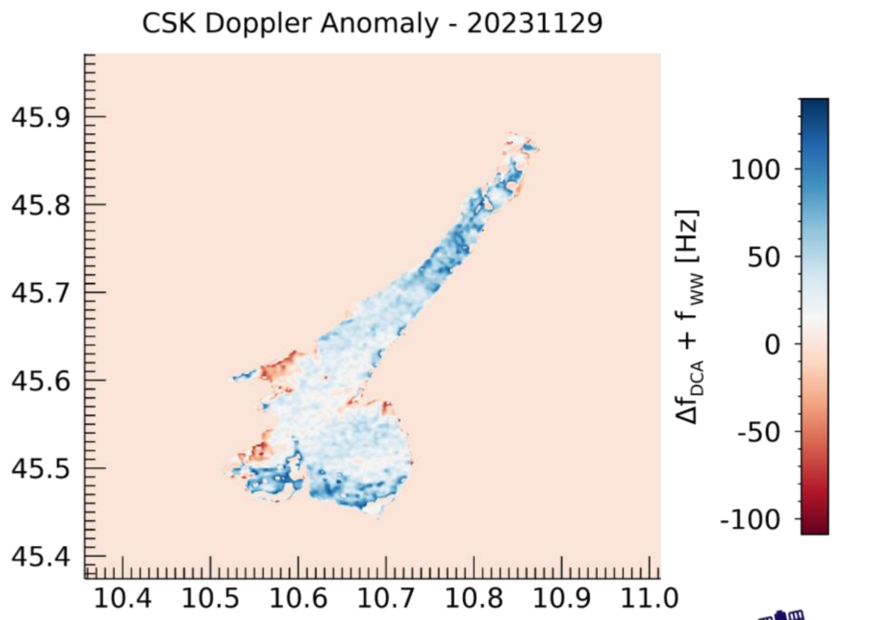
SAR sensitivity to the surface velocity

$$f_{WW} \approx \alpha_{pp} \frac{1}{1 + \exp[X(\theta, \varphi, U_{10}, pp)]} + \beta_{pp}$$



Geophysical Model Function

$$f_{WW} = \mathrm{XDOP}\left(U_{10}, \varphi, \theta, p, \lambda\right)$$



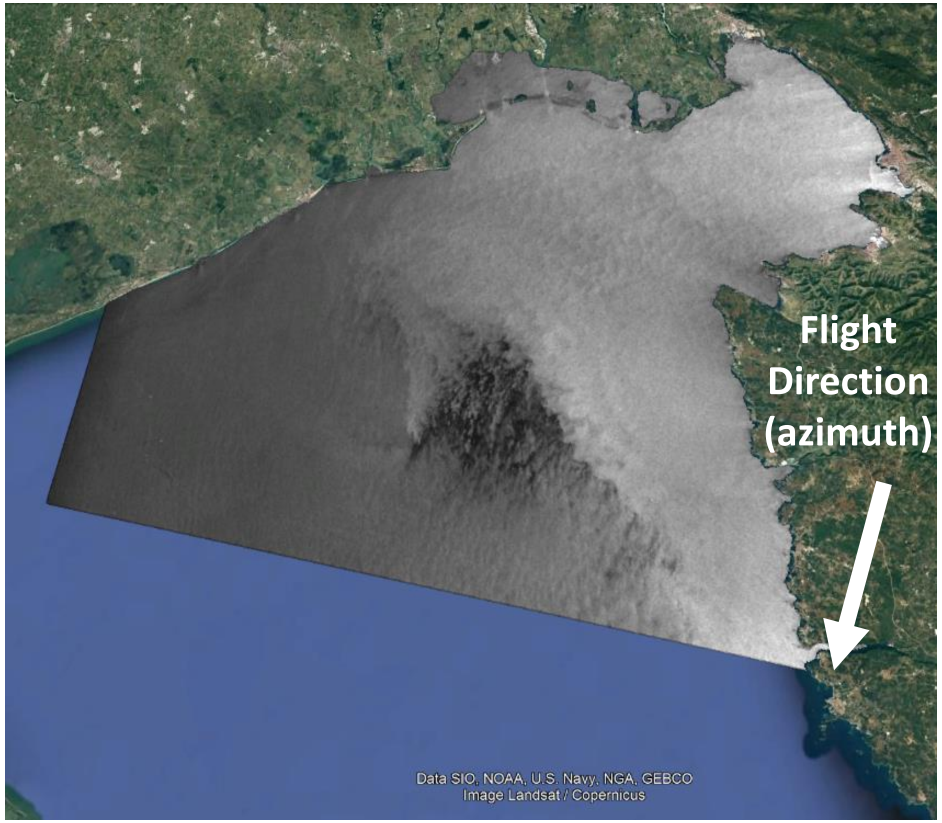
Previous experience on marine coastal areas

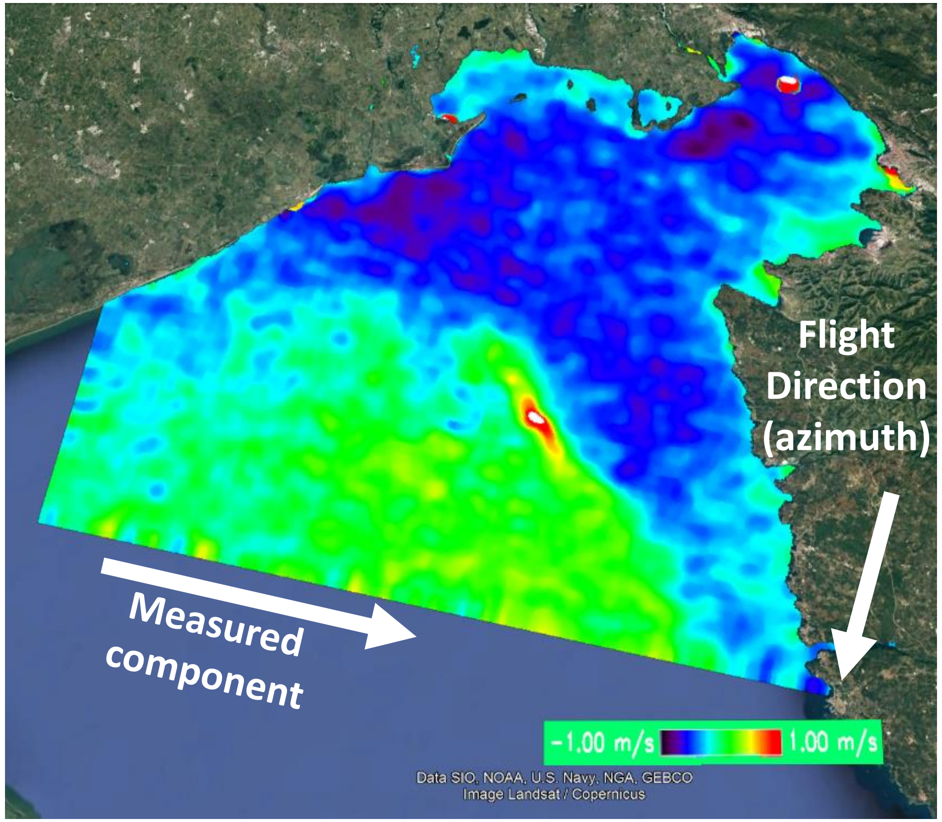
Study area: ***Gulf of Trieste*** **-** *Sensor:* ***ENVISAT*** *Orbit:* ***Descending***

