Cross-pol NRCS & Doppler for Ocean Remote Sensing

A. Mouche & B. Chapron
Ifremer

Content

- Doppler
- Cross-polarization

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- Doppler
  - Background
  - ENVISAT experience
  - Conclusions & Perspectives
- Cross-polarization
  - Cross-polarization and wind with RadarSat-2
  - Model & Understanding of the measurement
  - Conclusions & Perspectives

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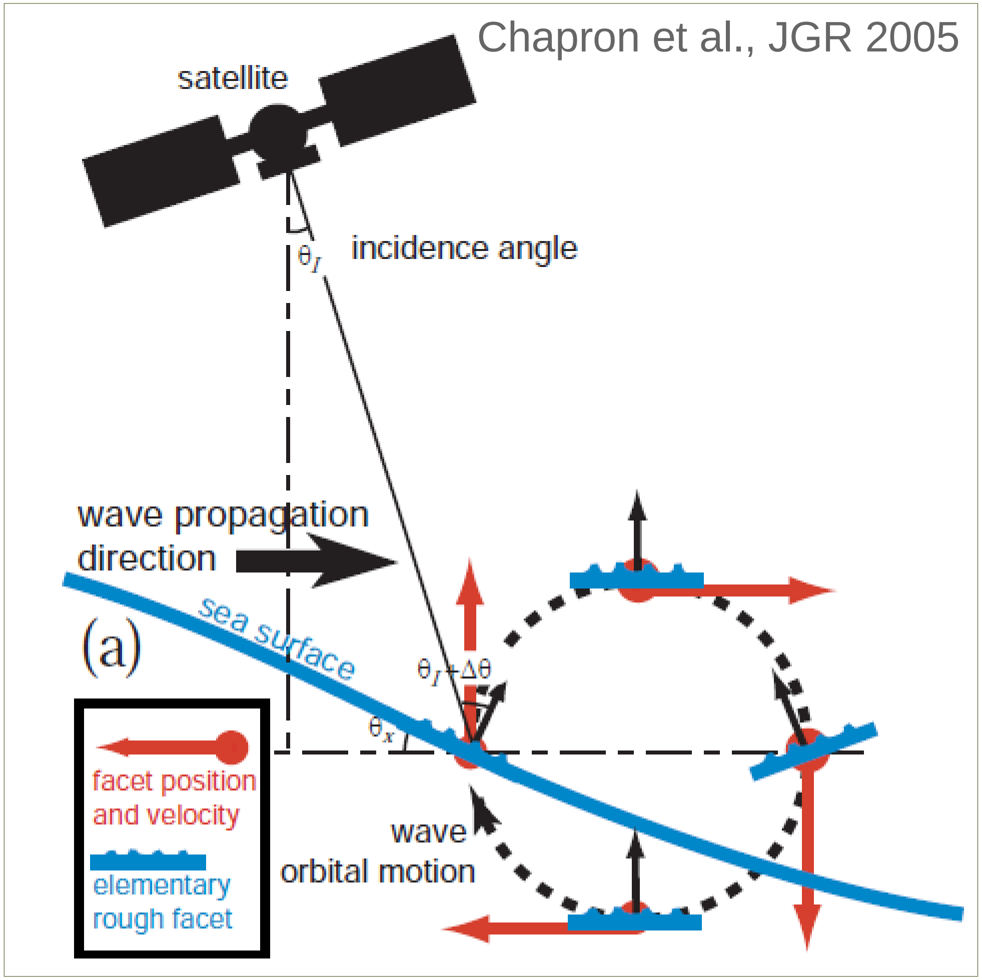
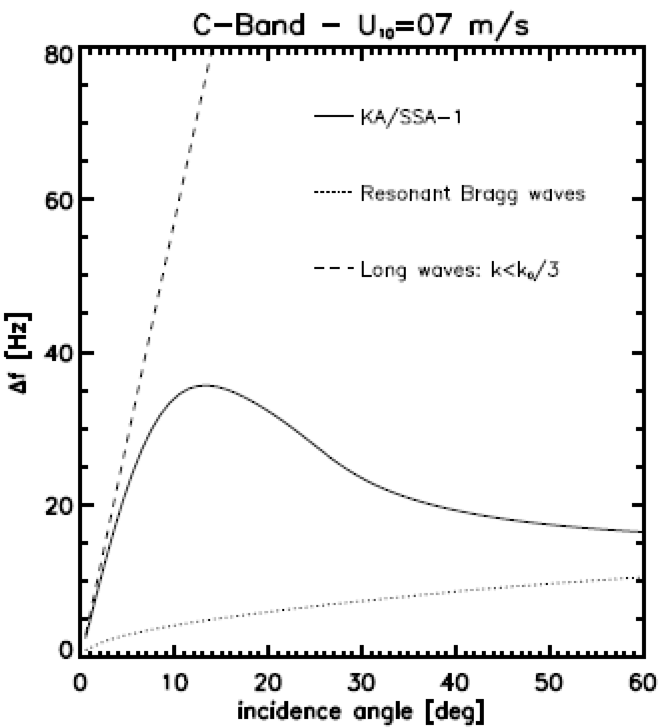


Observed Doppler velocities =
underlying current
+ background sea state
+ sea state perturbated by surface current

- First order : underlying current + background sea state
- Second order : sea state perturbated by surface current. Advanced models such as Doprim are needed to take into account modification of wave spectrum by surface current gradients.

$$\bar{c} = \int c(\vec{k})\Lambda(\vec{k})\mathrm{d}\vec{k} / \int \Lambda(\vec{k})\mathrm{d}\vec{k}$$

(a)



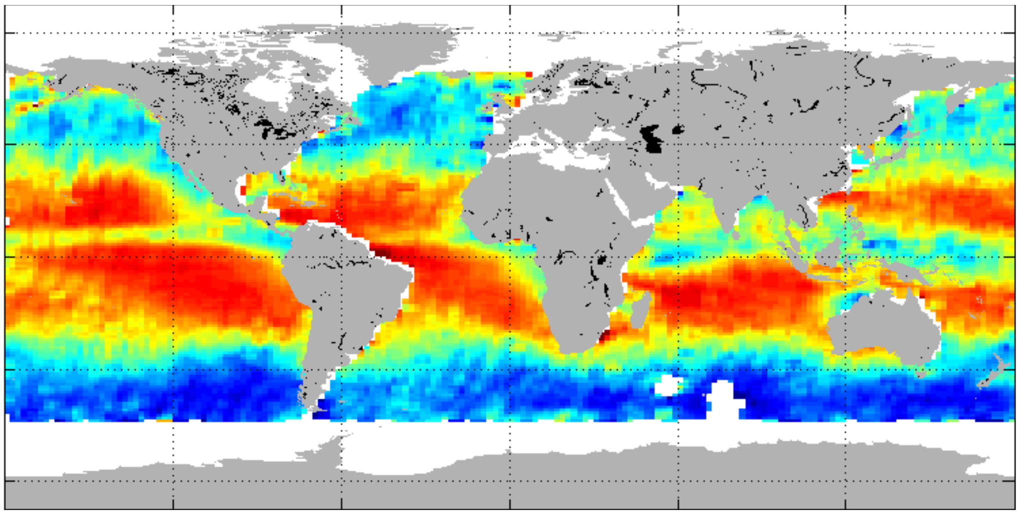
- Sea surface is a multi-scale surface
- The different individual scale contributions to the overall NRCS may be described by a distribution function Λ(k). Λ(k)dk represents the relative contribution to the total radar cross section related to wave number in the range k to k + dk.
- Λ(k) is different depending on the scattering mechanisms rôle for each scale and radar conf.
- For pure Bragg condition :

$$\Lambda(\vec{k}) = \delta(2k_e \sin\theta_I)S(\vec{k}).$$

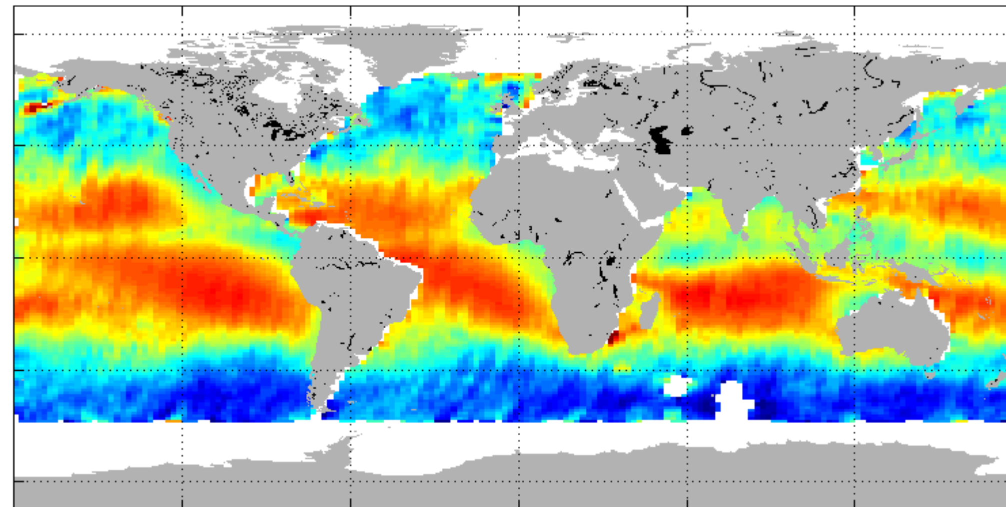
- For GO condition :

$$\Lambda(\vec{k}) = k^2 S(\vec{k})$$

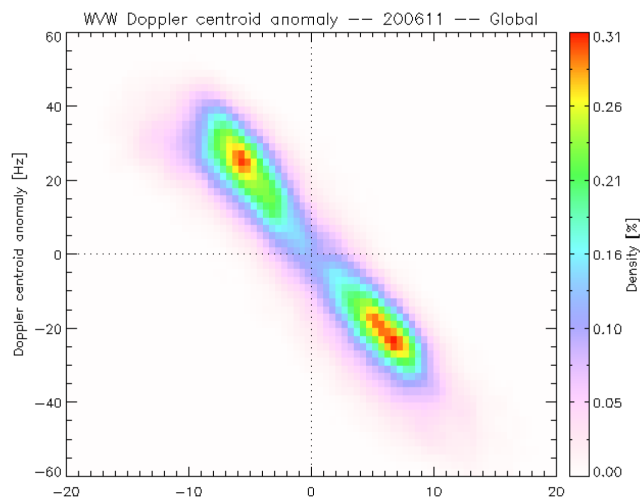
Monthly Mean of Doppler and Radial Wind speed



Doppler Anomaly/Velocity
(ASAR WM)



Radial Wind Speed
(ECMWF)



ENVISAT Cal-Val review in 2002

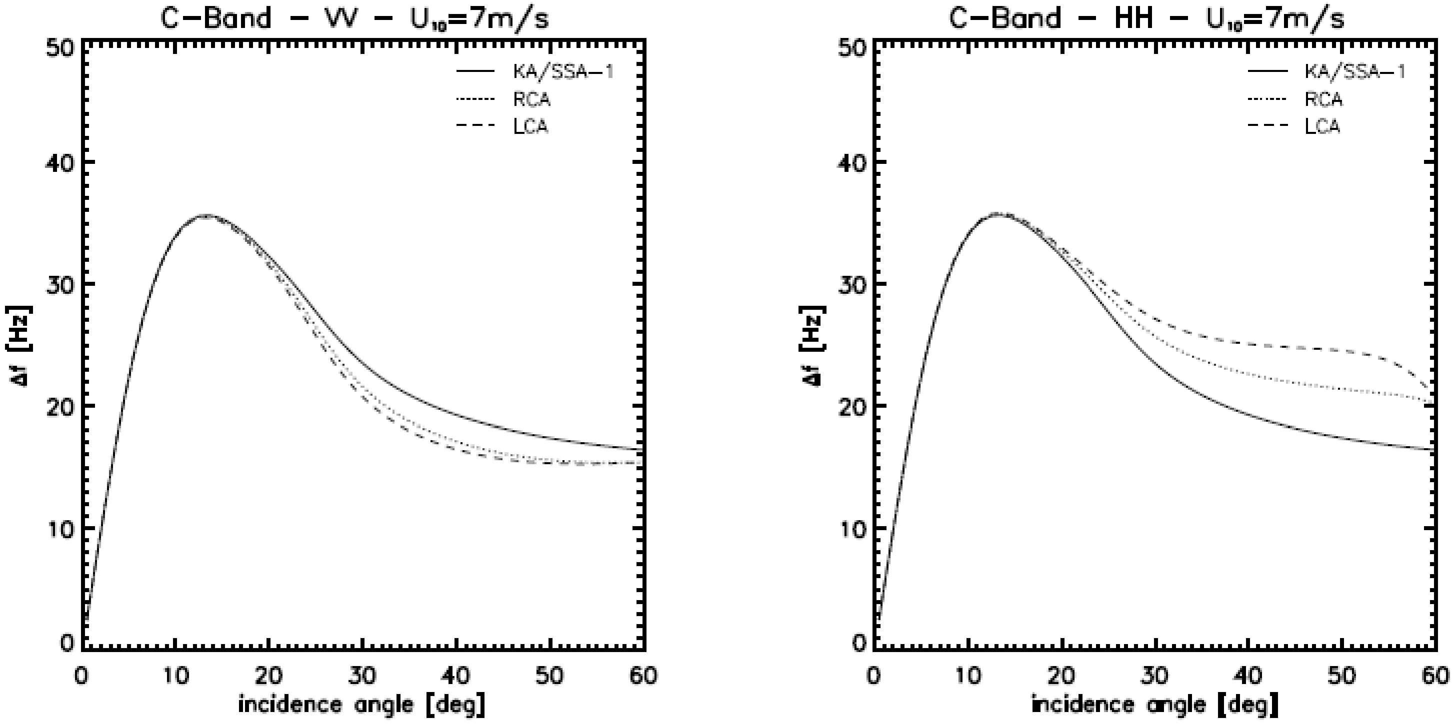


Figure 3. Doppler frequency at C-band predicted using KA/SSA-1 (solid), RCA (dotted) and LCA-1 (dashed) models as a function of incidence angle in up-wind configuration. Wind speed is 7 m/s. (a) VV polarization. (b) HH polarization.

- Doppler decreases with increasing incidence angle
  This is consistent with the fact that the relative relative impact of Bragg scatterers with small slopes increases with incidence angle.

- Over Sea surface, for a given wind speed, Doppler signal is expected to be higher in HH than in VV.
  This is consistent with the fact that the relative impact of scatterers with steep slopes (breaker) larger and faster than Bragg scatterers with small slopes is higher in HH than in VV.

Mouche et al., WRM 2008

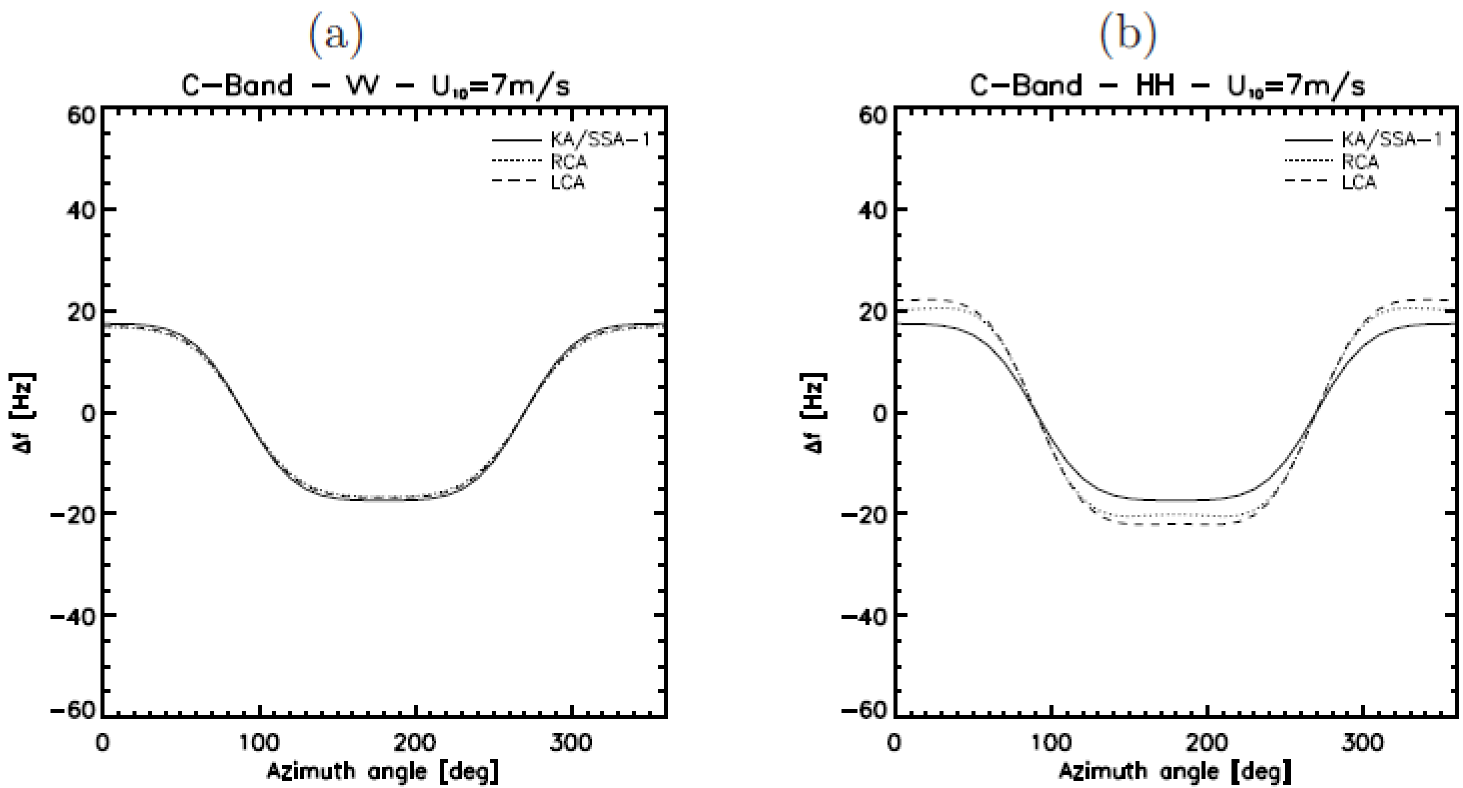


Figure 4. Doppler frequency at C-band predicted using KA/SSA-1 (solid), RCA (dotted) and LCA-1 (dashed) models as a function of azimuth angle at 50°. Wind speed is 7 m/s. (a) VV polarization. (b) HH polarization.

- Over sea surface, Doppler signal is wind direction dependent. It reaches Zero at crosswind.

Mouche et al., WRM 2008

Summary

Over sea surface, Doppler signal

- decreases with increasing incidence angle
- is higher in HH than in VV
- is wind direction dependent

A different set of antenna may with various incidence angle, azimuth look angle and polarization may allow to maximize/minimize geophysical signature.