Acquisition: ***3/11/2006 (9:26 (UTC)***

Wavelength	Frequency C band	Spatial Resolution
5.62 cm	5.33 GHz	20 m x 5 m

Spectral Estimation Box:	Spectral Resolution	Estimated velocity range
2.5 km x 2.5 km	2.85 Hz	±1 m/s





Envisat analysis on Garda lake

Open Access Article

Monitoring Lakes Surface Water Velocity with SAR: A Feasibility Study on Lake Garda, Italy

by Marina Amadori [1,2,†], Virginia Zamparelli [3,†], Giacomo De Carolis [1], Gianfranco Fornaro [3], Marco Toffolon [2], Mariano Bresciani [1], Claudia Giardino [1] and Francesca De Santi [1,*]

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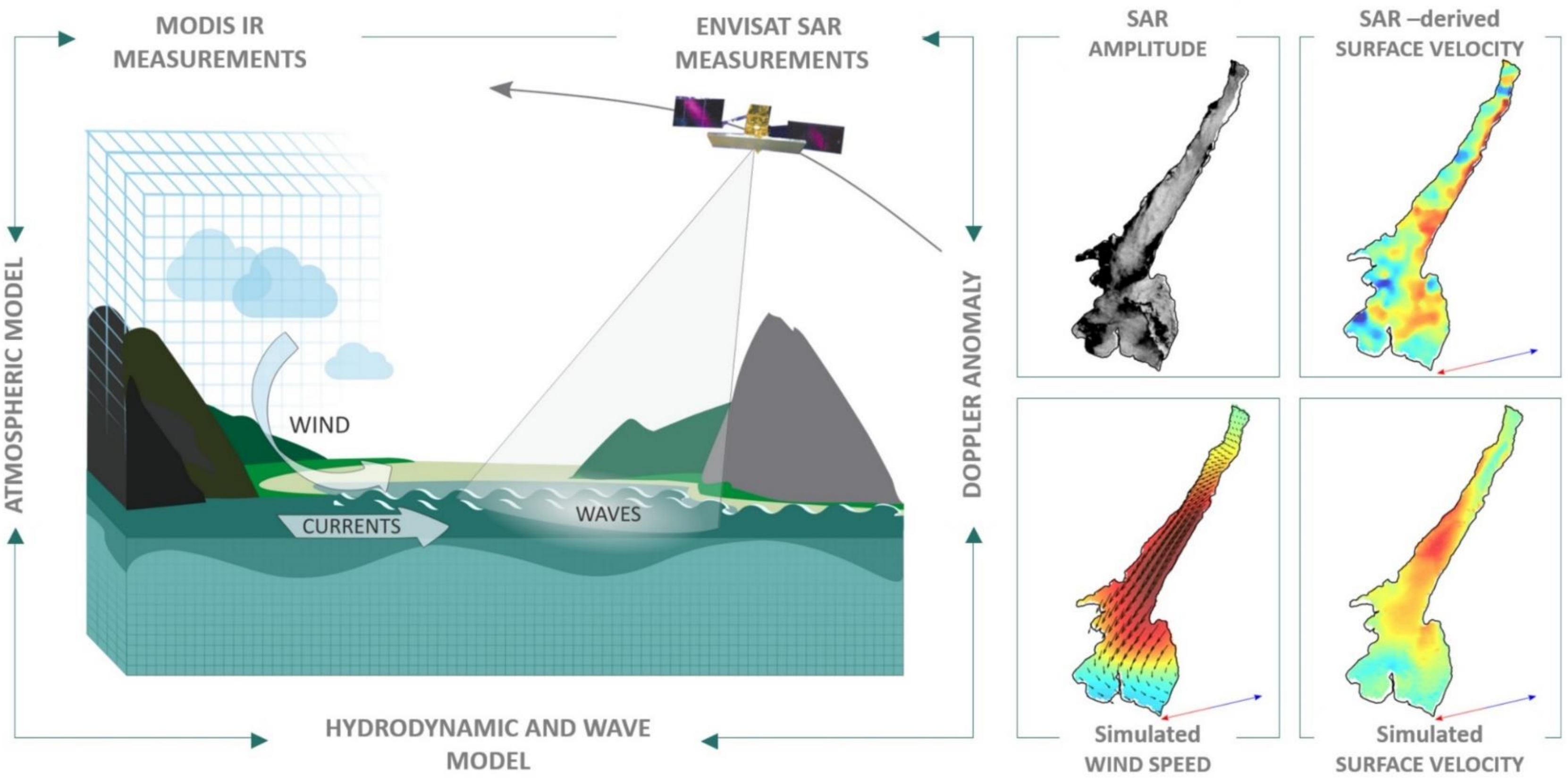
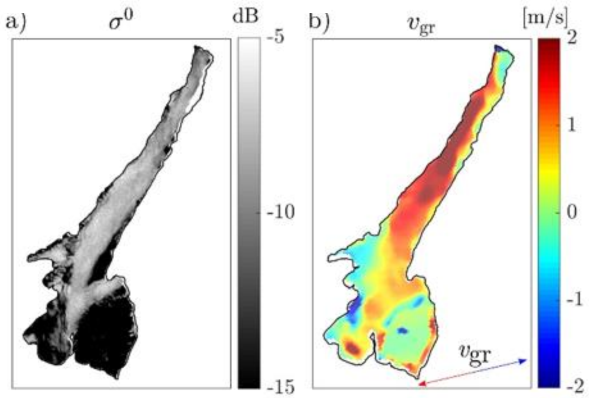
† These authors equally contributed to this work.