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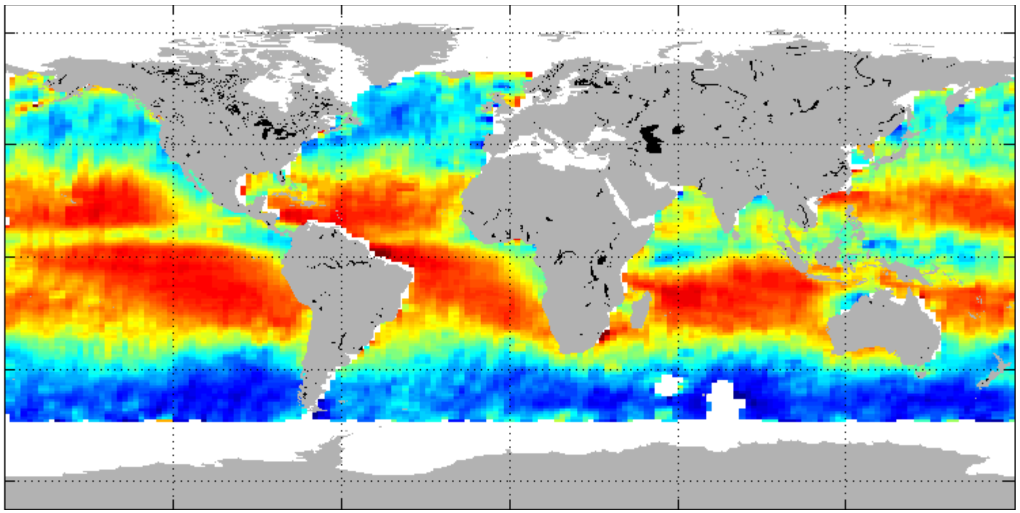

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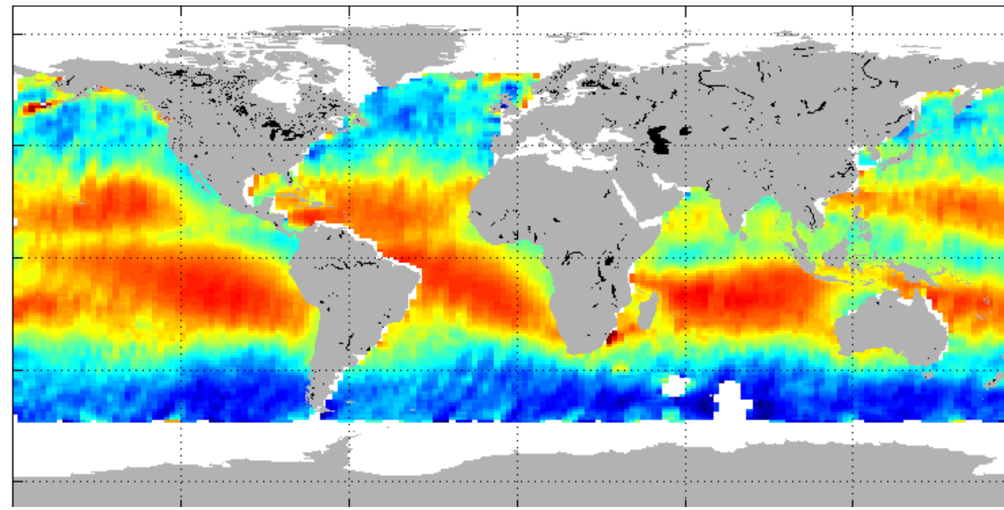

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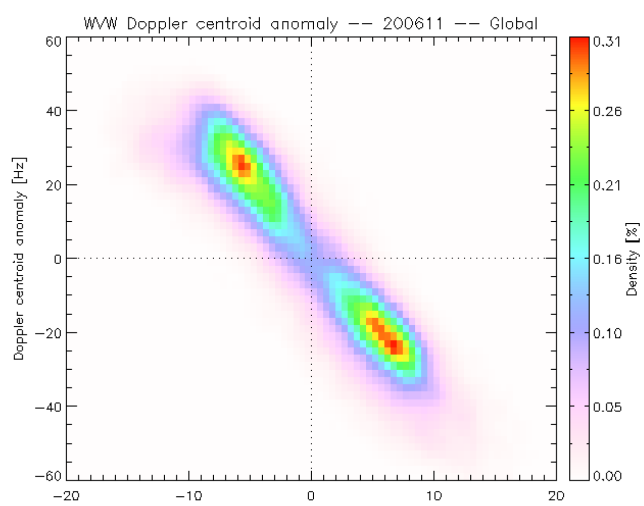
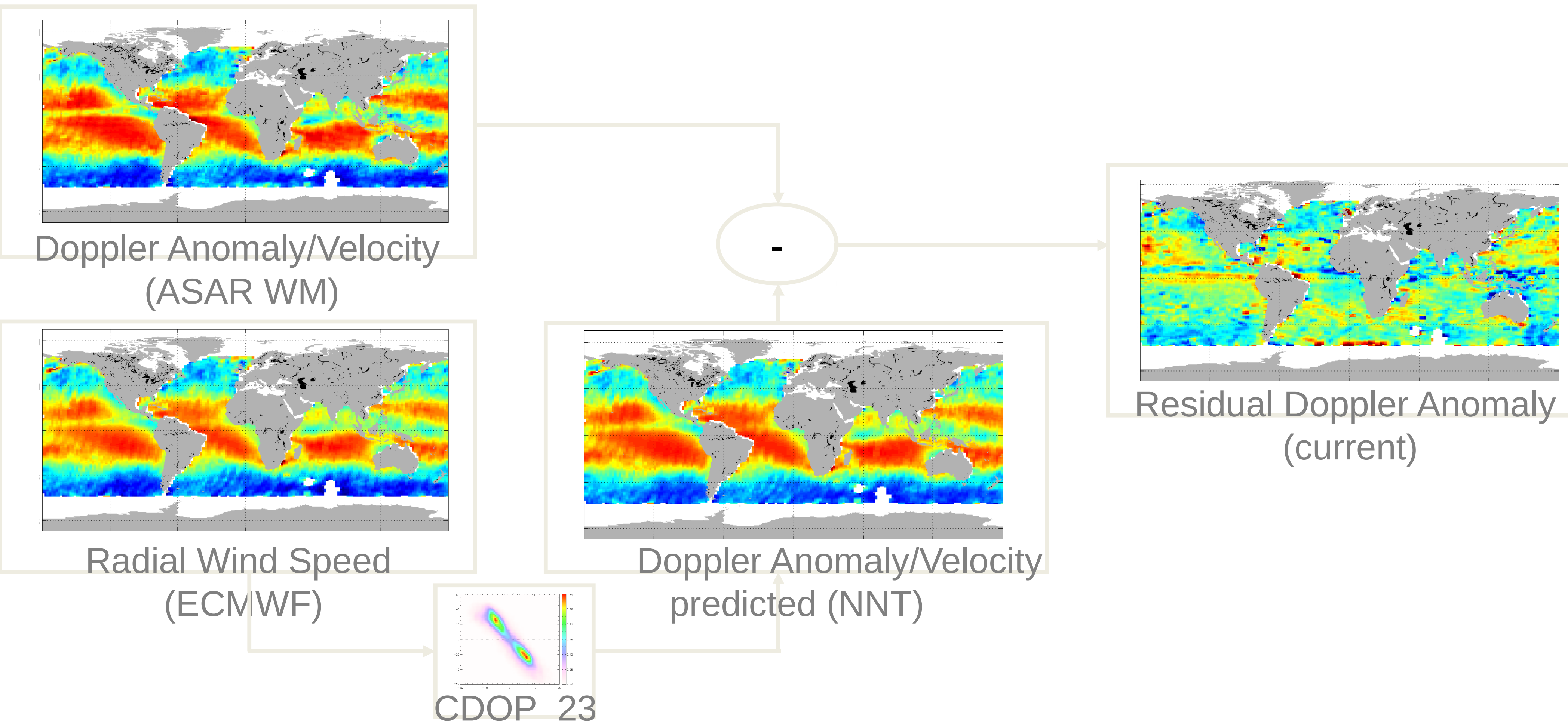


A NN GMF has been developed to get Doppler contribution from sea state based on wind

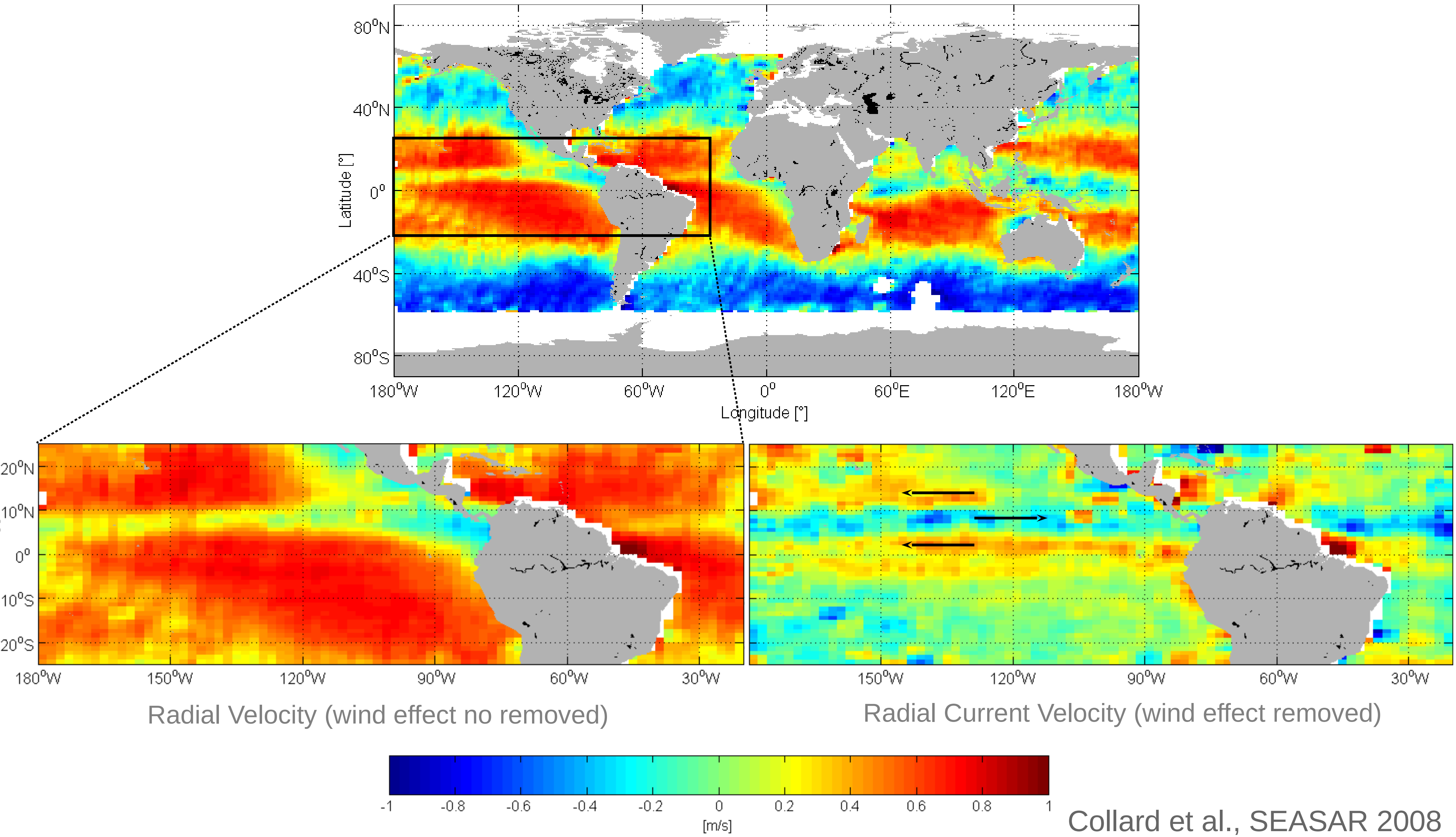
Collard et al., SEASAR 2008

Simple Methodology to remove sea state contribution



Collard et al., SEASAR 2008

Simple Methodology to remove sea state contribution
Application to Equatorial Pacific Area



Collard et al., SEASAR 2008

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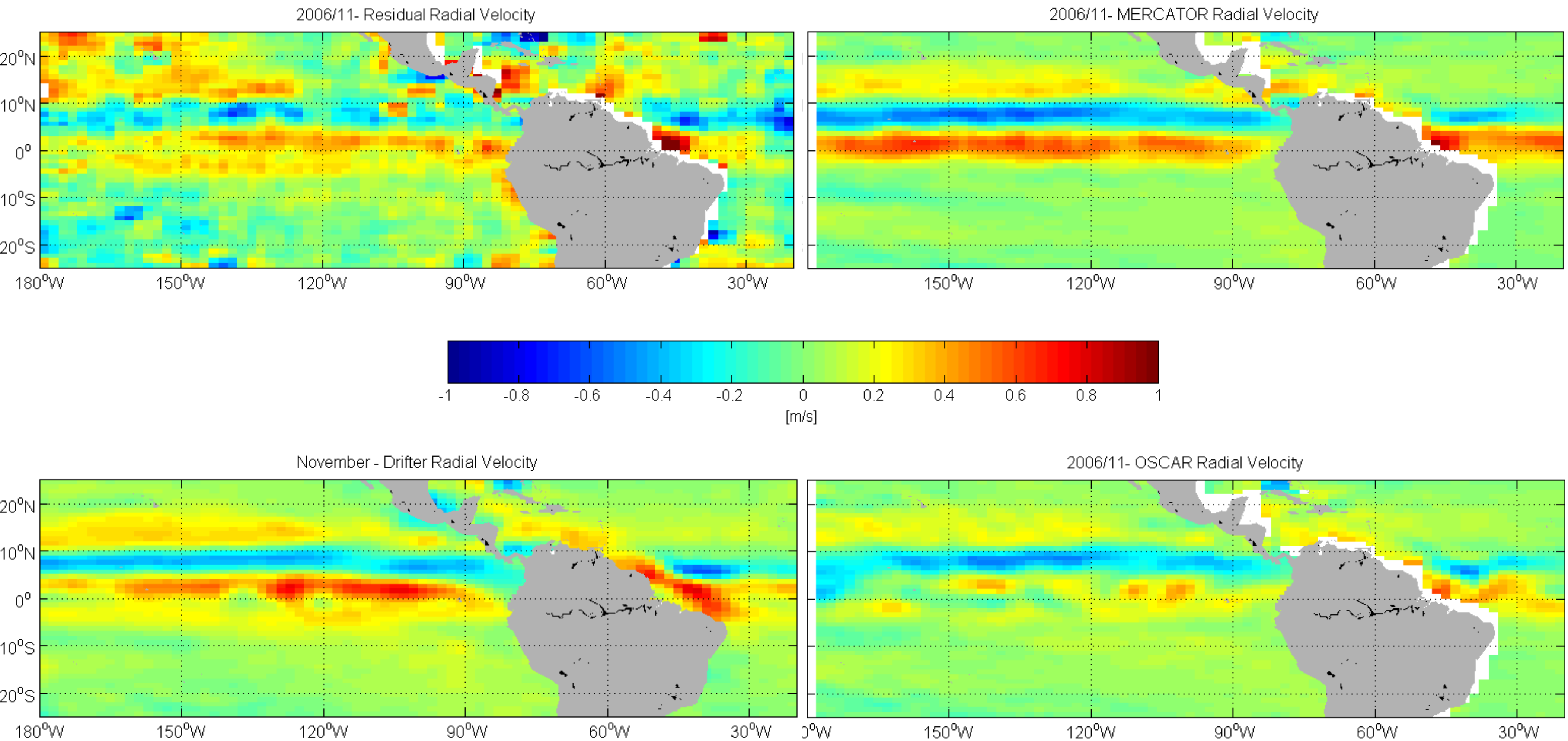

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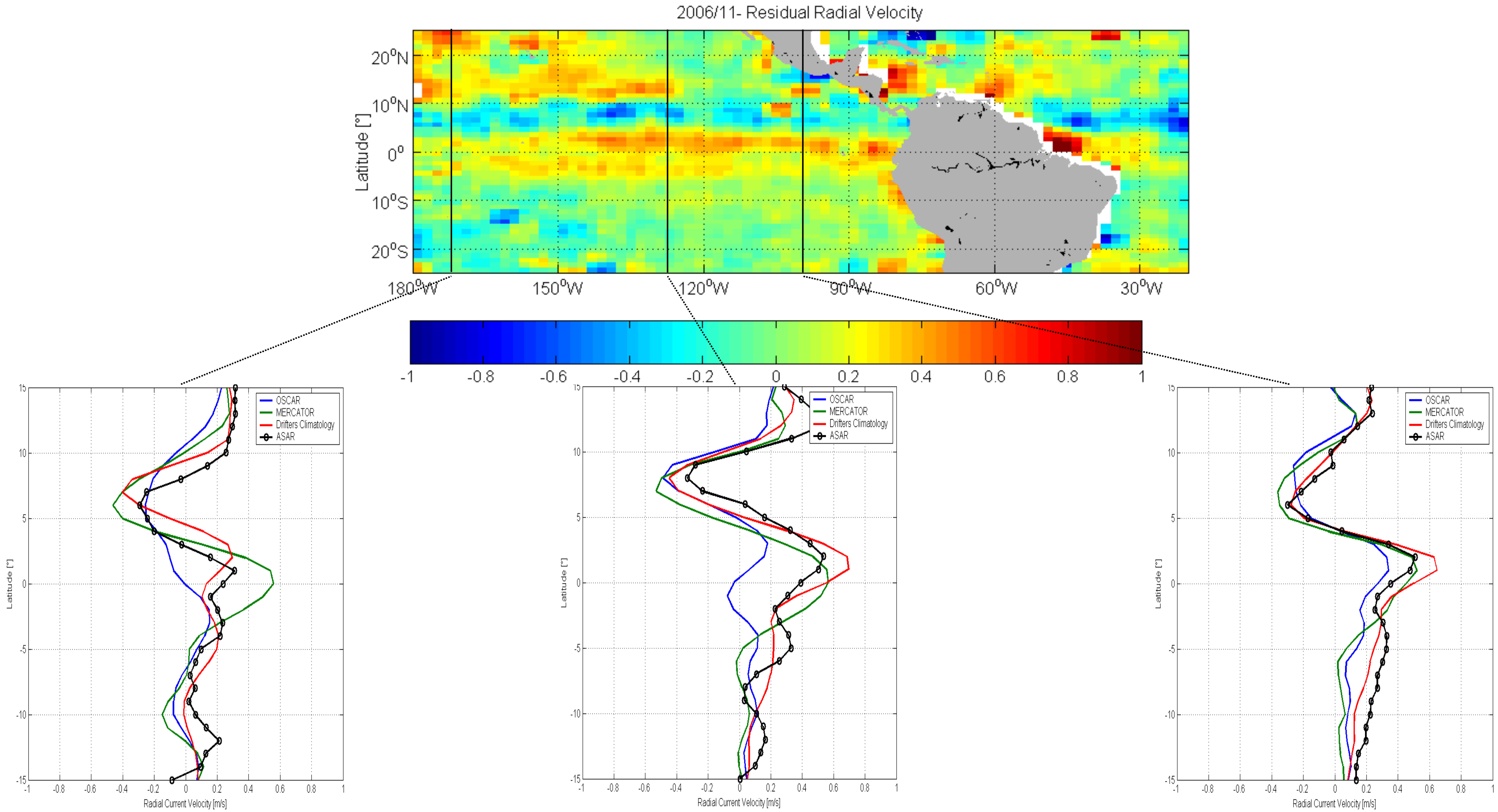


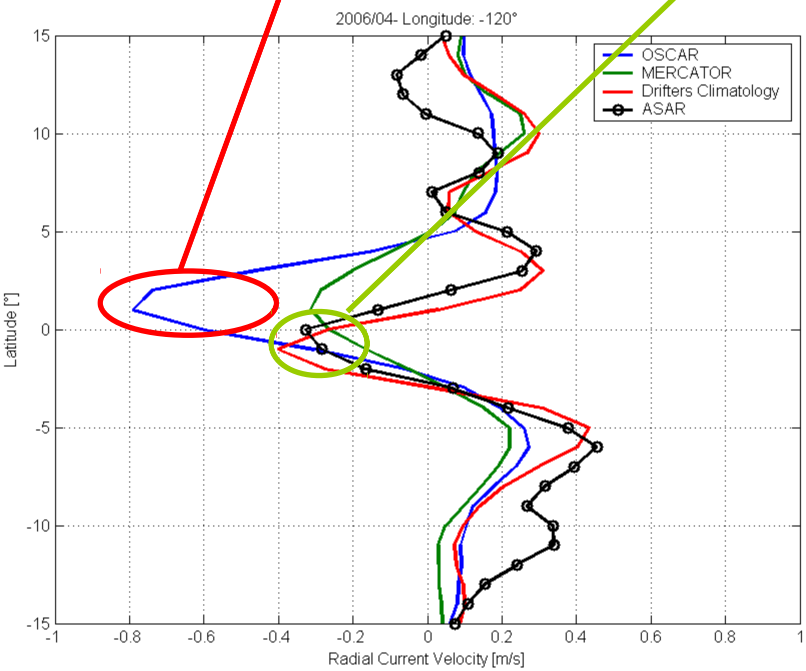
Collard et al., SEASAR 2008

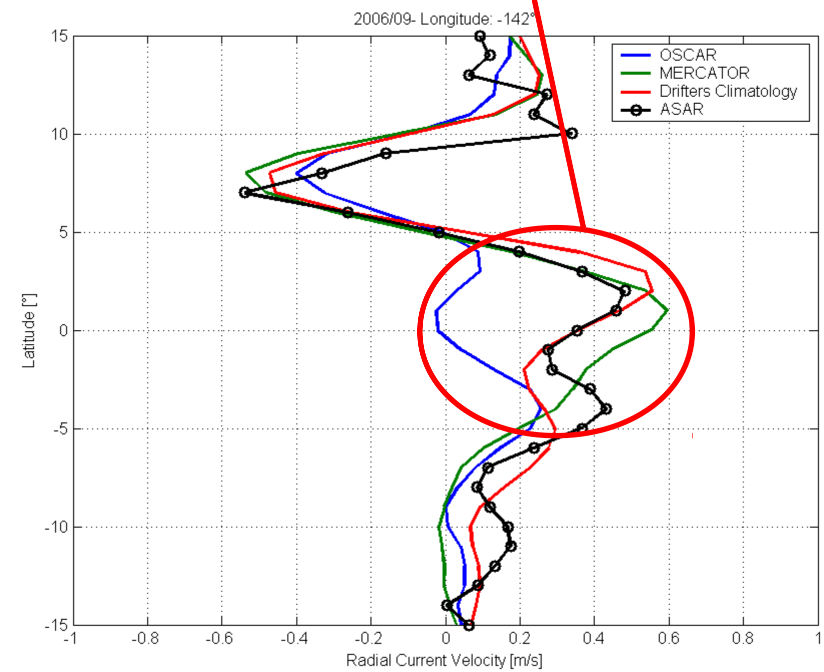
Example of differences between several sources of Sea surface current

The position of the radial current minima obtained from MERCATOR and OSCAR differs from ASAR and Drifters.

Agreement in the position and amplitude of the minima between ASAR and Drifters

MERCATOR does not predict the second minimum.





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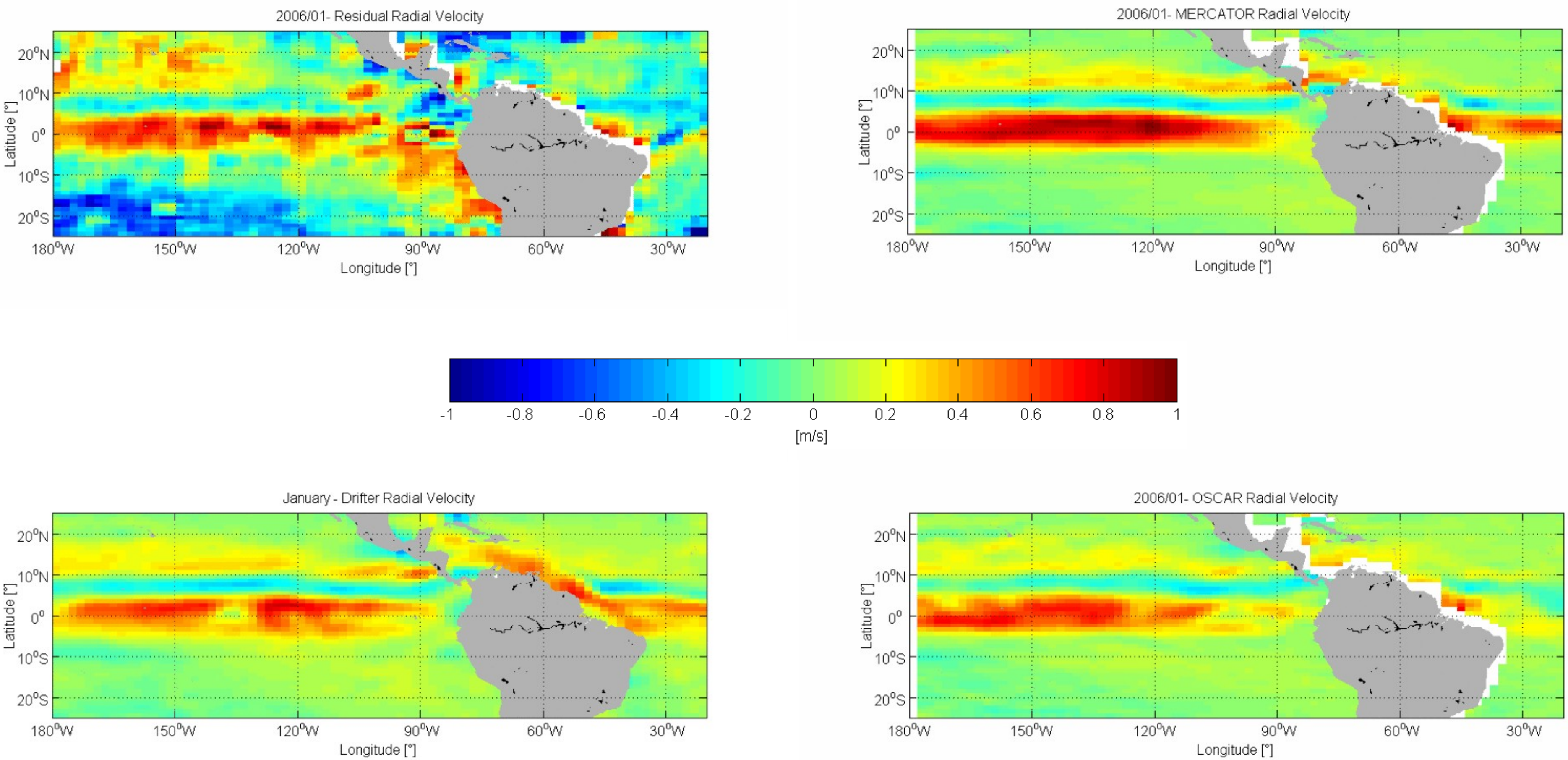
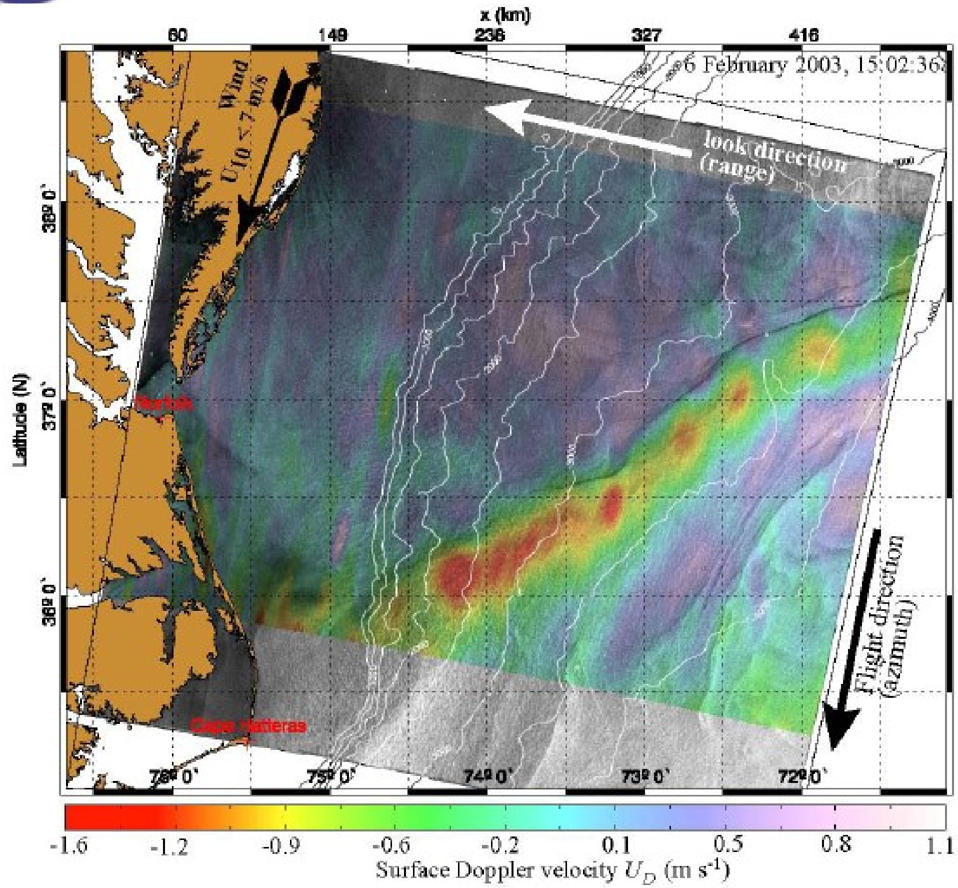


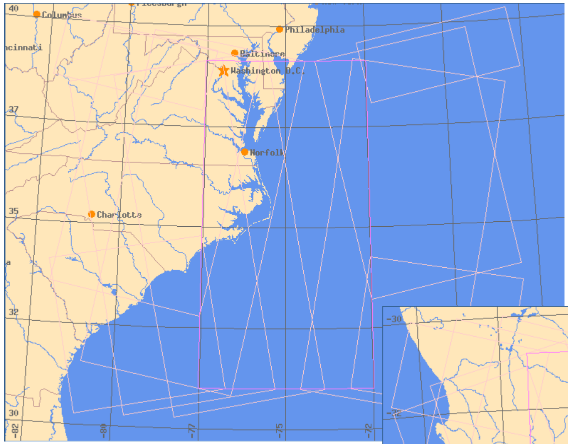
Collard et al., SEASAR 2008

ENVISAT Experience

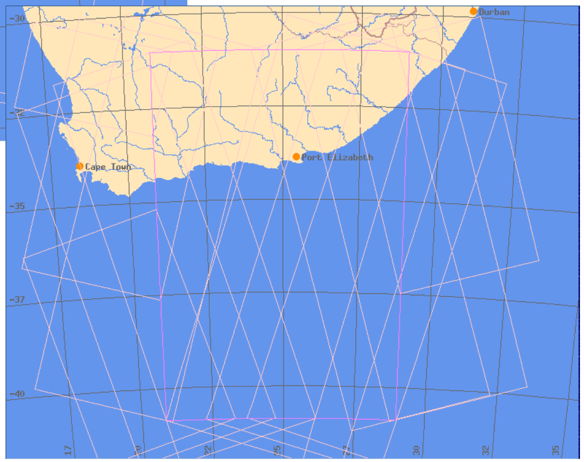


First evidence of Gulf Stream signature on Doppler from space with ENVISAT

Chapron et al., JGR 2005.



North Carolina
Gulf Stream



South Africa
Agulhas Current

In 2007,

- Supersites (or natural lab) for systematic acquisition of ASAR Wide Swath scenes (400km width).

- Doppler Centroid Estimation now provided in all ASAR WS products

Wide Swath products have :

- polarization in VV or HH.

- incidence angles from 17 to 42 degrees.

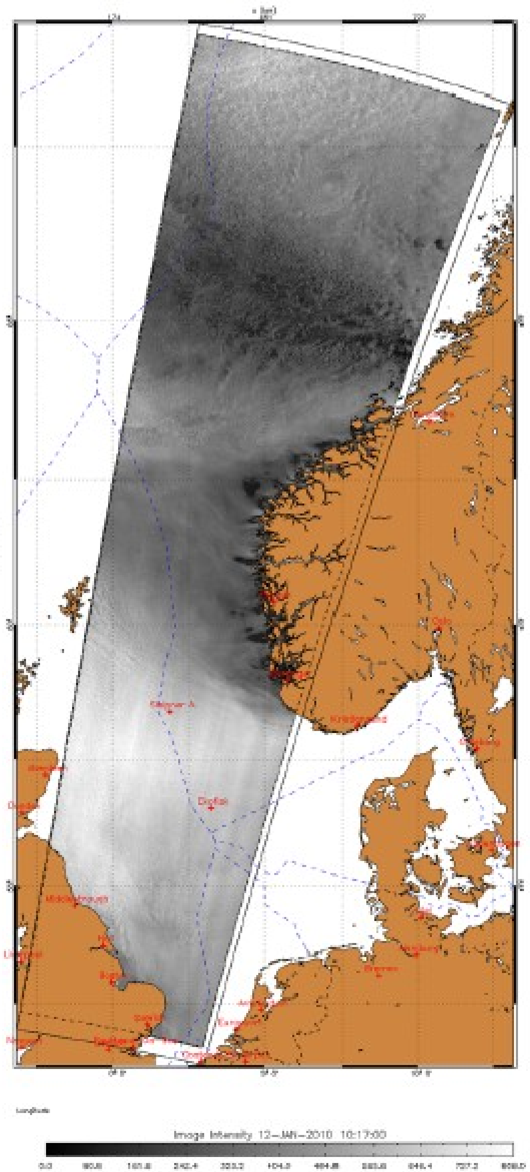
→ Need to extend the CDOP GMF

We performed a massive colocations between
- Radar parameters from ASAR in both co-polarisation
  Incidence angles, look angle, NRCS and doppler
- Wind speed and direction from ASCAT

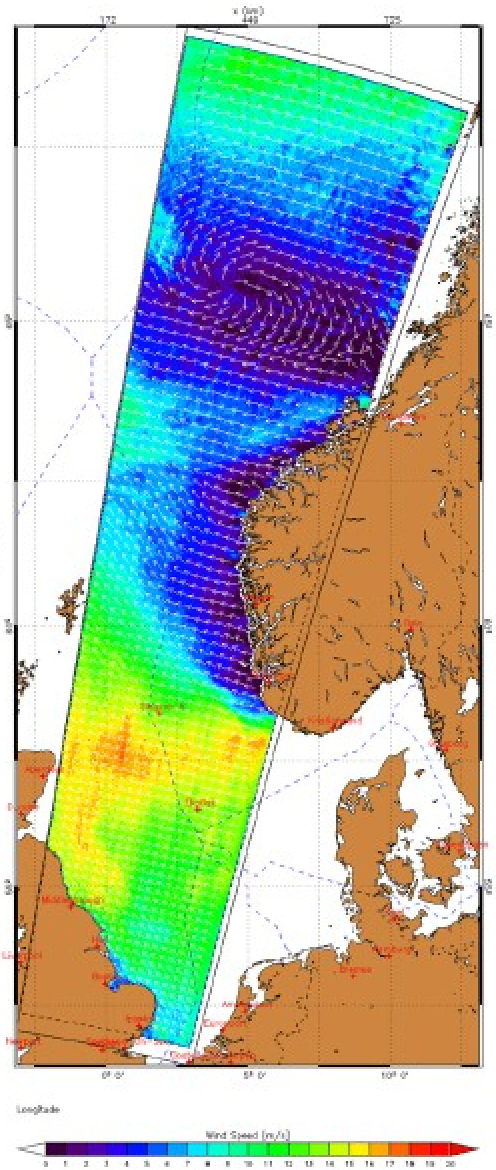
Collocations are done in areas where sea surface current signature are expected to be negligible (European waters)