Remote Sens. **2021**, *13*(12), 2293; https://doi.org/10.3390/rs13122293

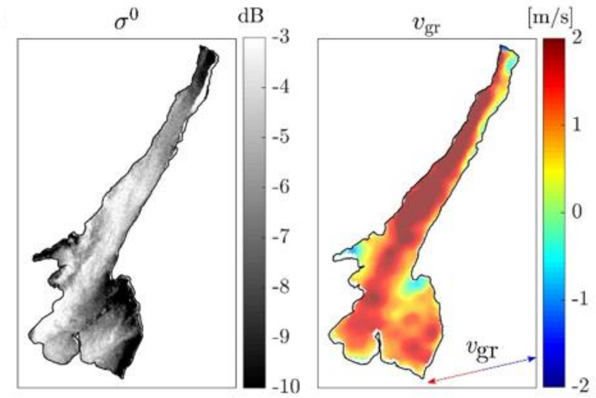


Results from ENVISAT SAR imaging

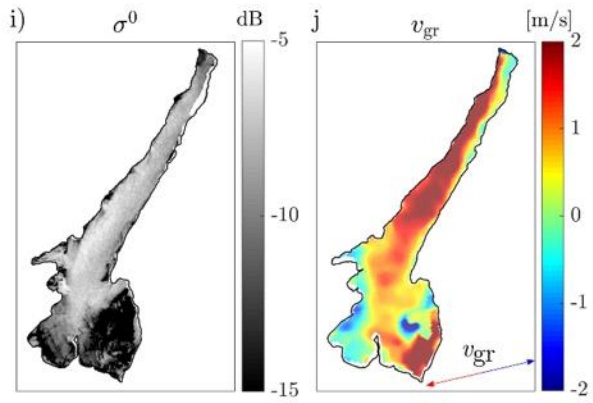
29/10/2009



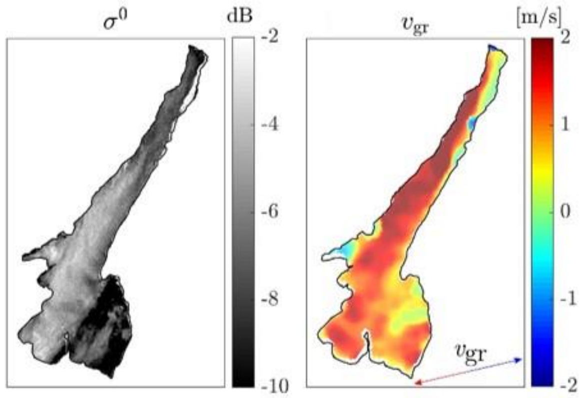
05/08/2010



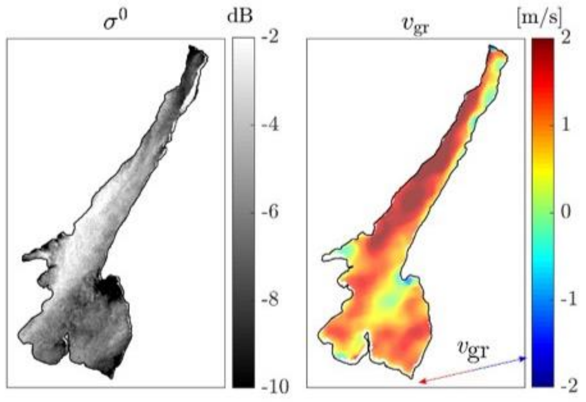
14/10/2010



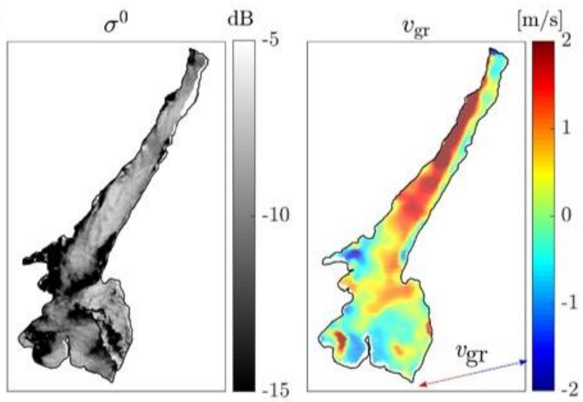
07/02/2008



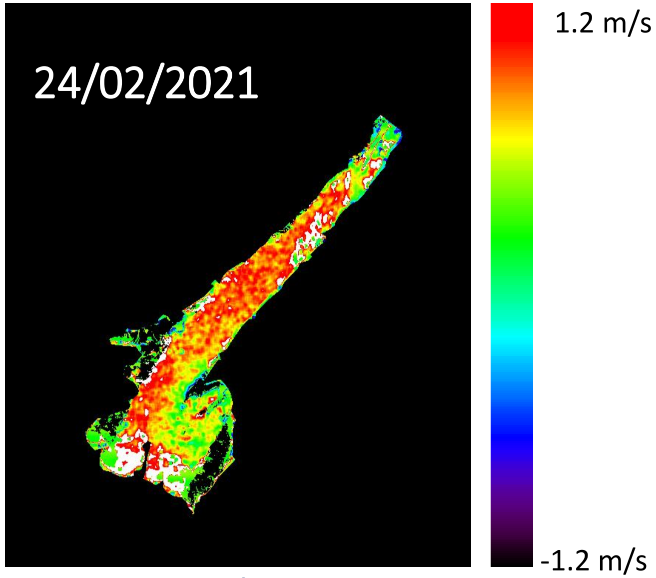
13/11/2008



11/06/2009

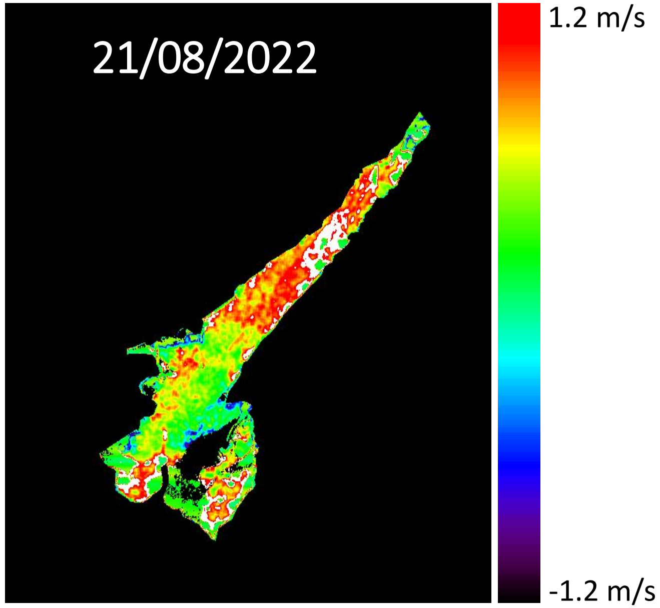


Estimation of LOS water velocity from X band CSK SAR images