Collocation time is less than 1 hour

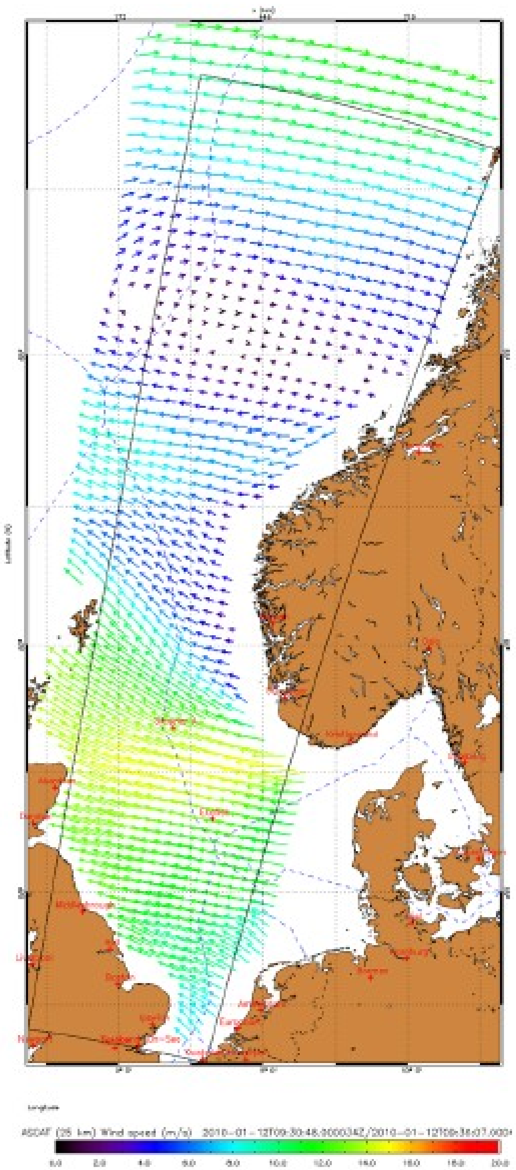
Colocation exemple



ASAR NRCS

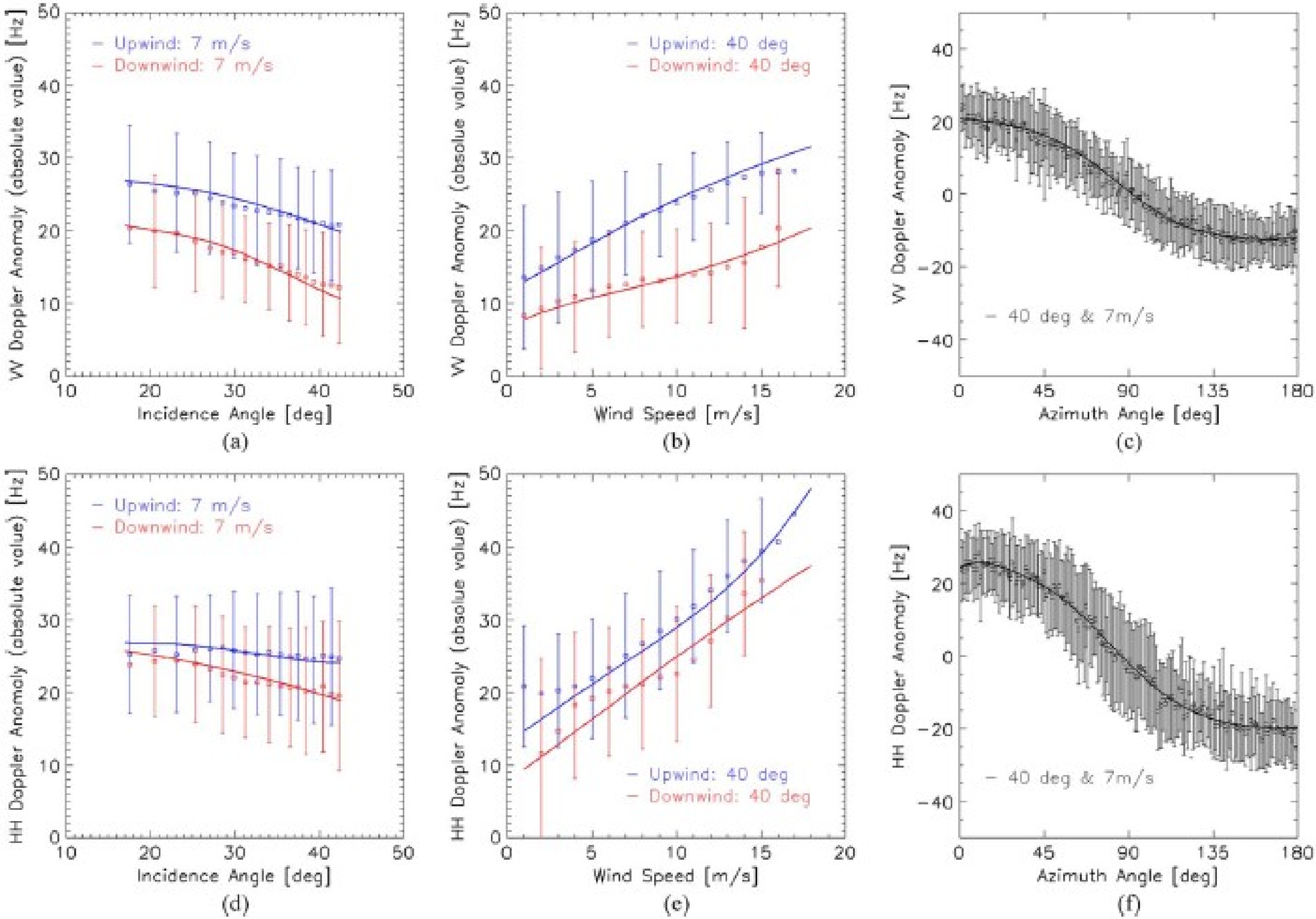


ASAR Wind



ASCAT Wind

GMF



Mouche et al., IEEE TGRS 2012

Based on CDOP results efforst are done :

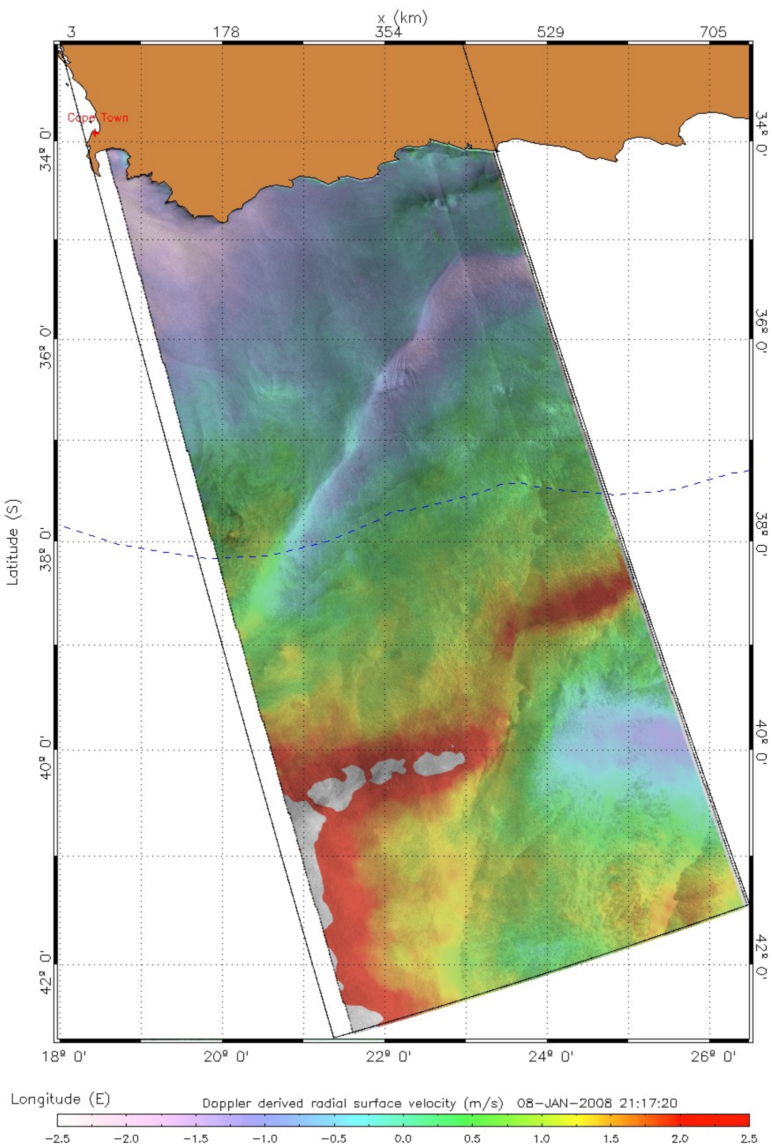
- to retrieve Sea Surface Current

- to retrieve Ocean surface wind

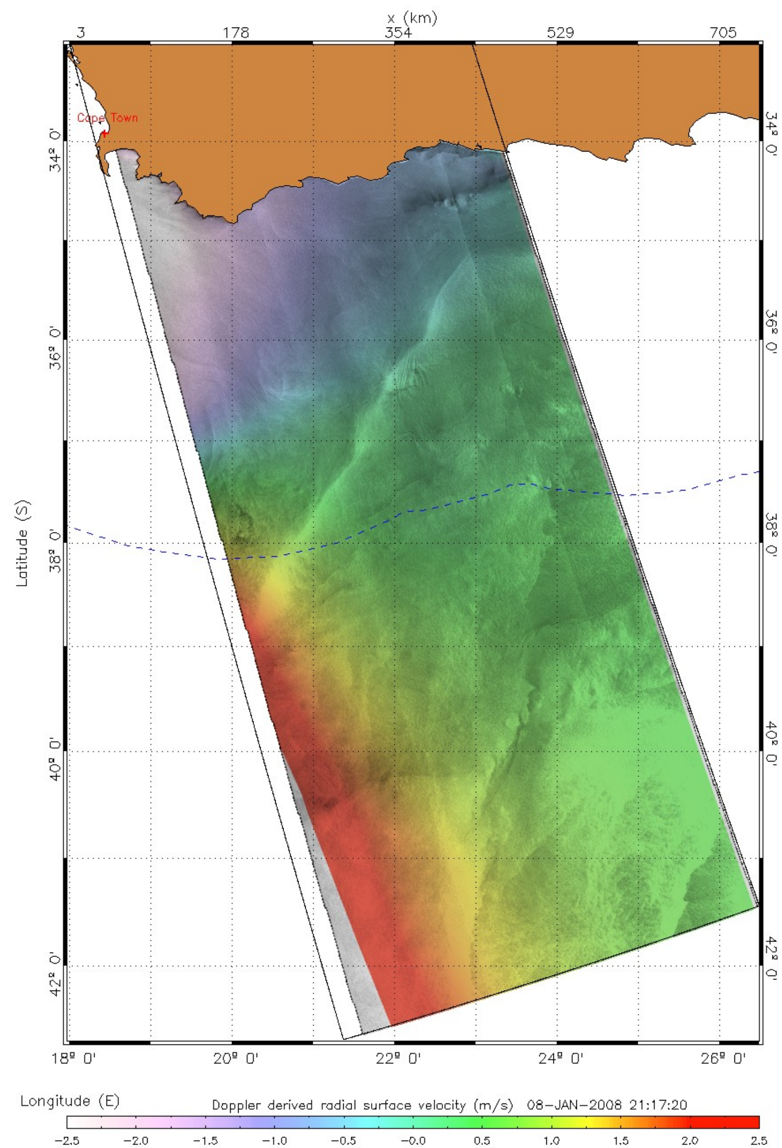
- improve our understanding on the EM mechanisms

ENVISAT Experience : Doppler and Sea surface Current from Wide Swath

- Total velocities



- CDOP velocities



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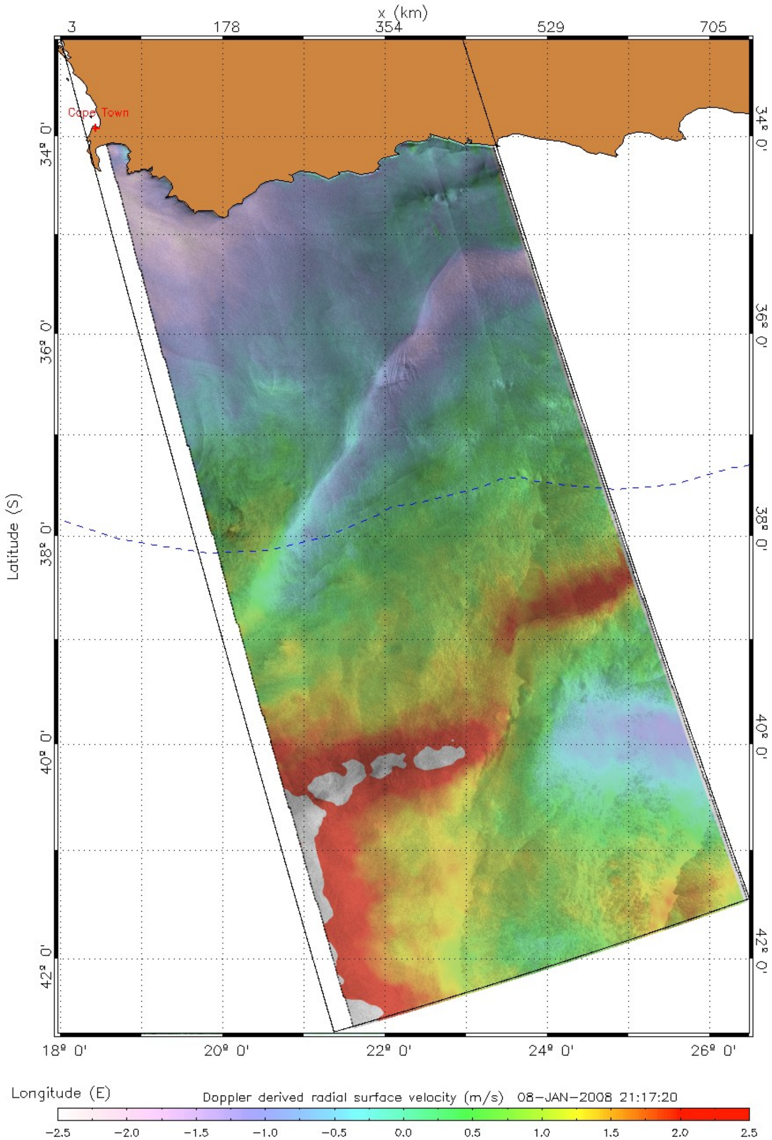
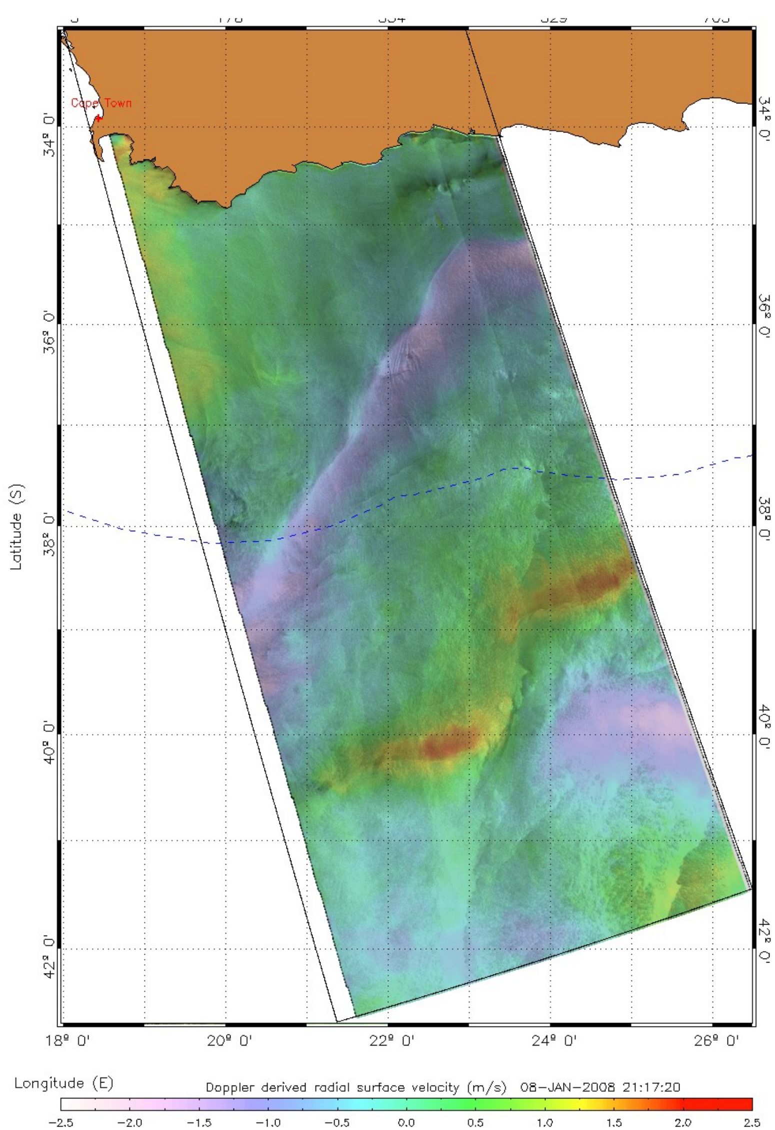
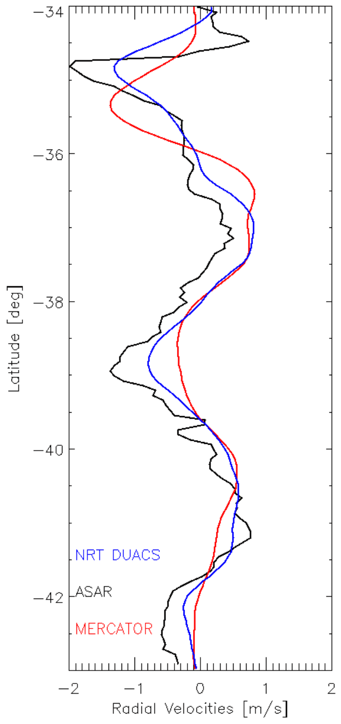
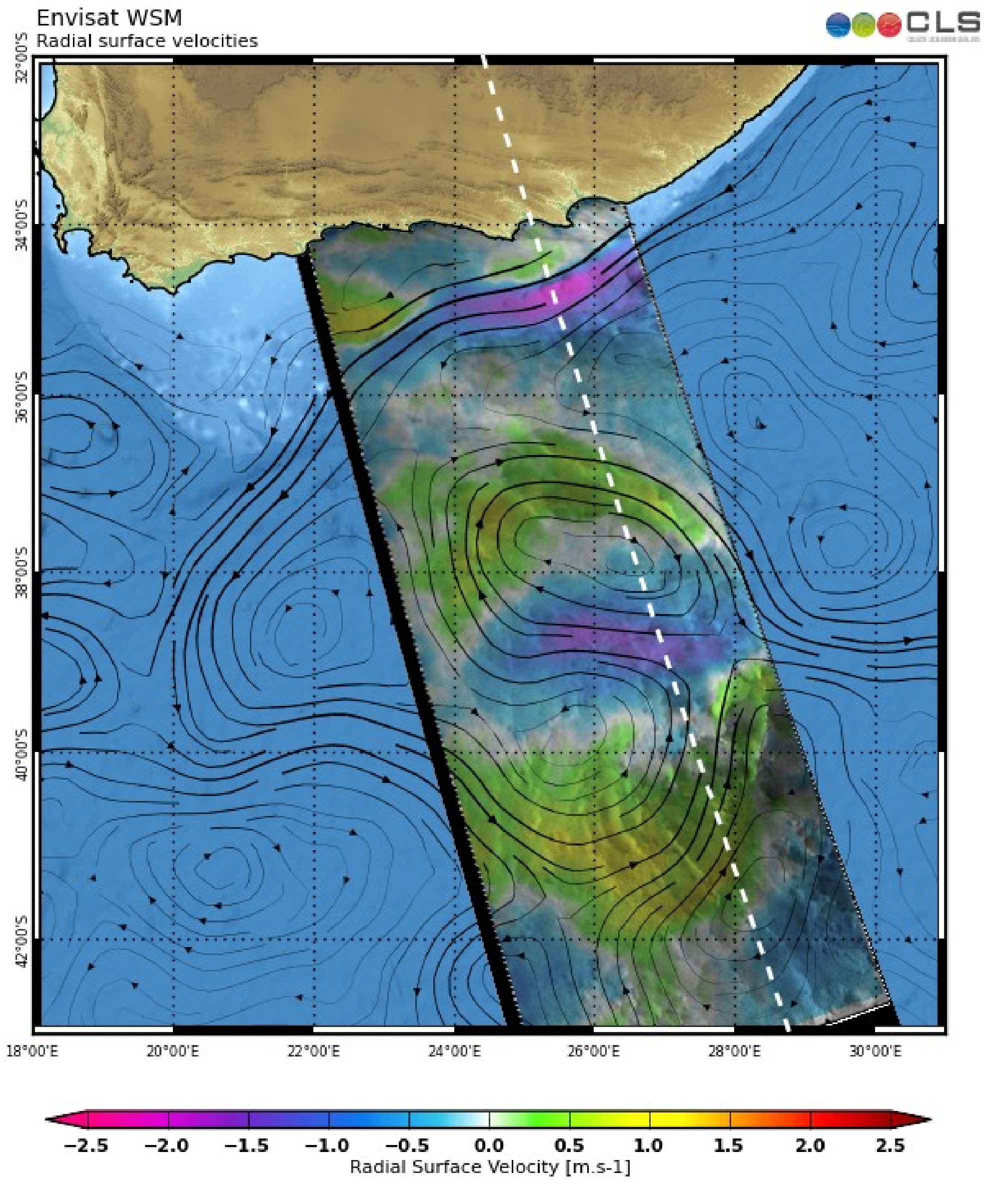


- Residual velocities



- Image-by-image analysis
  - **Comparison with Altimetry**
  - Comparison with Drifters
  - Comparison with SST





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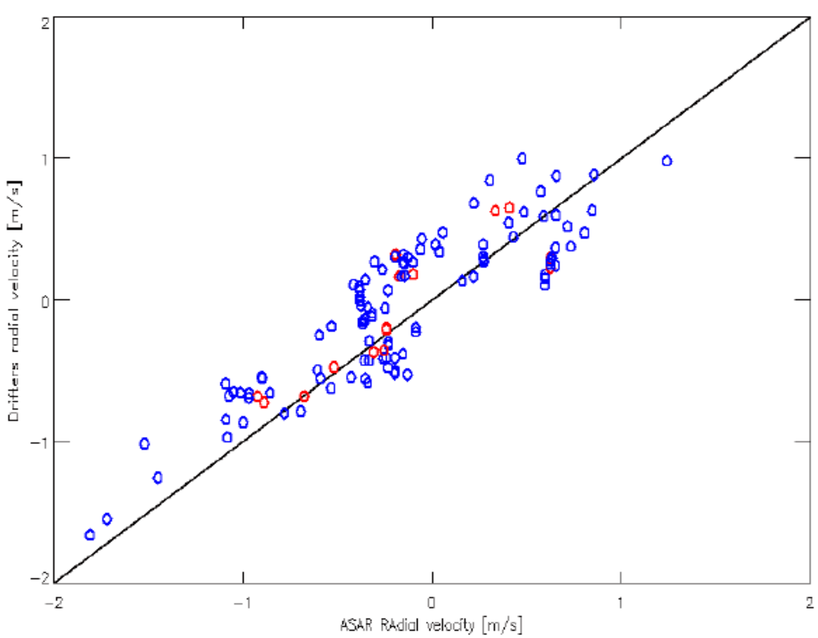

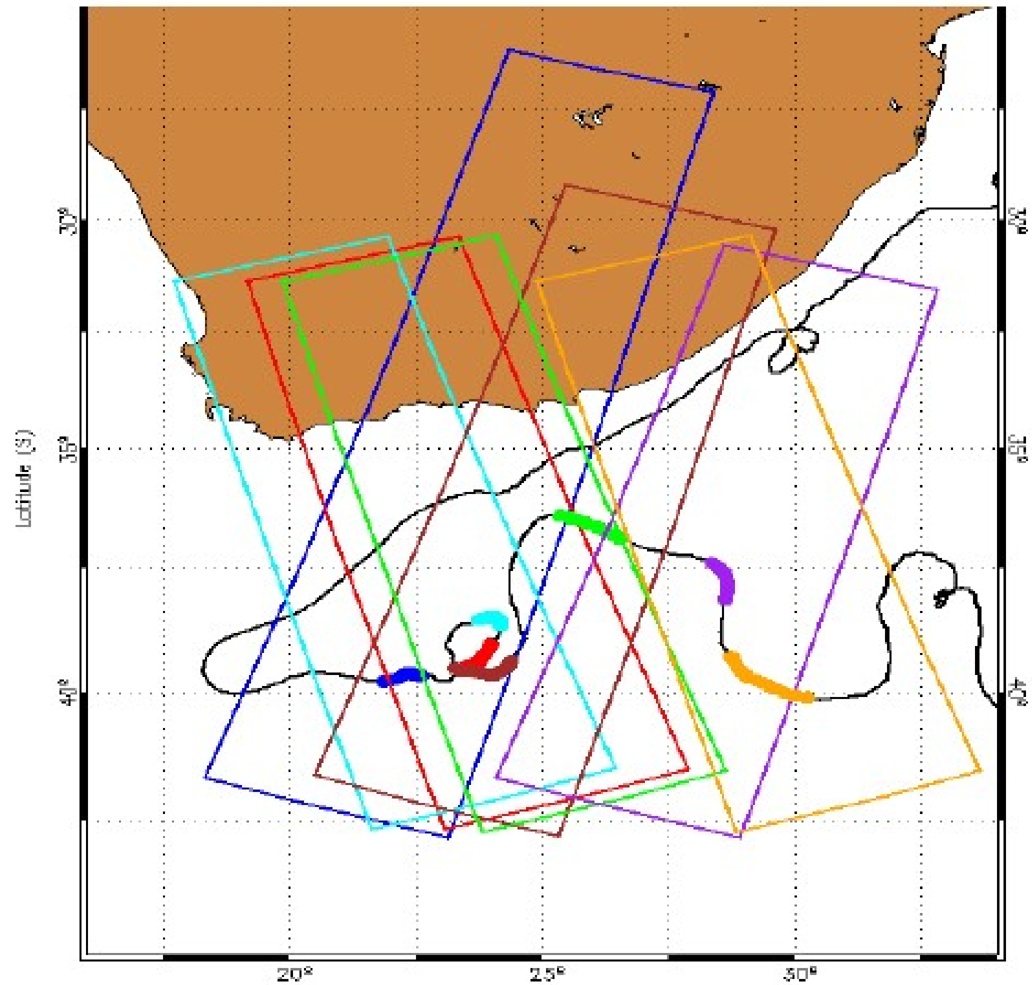

rms:0.28 m/s

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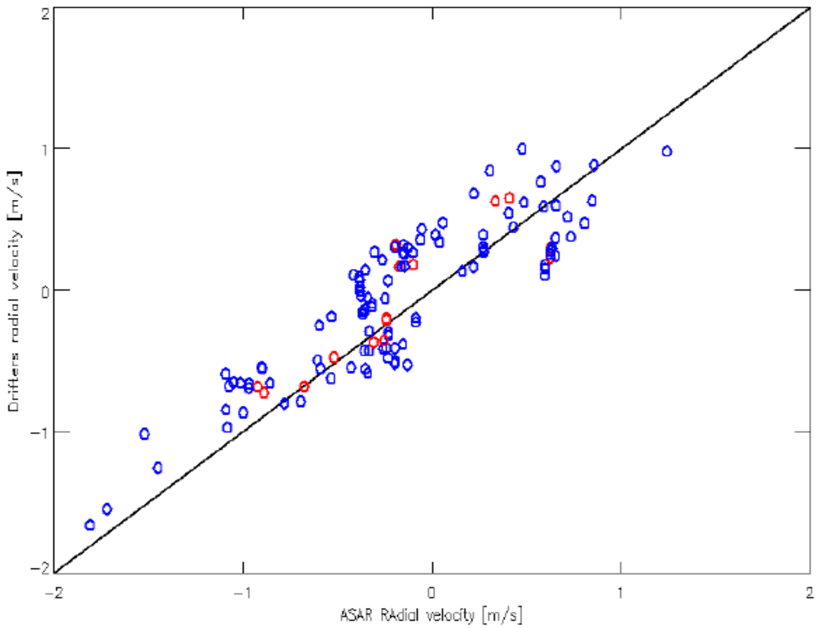

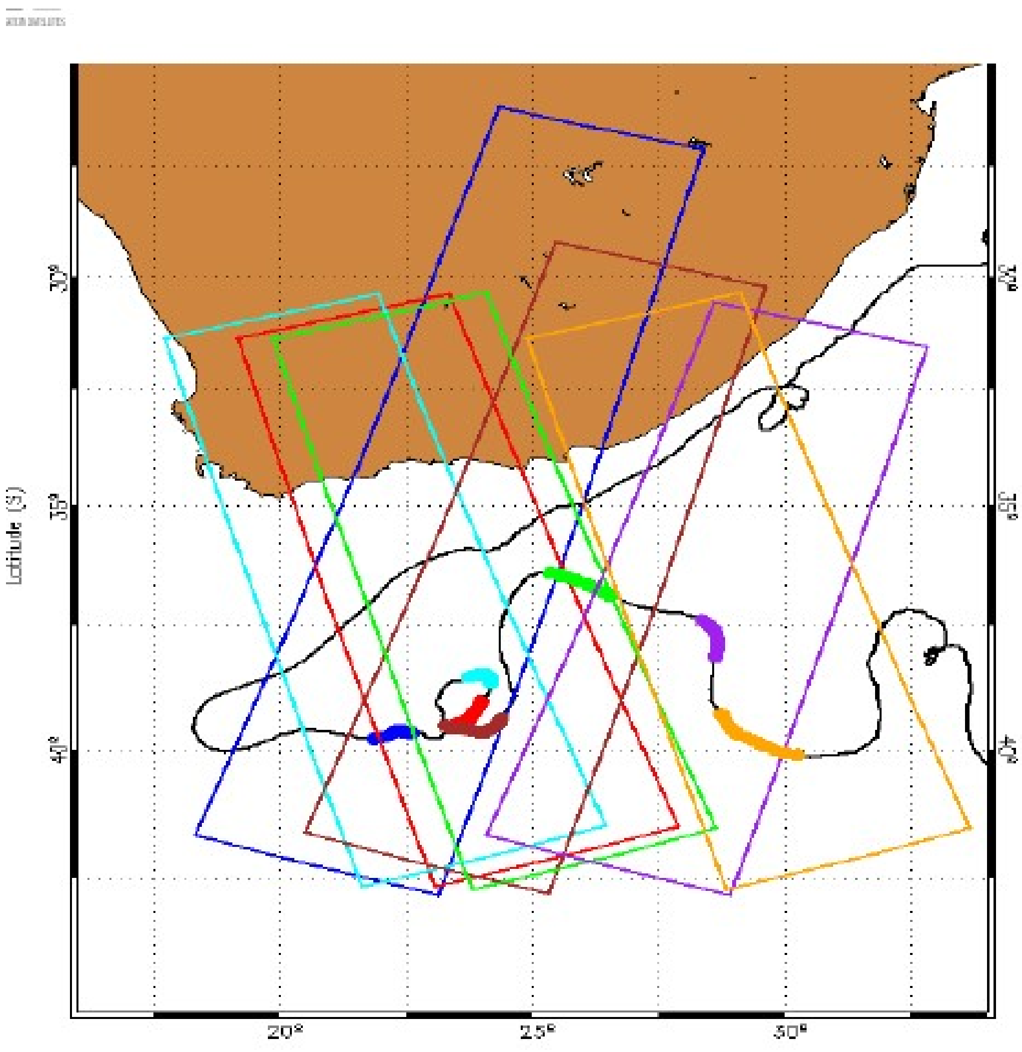

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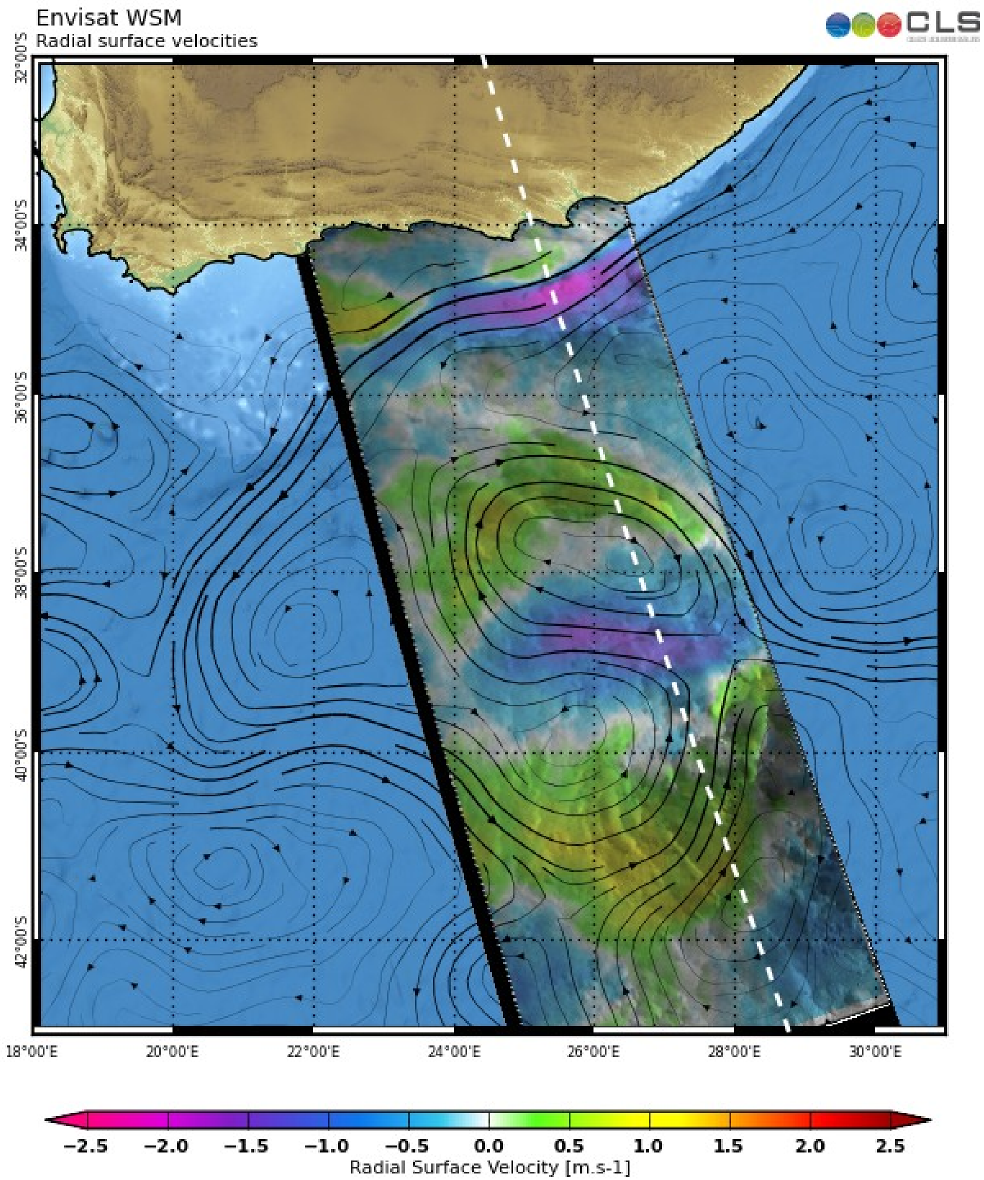
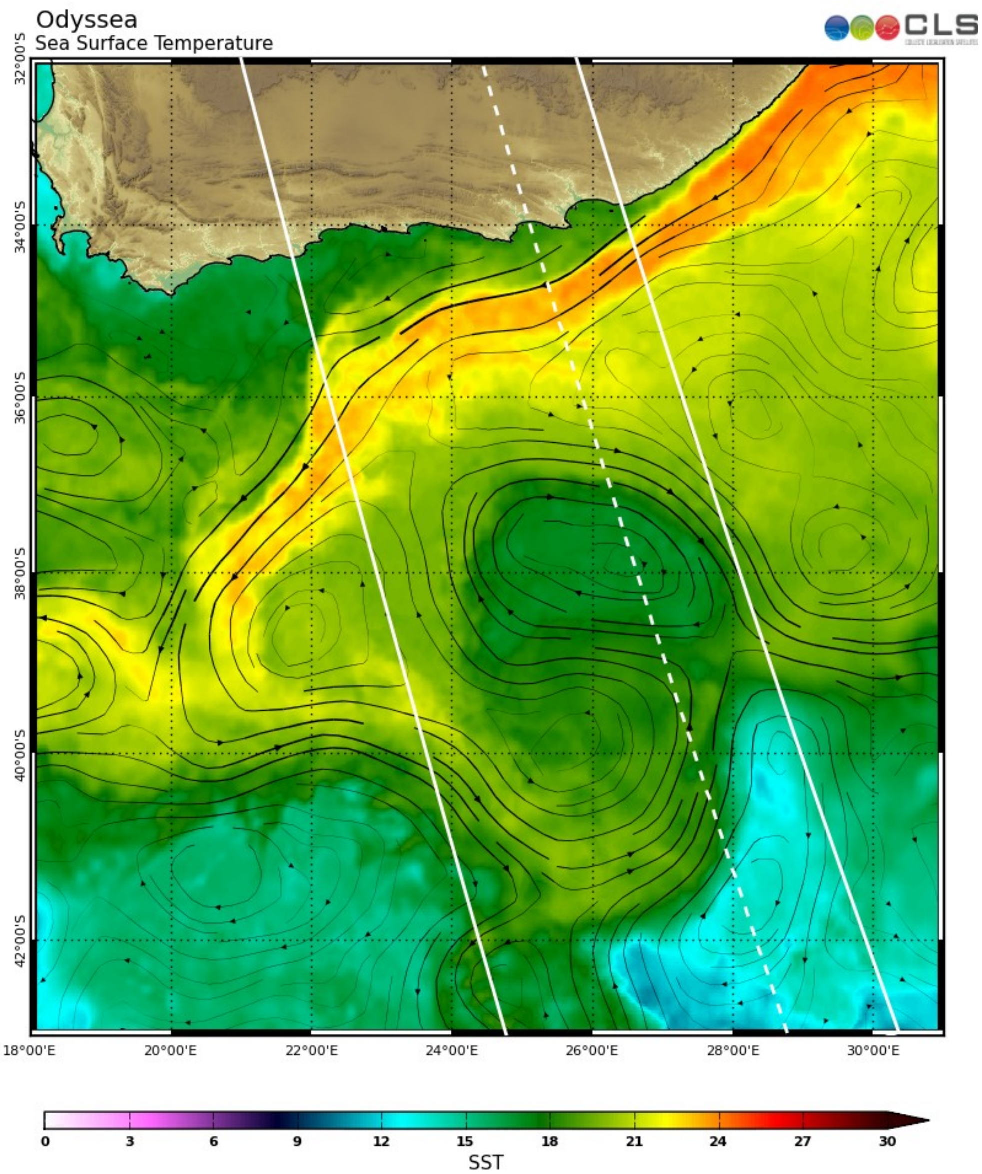
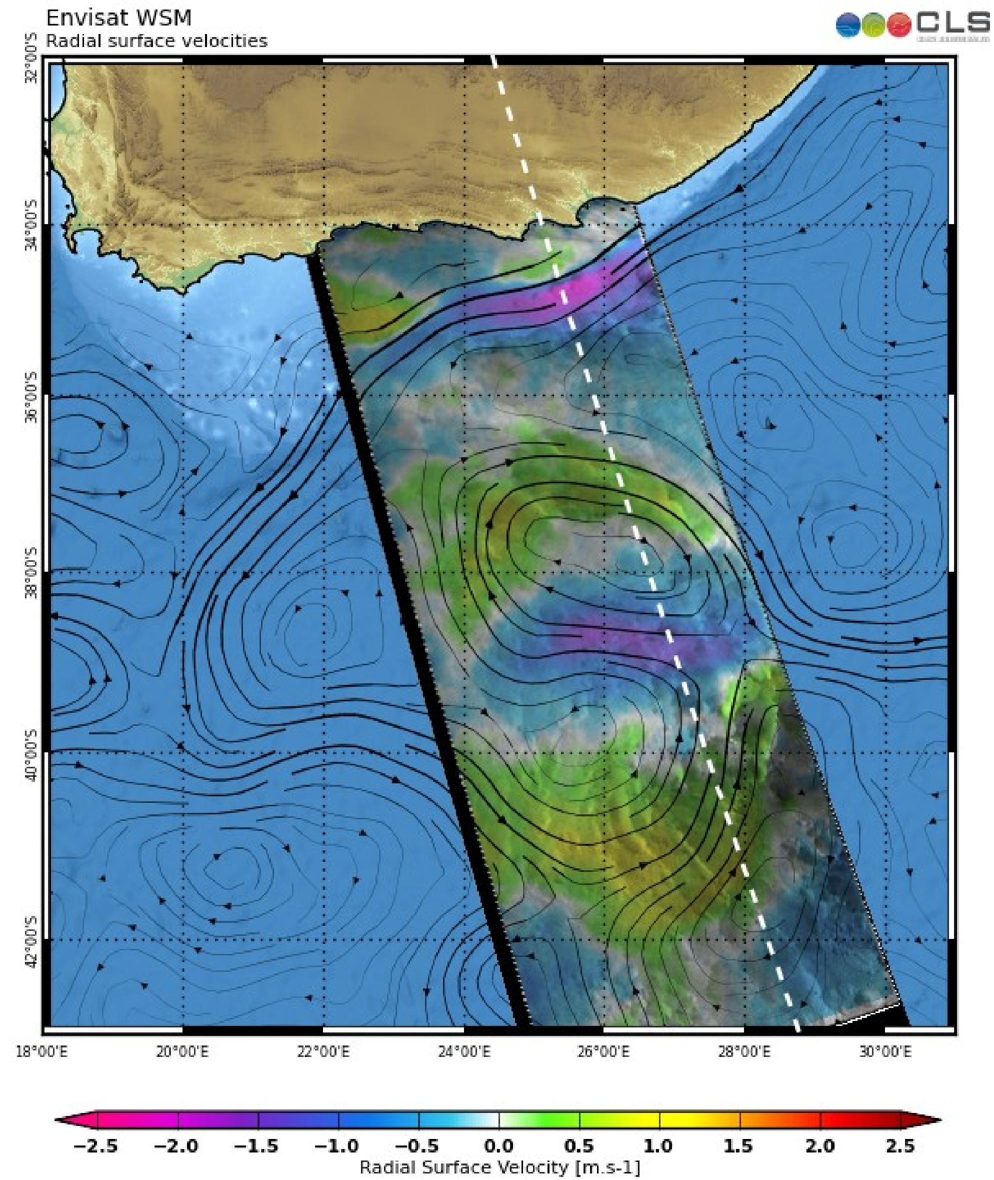


ENVISAT Experience : Doppler and Sea surface Current from Wide Swath





Motivations : SAR has one single antenna and in complex meteorological situations such as low pressure system or atmospheric fronts, inversion scheme that strongly relies on ancillary information for wind direction often fails.