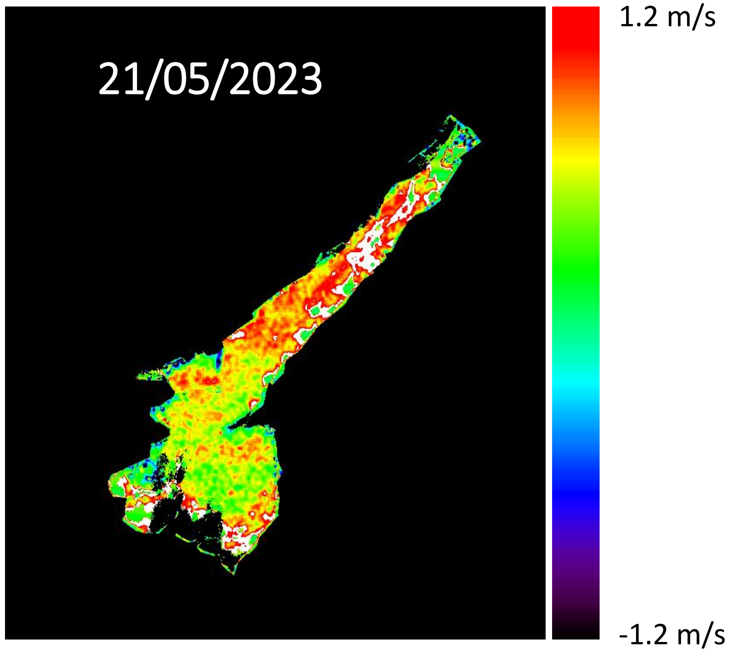


Backscatter

LOS velocity



HH polarization
spatial resolution ≈ 3 m x 3 m
spectral estimation box ≈ 0.5 km x 0.5 km
spectral resolution ≈ 5 Hz



Higher spatial resolution wrt Envisat allows detailed imaging related to wind and water movement features

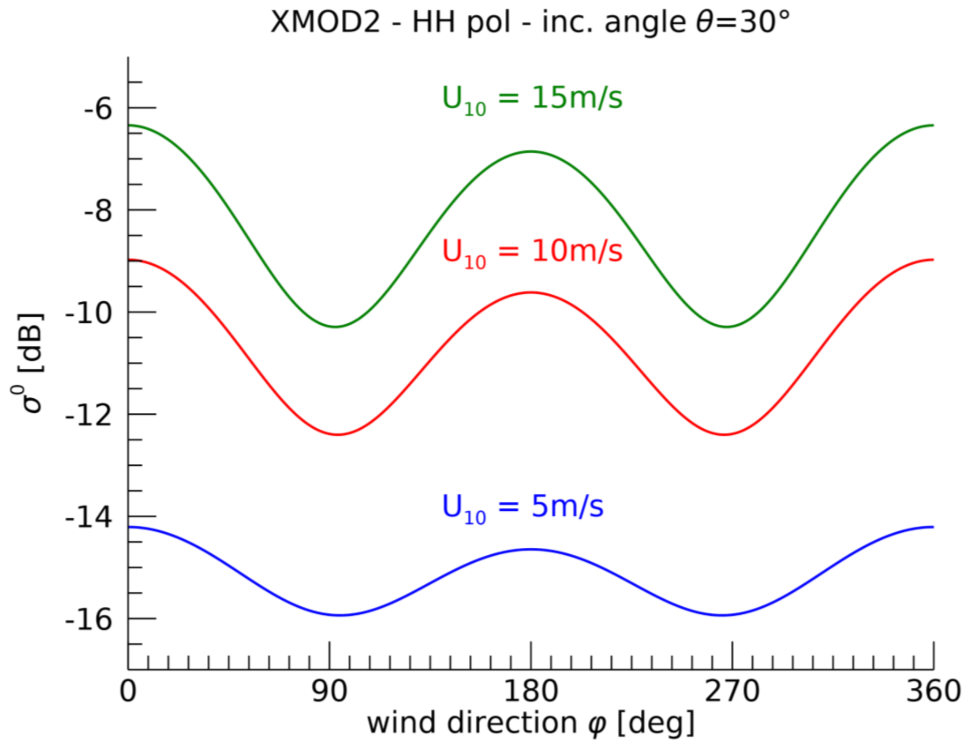
SARLAKES

Wind vector estimation from SAR: Inversion problems

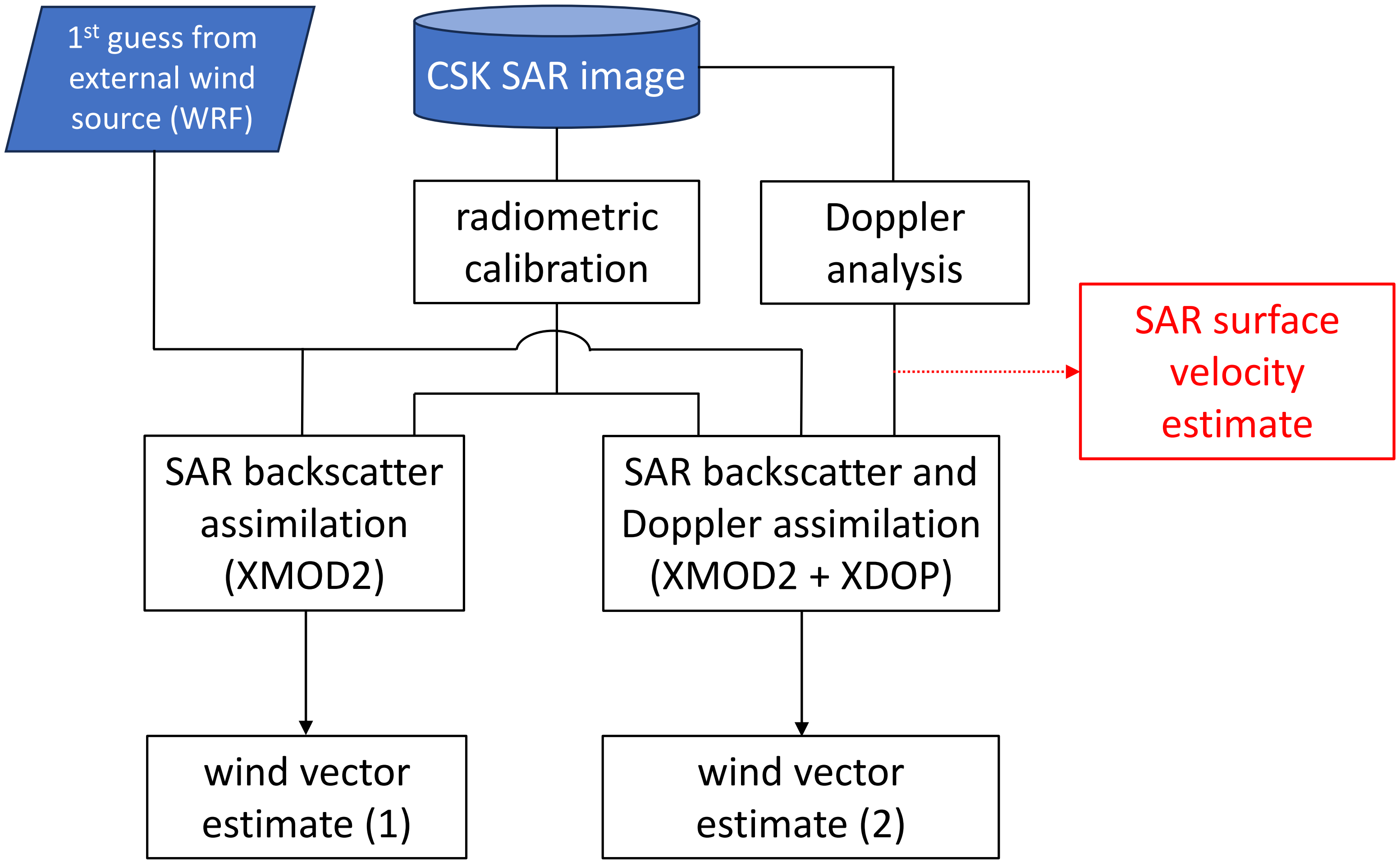
$$\sigma^{o} = B_0[1 + B_1 \cos\varphi + B_2 \cos 2\varphi]^n$$

- Two unknowns:
  - wind speed (B coefficients)
  - wind direction (φ)

- Main problems:
  - non-linearity
  - errors
  - number of independent observations over same scene (e.g., different azimuth angles, incidence angles)



Wind field retrieval from CSK SAR imagery



Bayesian estimation of the wind vector

$$J_1 = \left(\frac{\sigma^o_{CSK} - \sigma^o_{XMOD2}}{\Delta\sigma^o_{CSK}}\right)^2 + \left(\frac{U_{WRF} - U_{TRIAL}}{\Delta U_{WRF}}\right)^2 + \left(\frac{V_{WRF} - V_{TRIAL}}{\Delta V_{WRF}}\right)^2$$

$$J_2 = \left(\frac{\sigma^o_{CSK} - \sigma^o_{XMOD2}}{\Delta\sigma^o_{CSK}}\right)^2 + \left(\frac{U_{WRF} - U_{TRIAL}}{\Delta U_{WRF}}\right)^2 + \left(\frac{V_{WRF} - V_{TRIAL}}{\Delta V_{WRF}}\right)^2 + \left(\frac{f_{DC} - f_{XDOP}}{\Delta f_{DC}}\right)^2$$

$\Delta U_{WRF} = \Delta V_{WRF} = 1.73$ m/s (assumed as ECMWF)

$$\Delta\sigma^o_{SAR} = 0.1\sigma^o_{CSK}$$

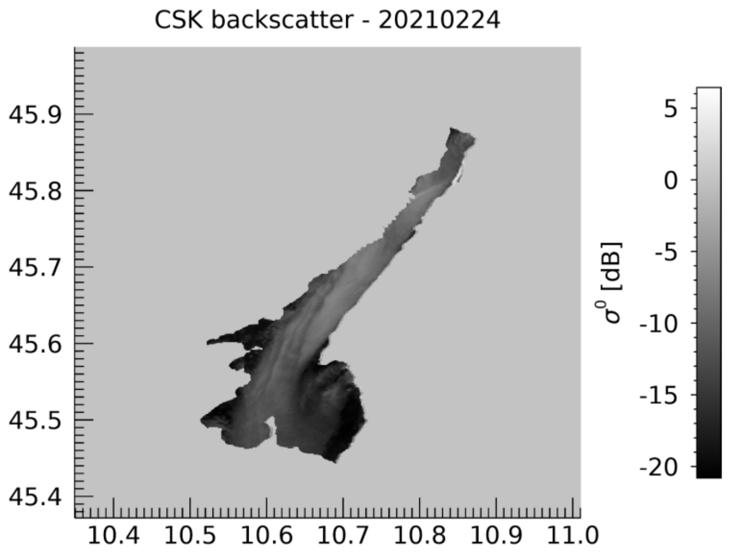
$$\Delta f_{DC} = 5\ Hz$$

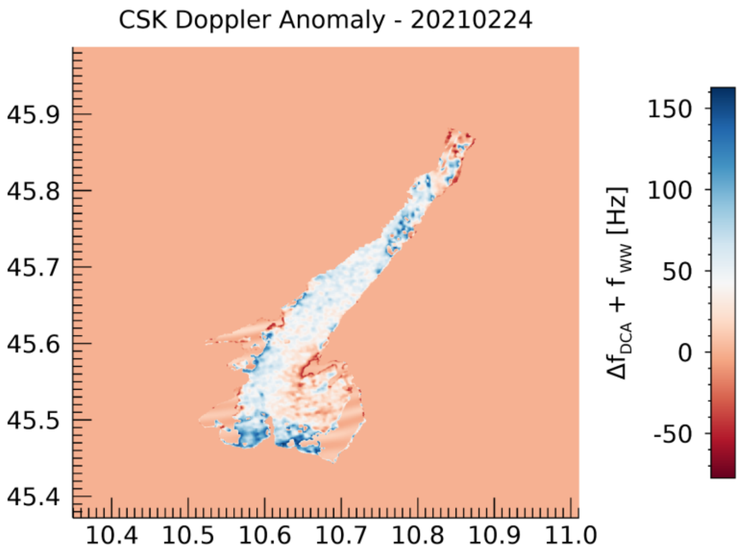
SAR retrieval of wind field

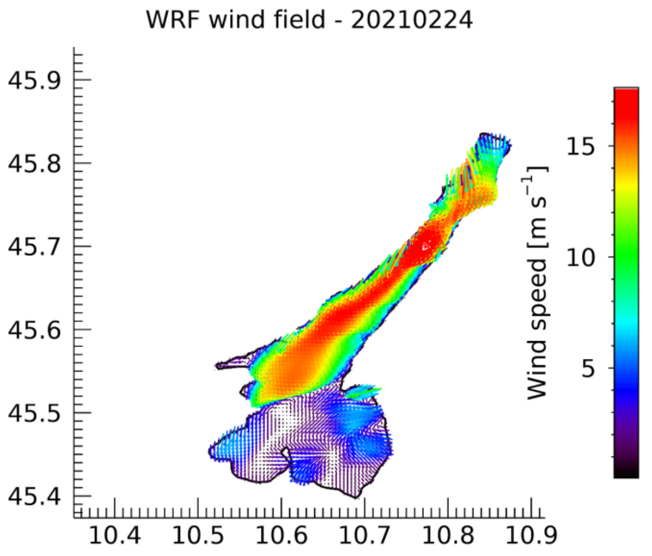
- Sensor: CosmoSkyMed
- Polarization: HH
- Mean incidence angle: ≈30 deg
- Spatial resolution: 3 m (azimuth/ground range)