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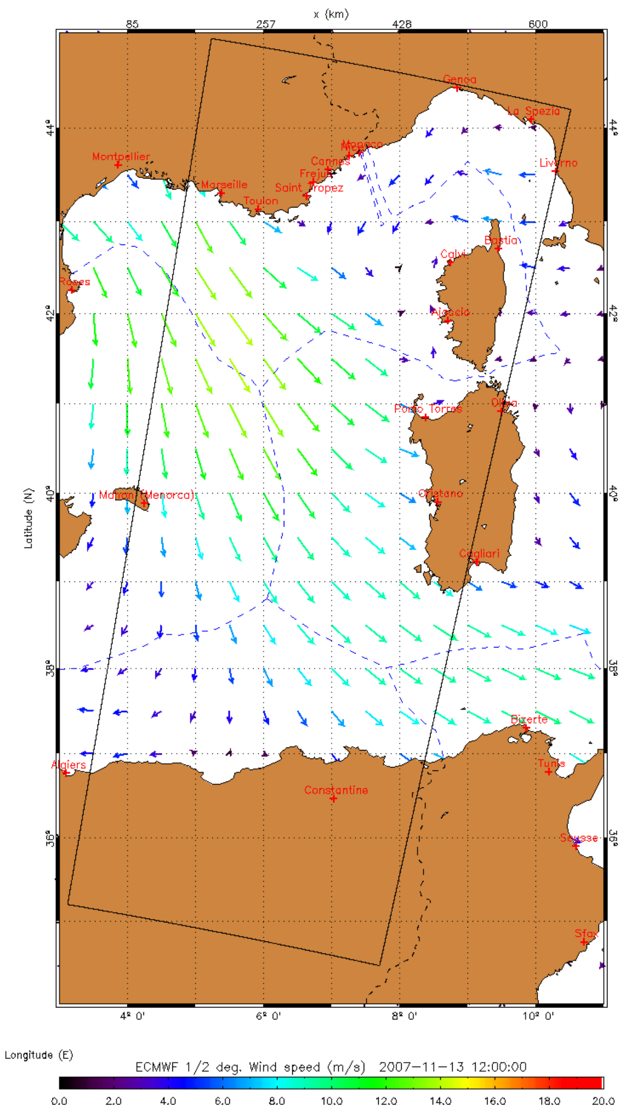

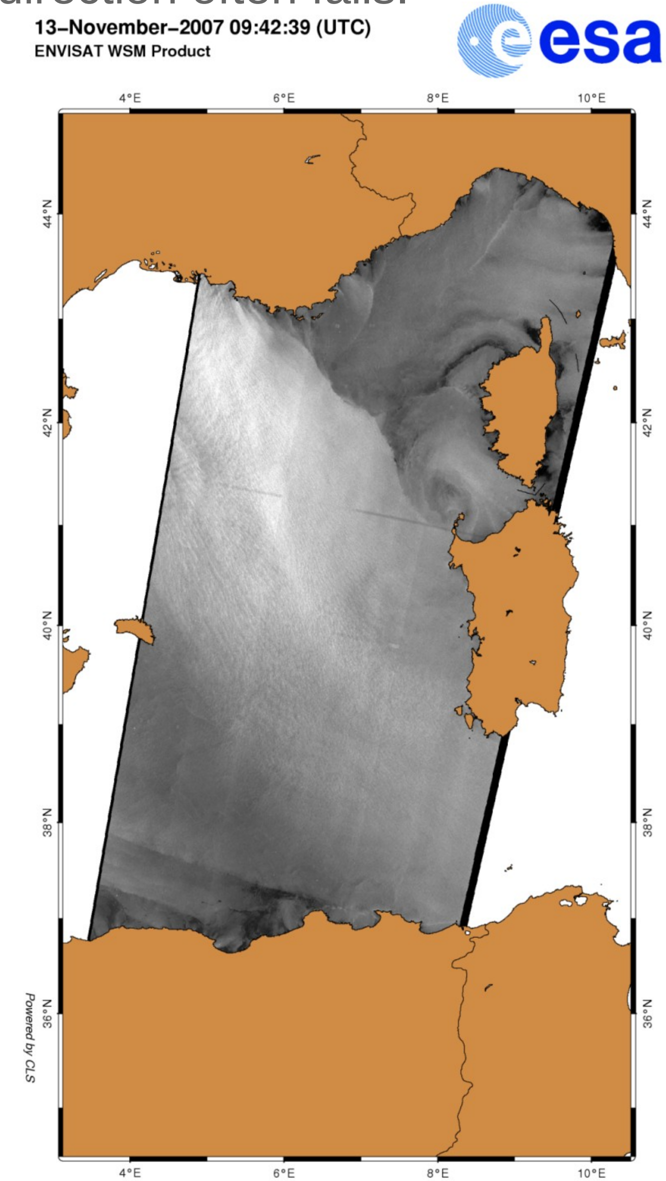

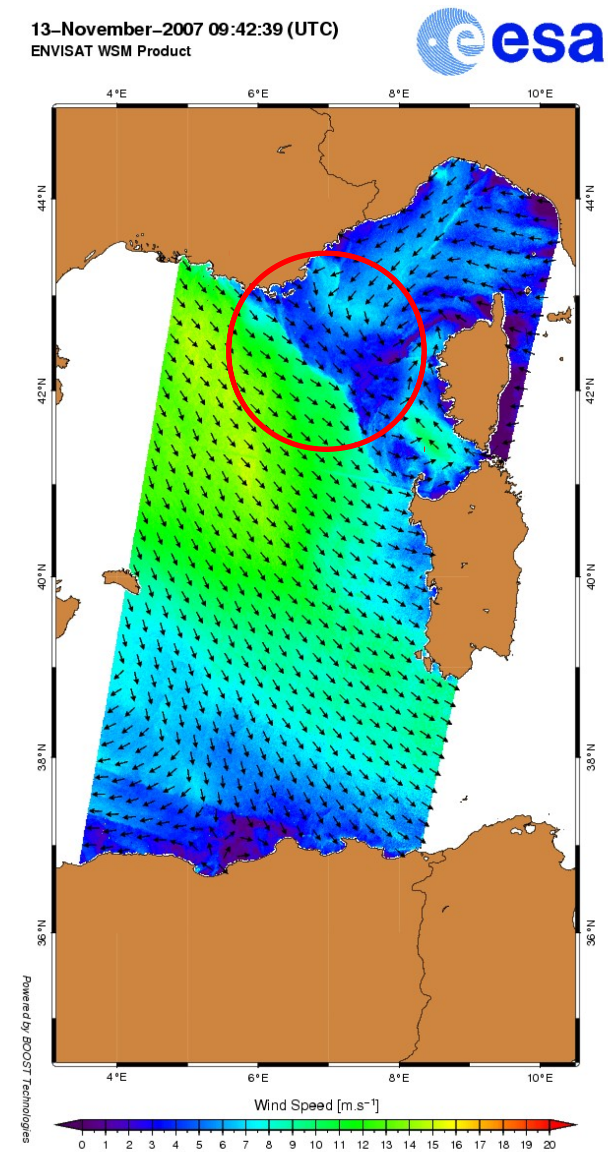

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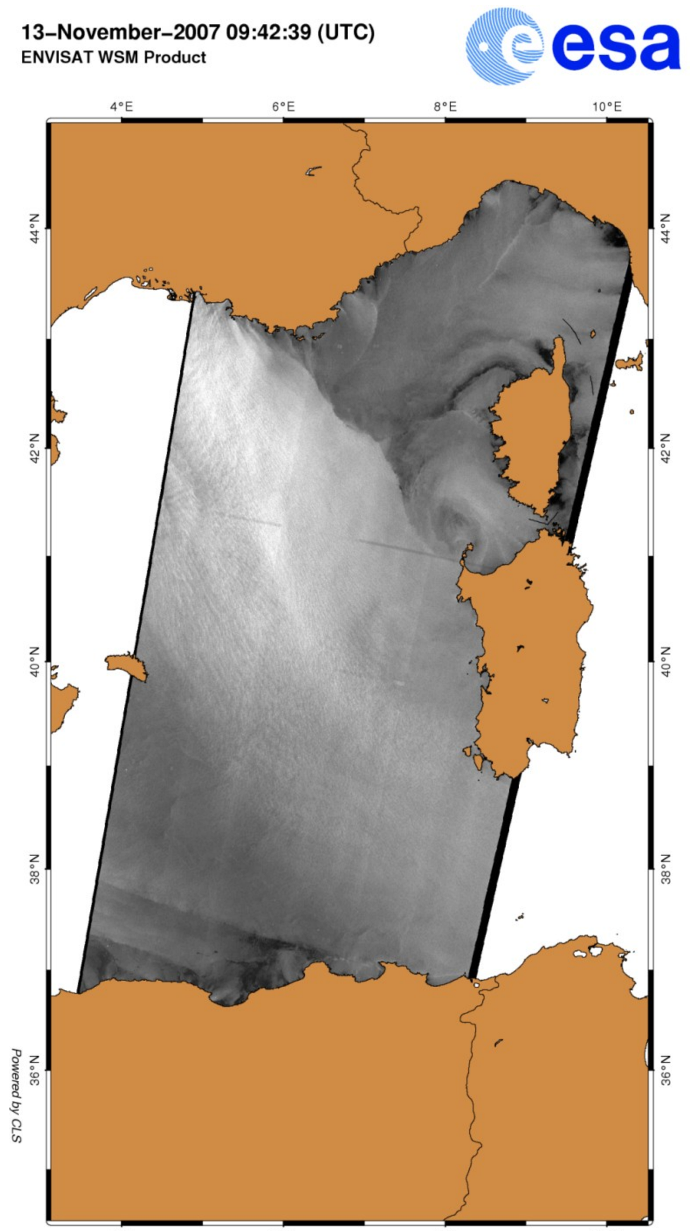

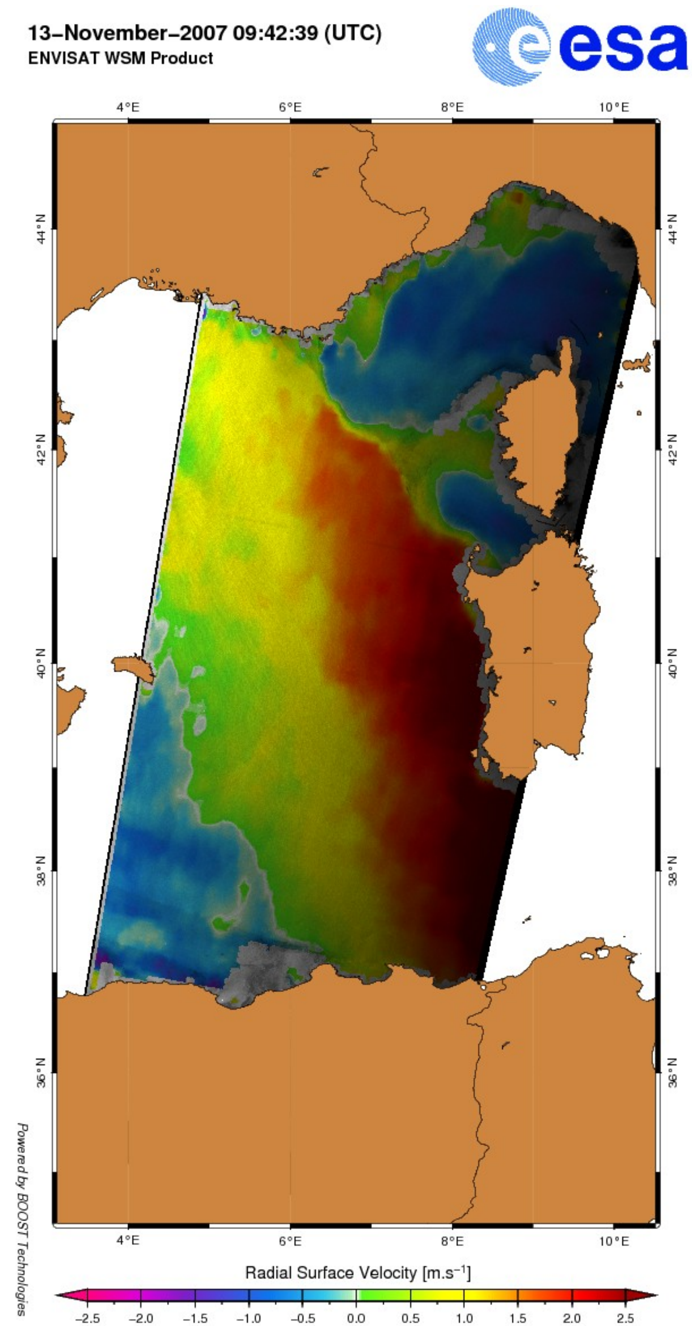

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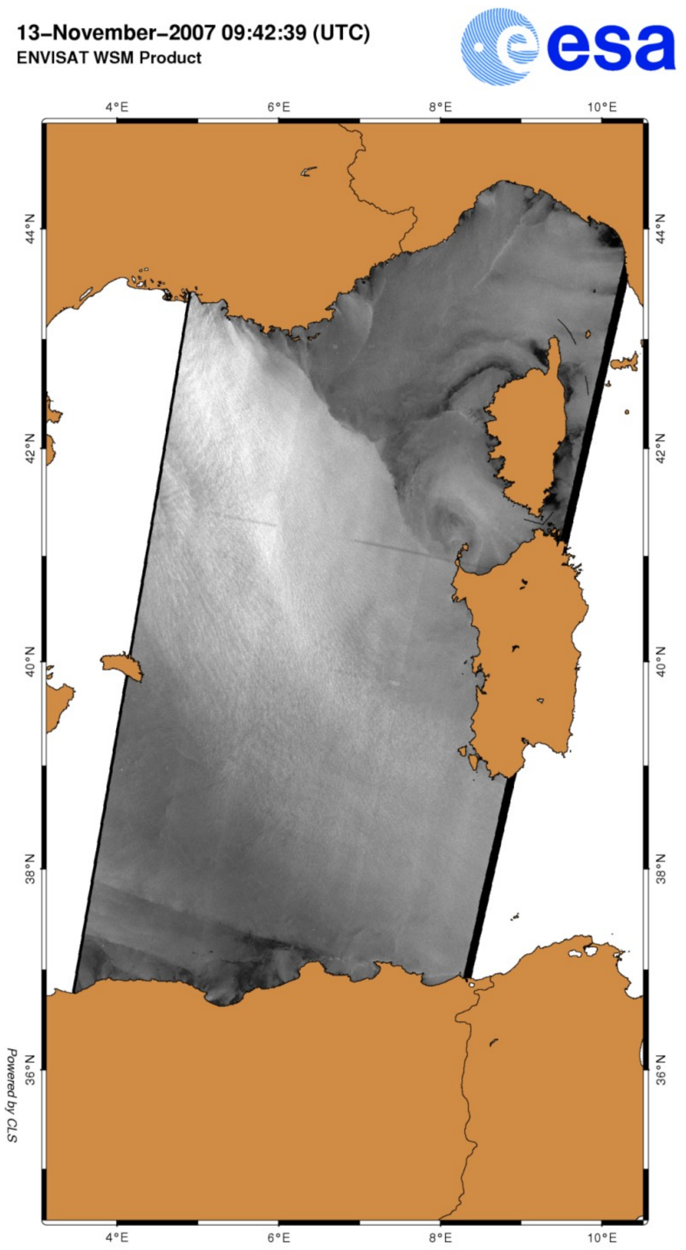

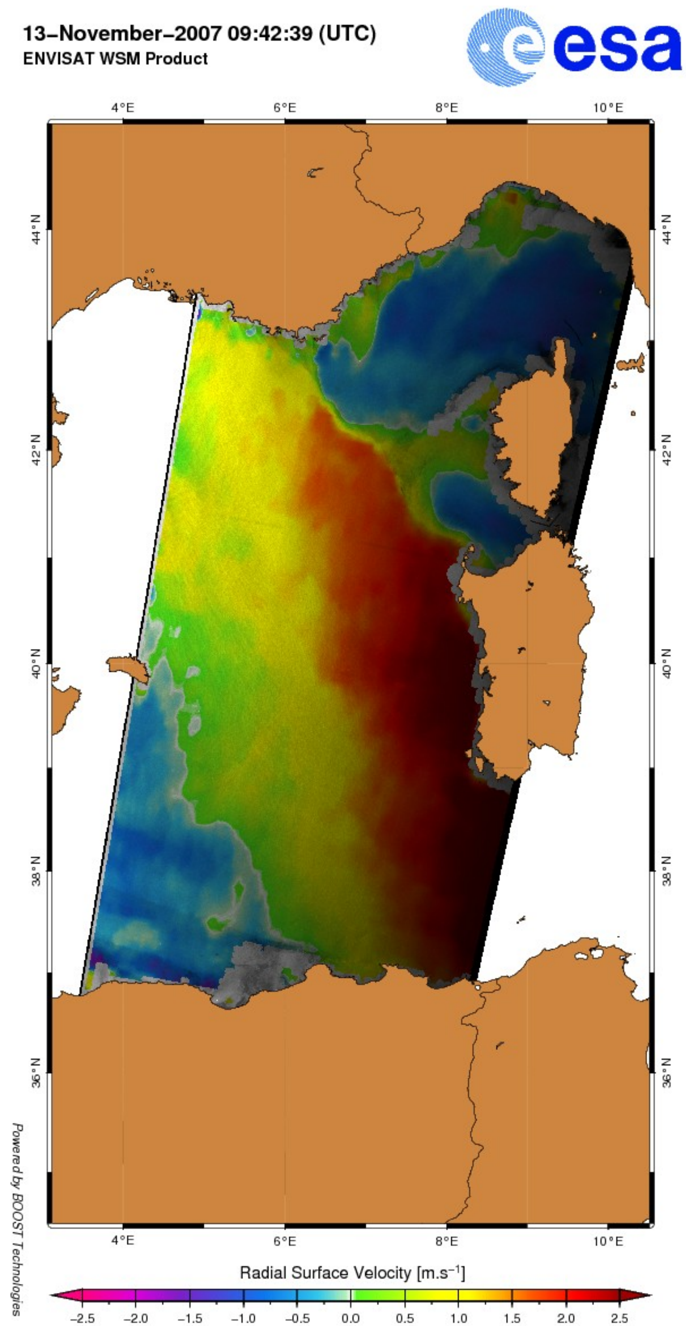

We include Doppler in the cost function used to retrieve SAR wind from SAR.