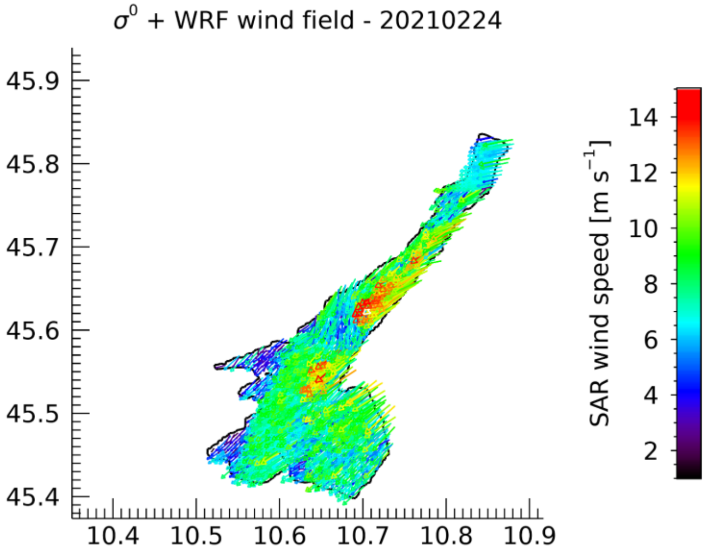
❑ 4 images selected over the Garda Lake according to favorable wind conditions ($\gtrsim 5m/s$) recorded by available anemometer stations

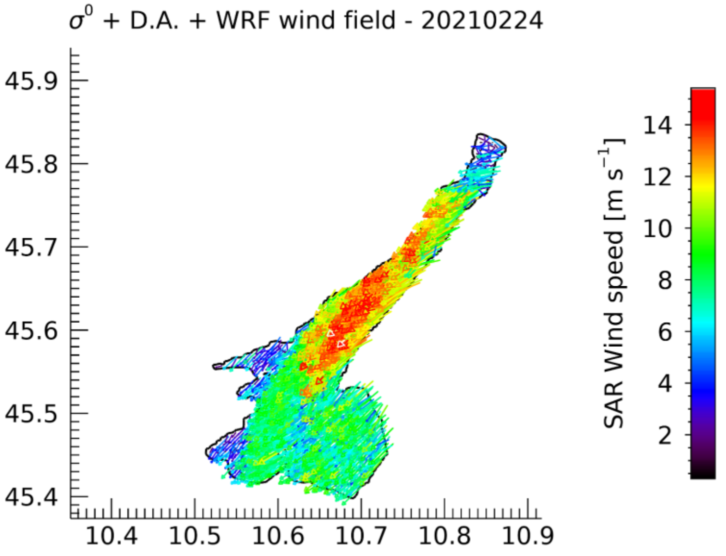
SAR retrieval of wind field – CSK 24 02 2021

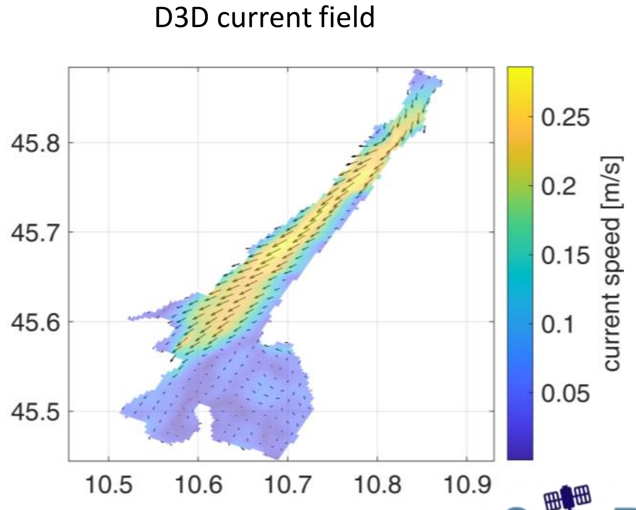




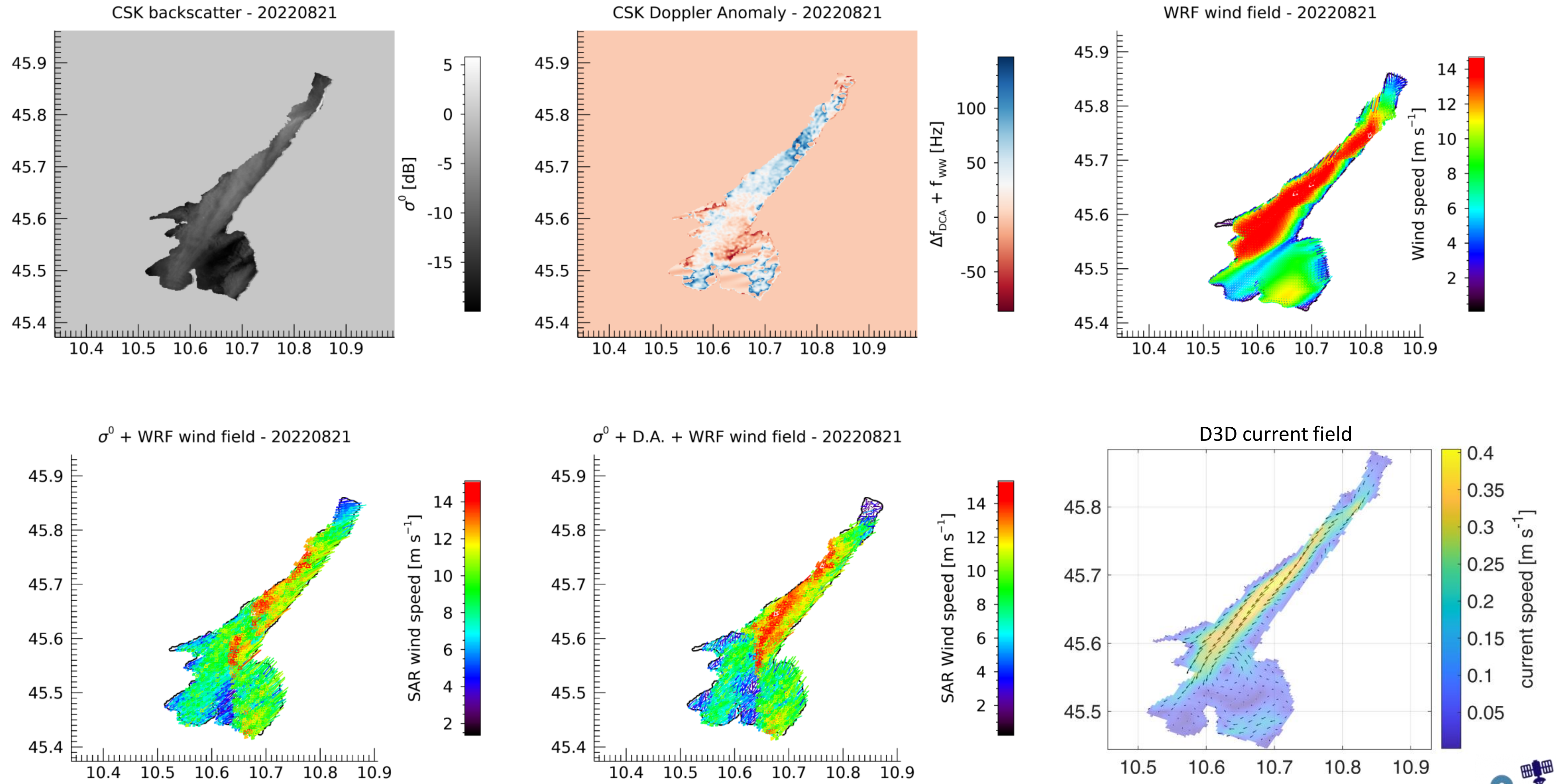




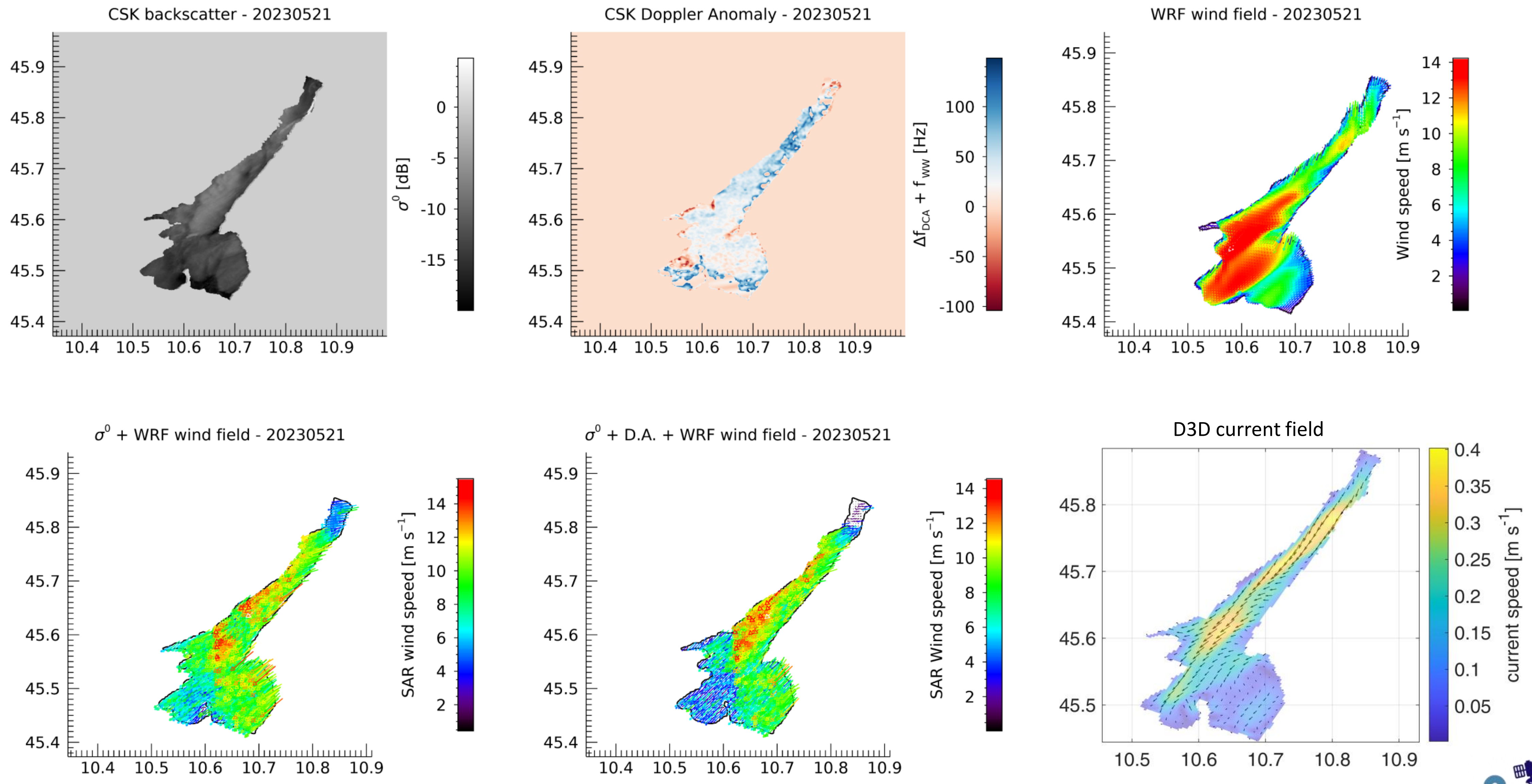




SAR retrieval of wind field – CSK 21 08 2022



SAR retrieval of wind field – CSK 21 05 2023



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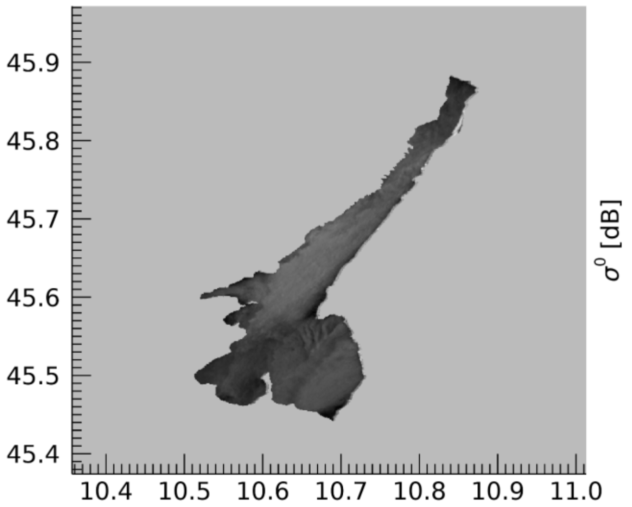
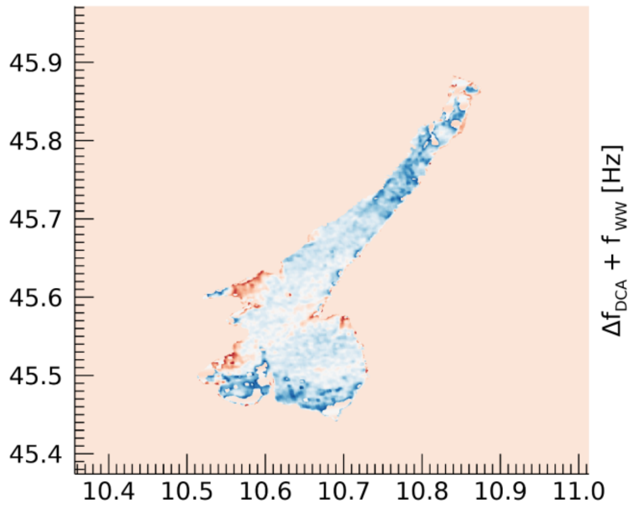
SAR retrieval of wind field – CSK 29 11 2023

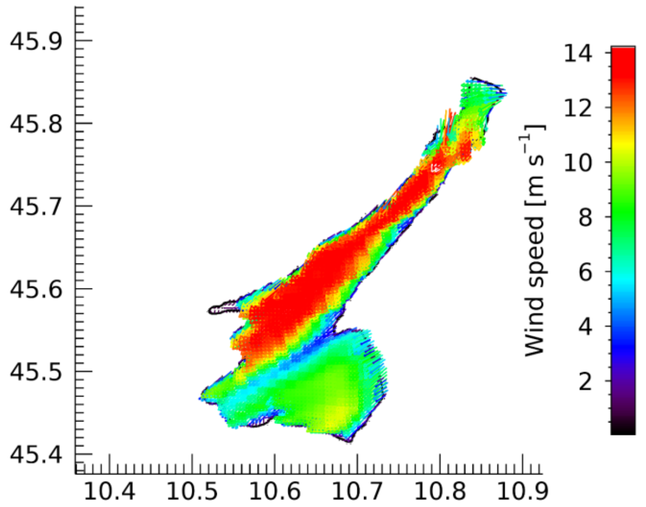
CSK backscatter - 20231129



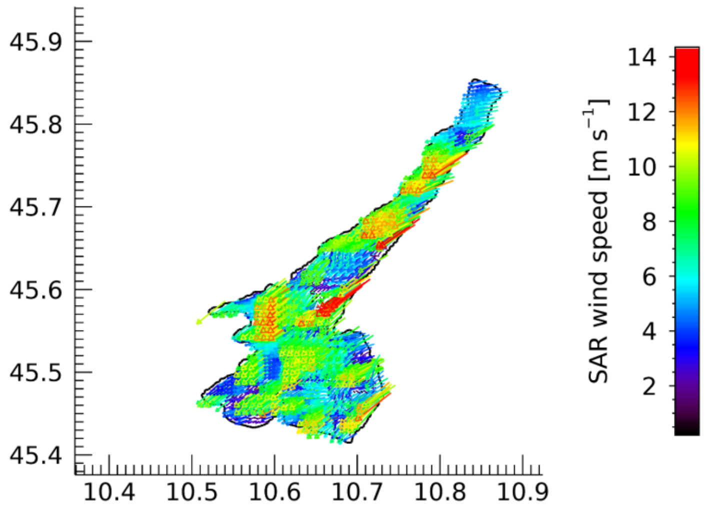
CSK Doppler Anomaly - 20231129



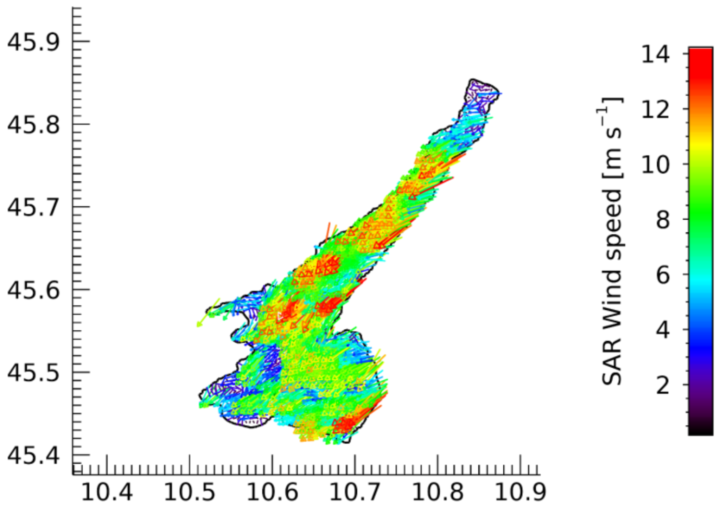
WRF wind field - 20231129



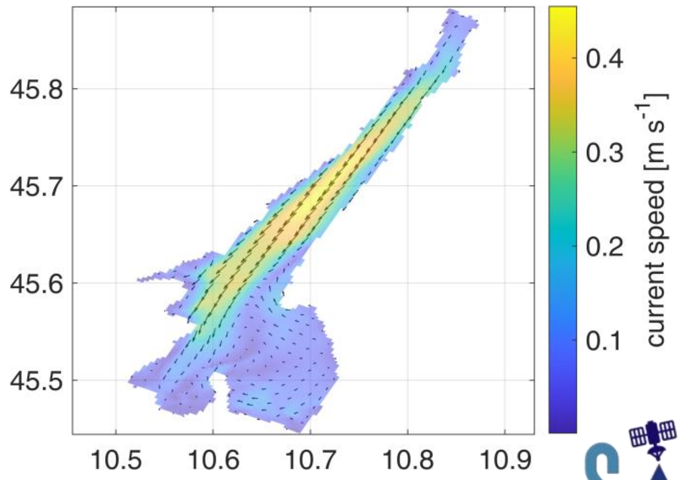
σ^0 + WRF wind field - 20231129



σ^0 + D.A. + WRF wind field - 20231129



D3D current field



Conclusions

- Garda lake is a large water body with dimensions comparable to an enclosed sea;
- Methodologies and procedures developed for open sea and coastal areas have been applied after proper changes to retrieve wind and water velocity fields over the Garda lake;
- SAR inversion procedures need support from atmospheric, current and wave models running at basin scale with proper temporal and spatial resolution;
- Results encourage to continue research aimed at refining GMFs to better describe the environmental conditions typical of Garda lake.

Thank you for your attention!!