$$J(\mathbf{u}) = \underbrace{\left(\frac{\sigma^0 - \mathrm{CMOD}(\mathbf{u})}{\Delta\sigma^0}\right)^2}_{\mathrm{NRCS.term}} + \underbrace{\left(\frac{f^{\mathrm{DA}} - \mathrm{CDOP}(\mathbf{u})}{\Delta f^{\mathrm{DA}}}\right)^2}_{\mathrm{Doppler.term}} + \underbrace{\left(\frac{\mathbf{u} - \mathbf{u}_B}{\Delta\mathbf{u}}\right)^2}_{A.priori.\mathrm{model.term}}$$

Mouche et al., IEEE TGRS 2012

ENVISAT Experience : Doppler and Sea surface Wind from Wide Swath

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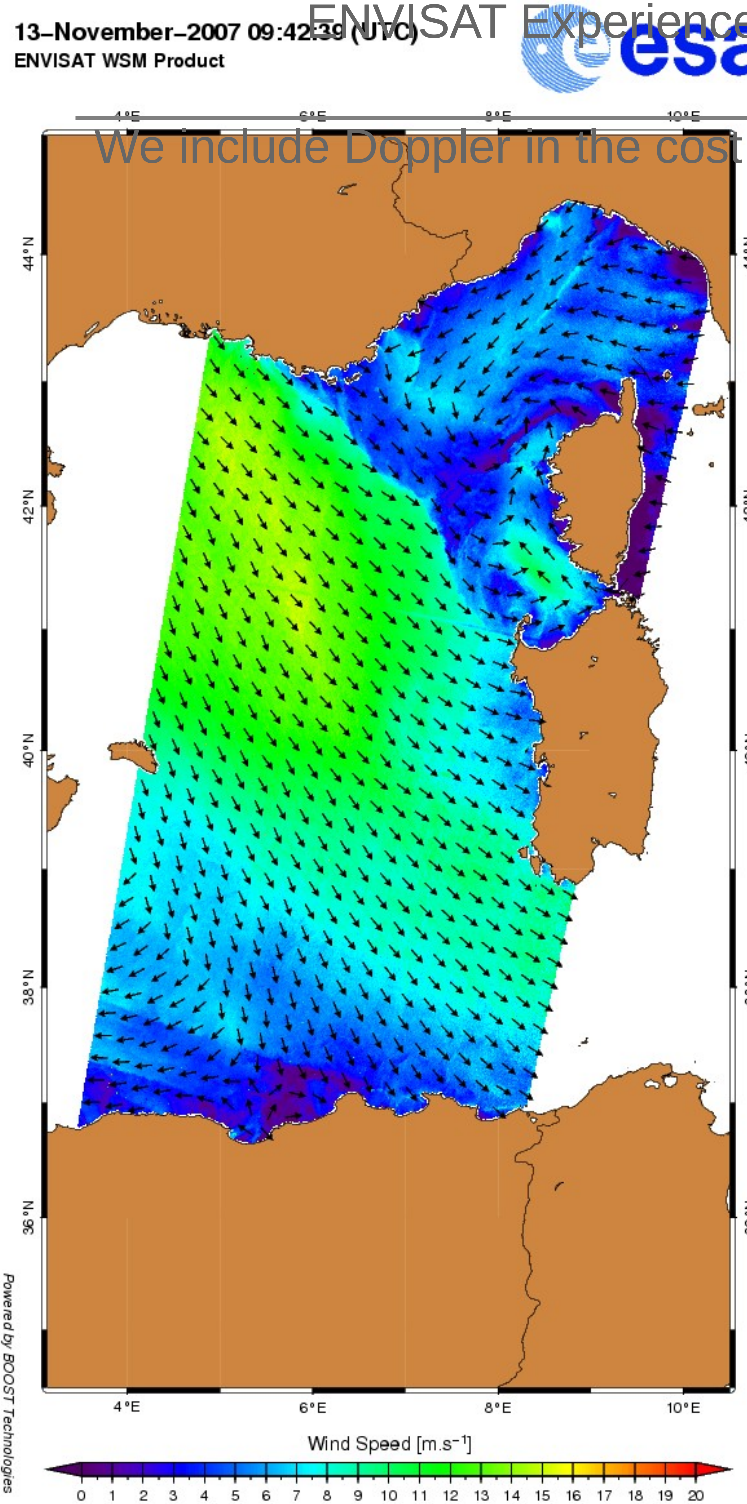

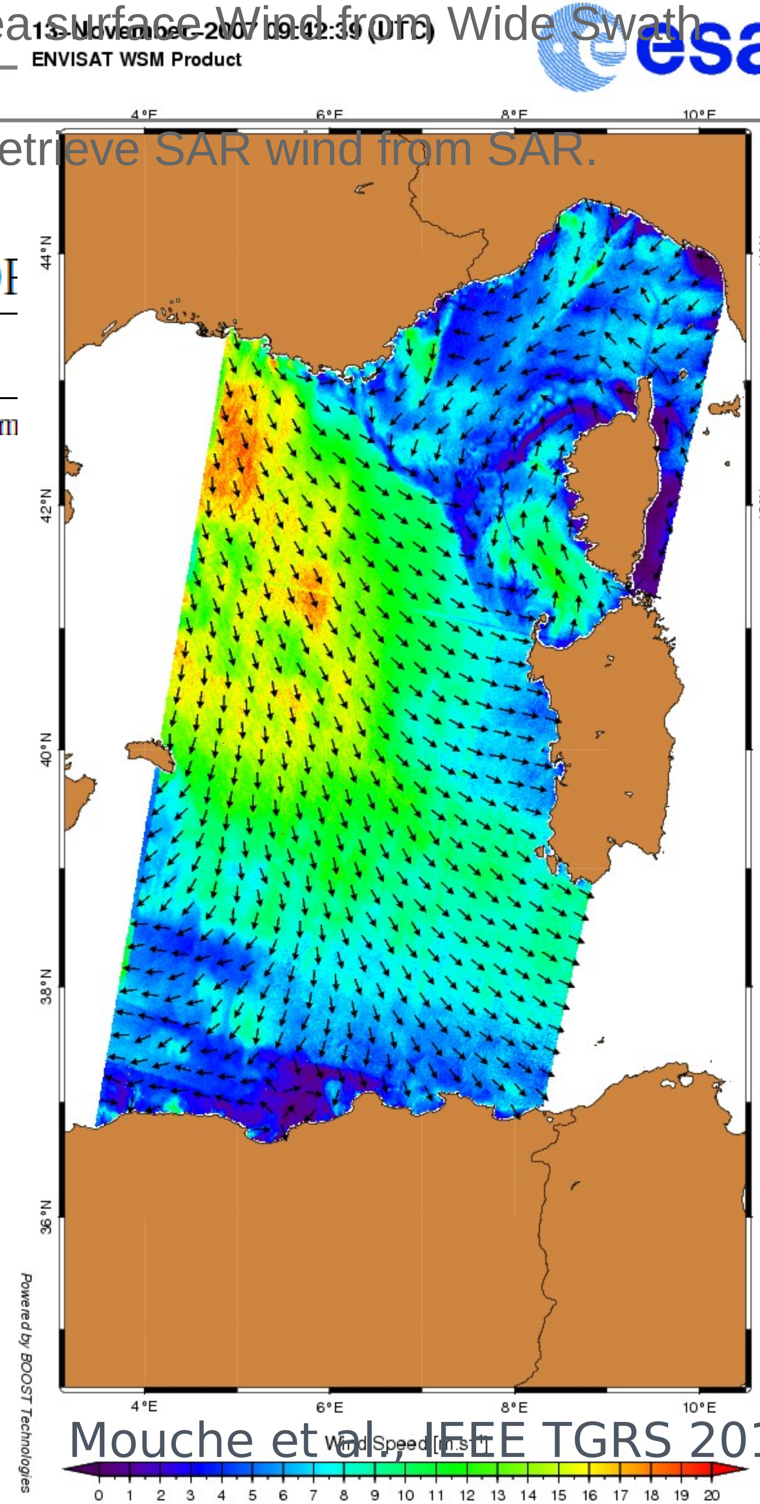

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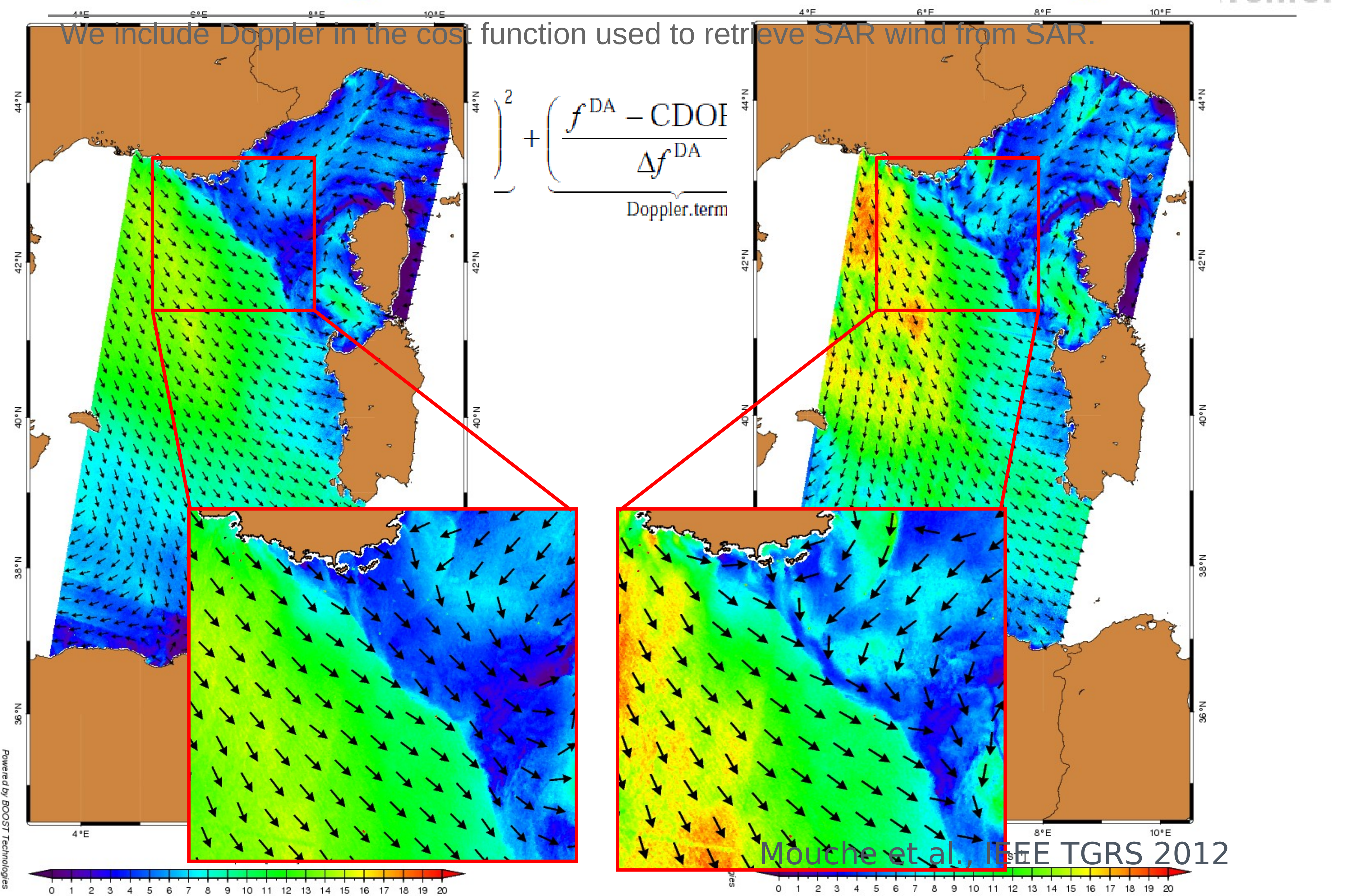

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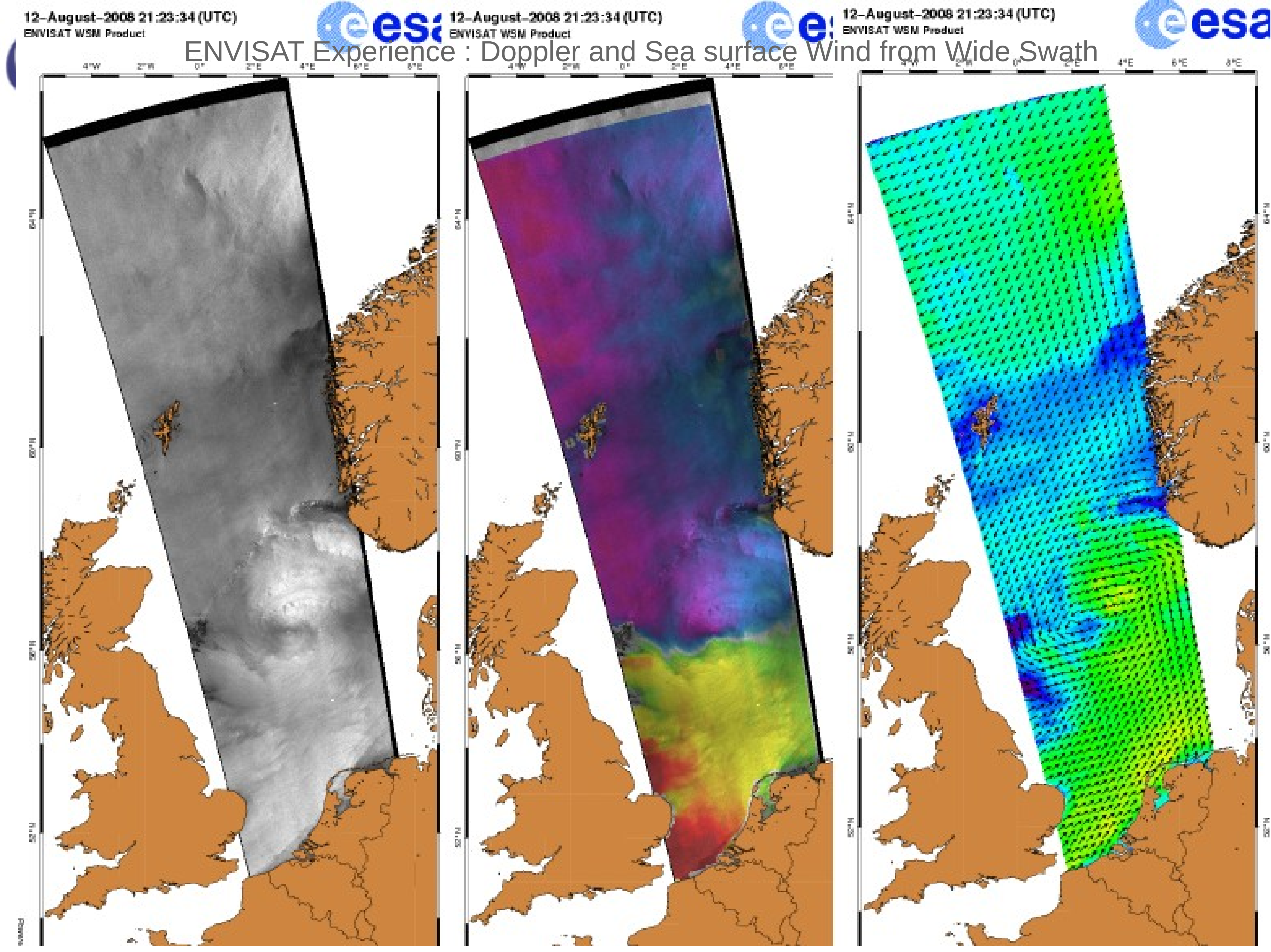

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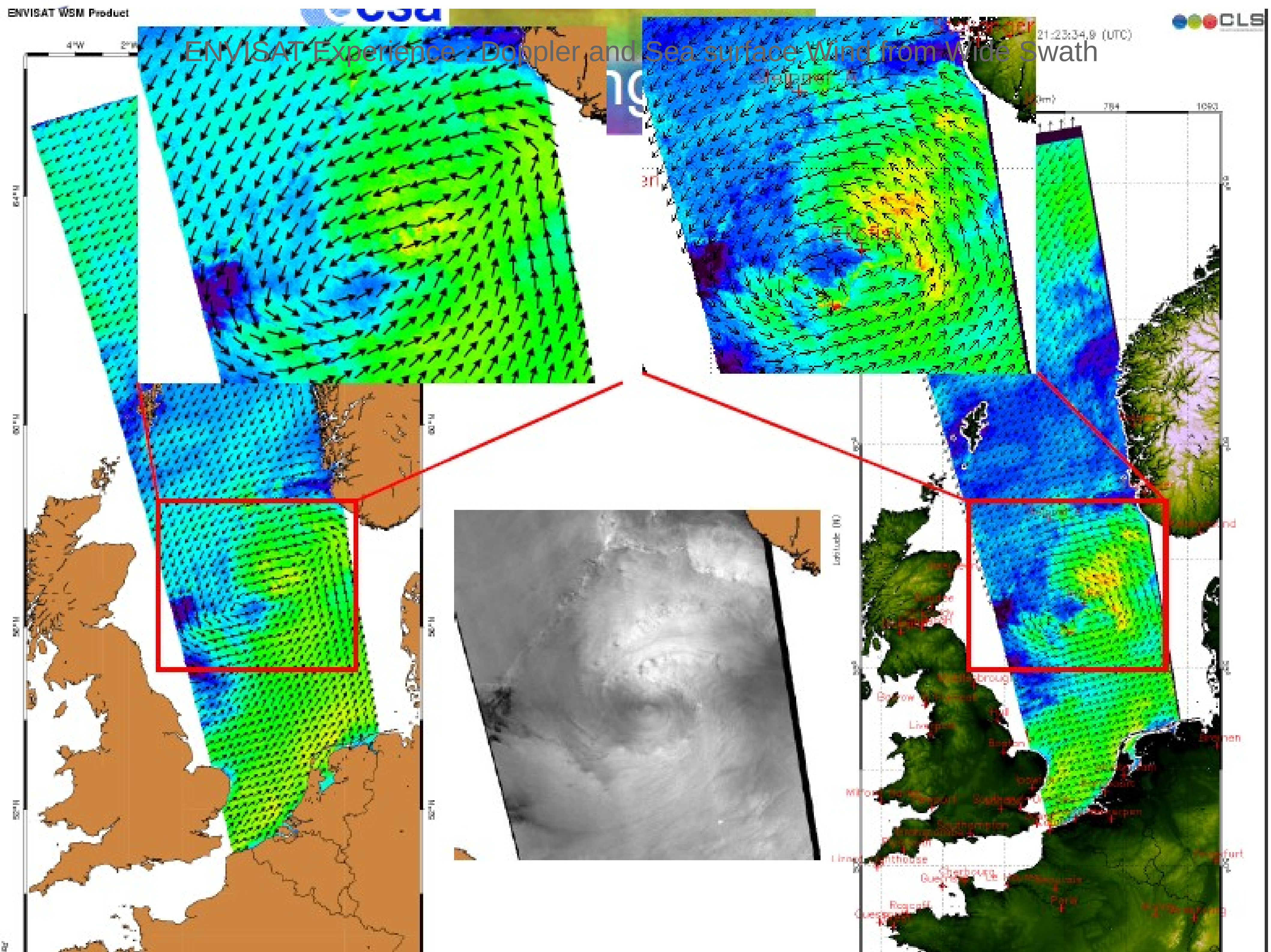
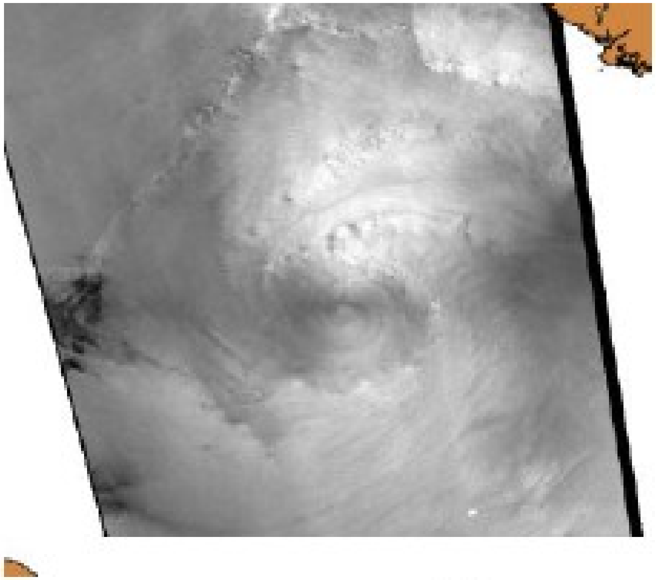
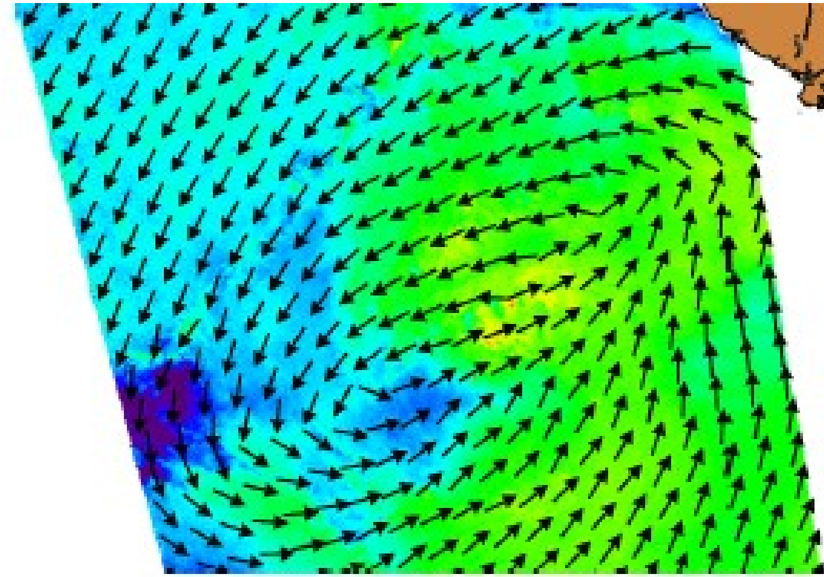
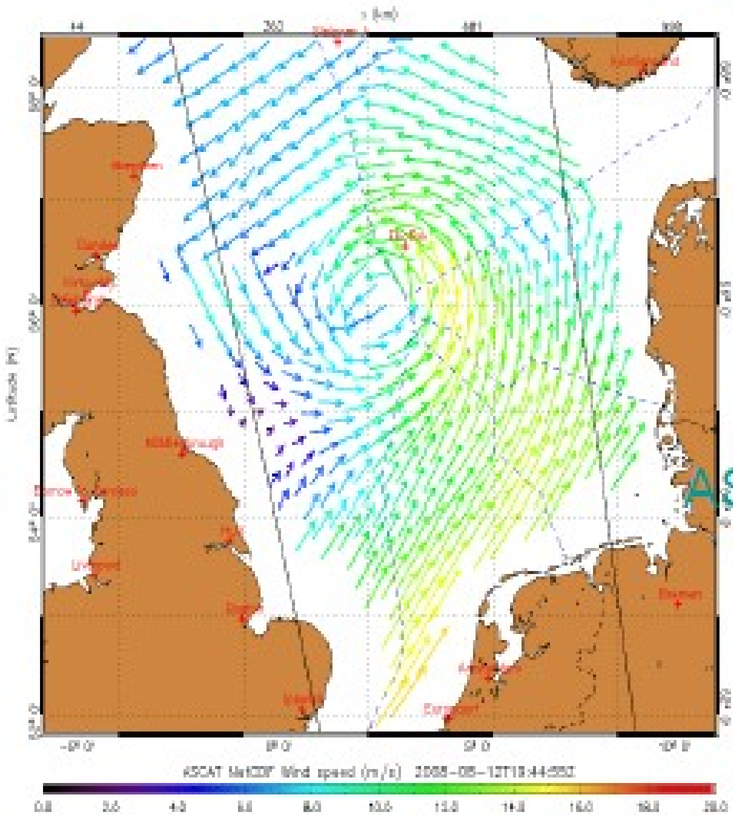
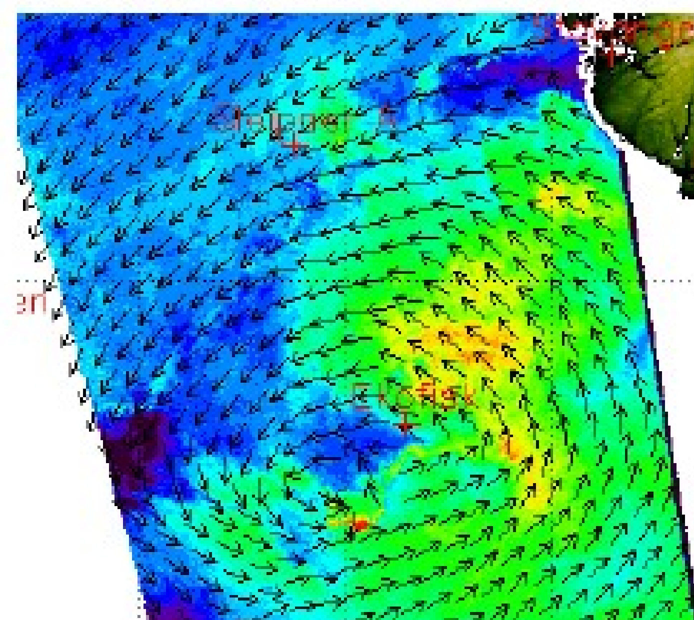






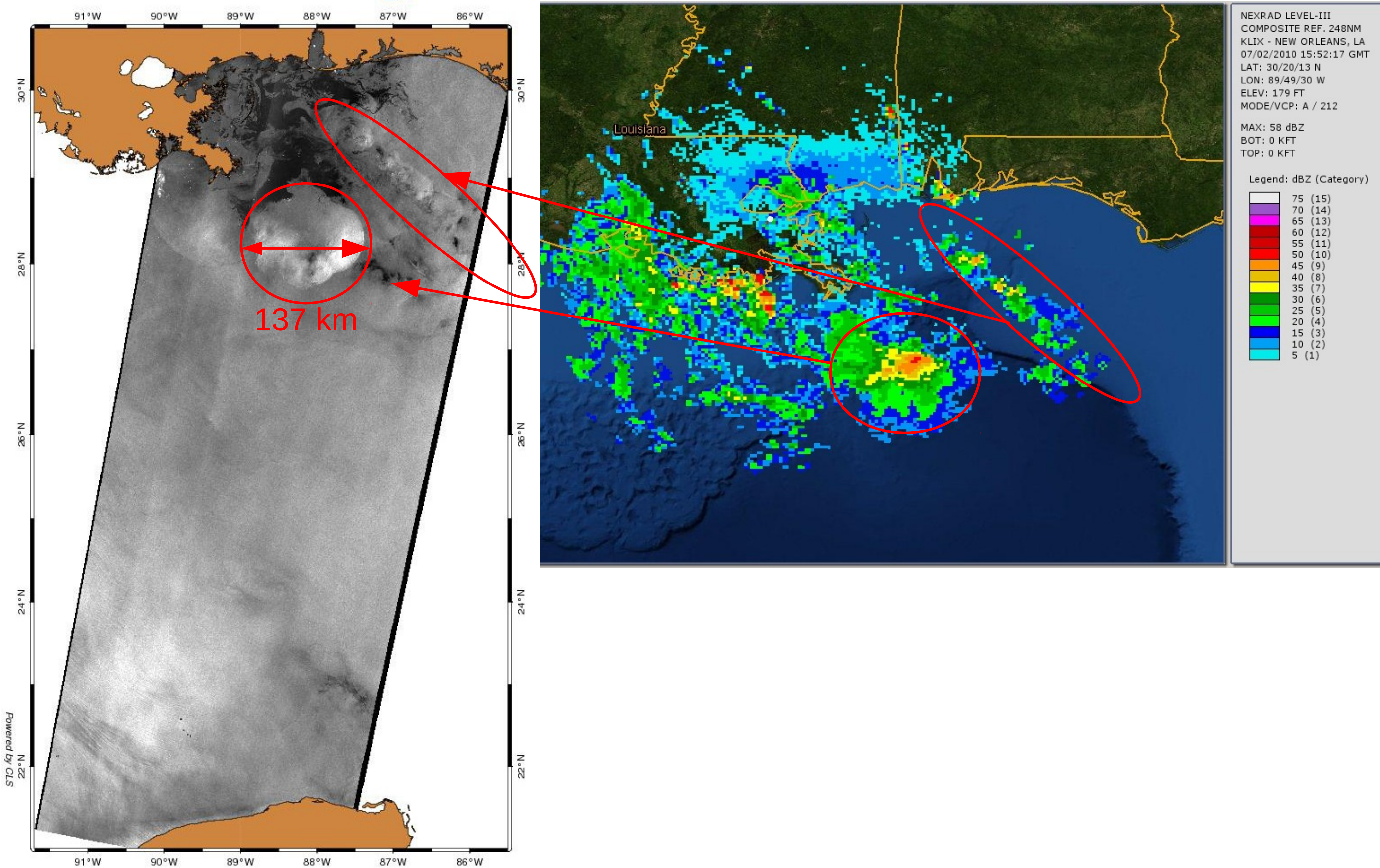


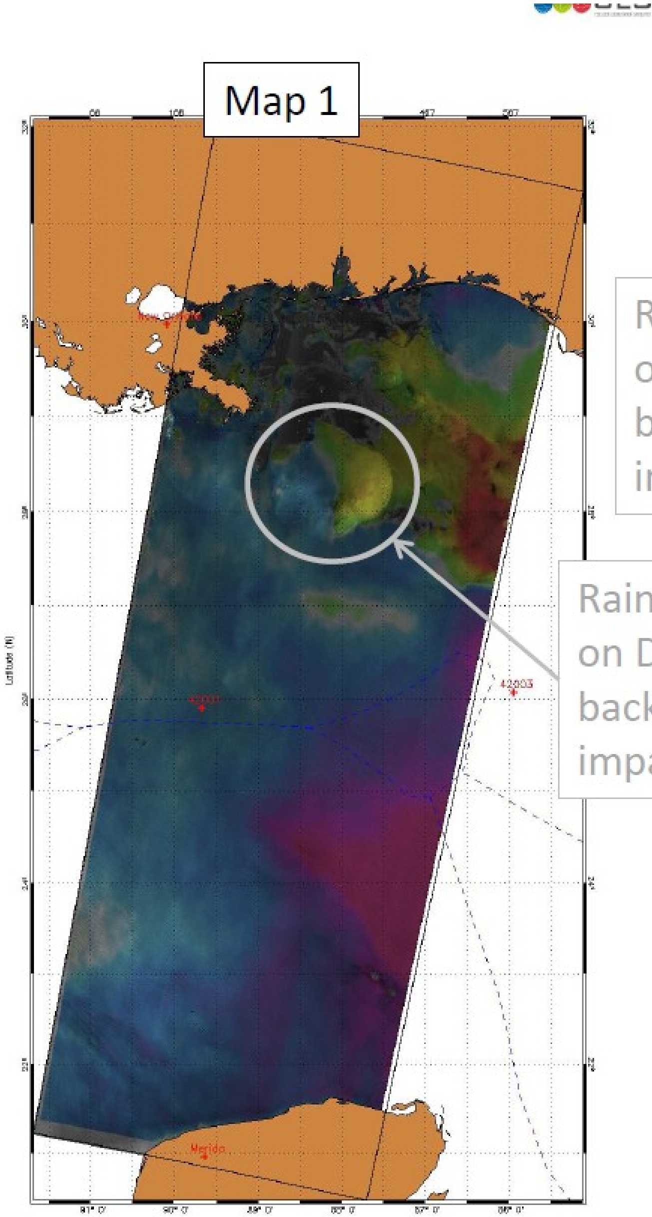
ASCAT



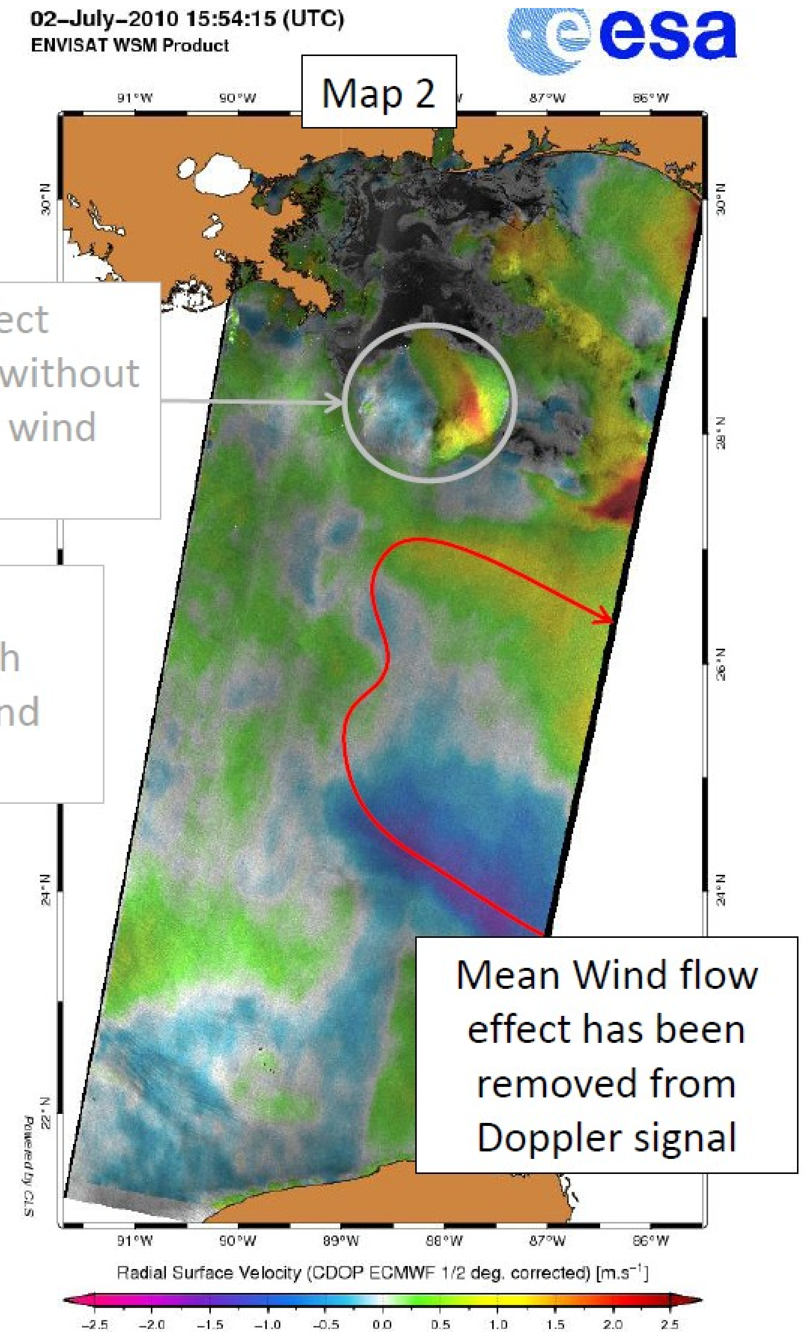
ENVISAT Experience : Doppler and Sea surface Wind from Wide Swath

02–July–2010 15:54:15 (UTC)
ENVISAT WSM Product

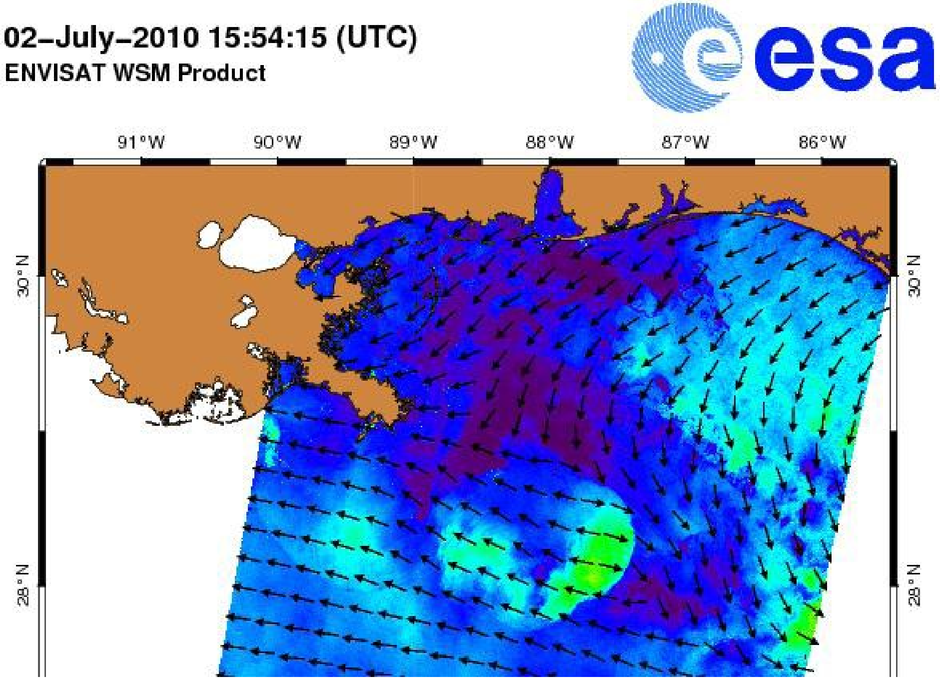


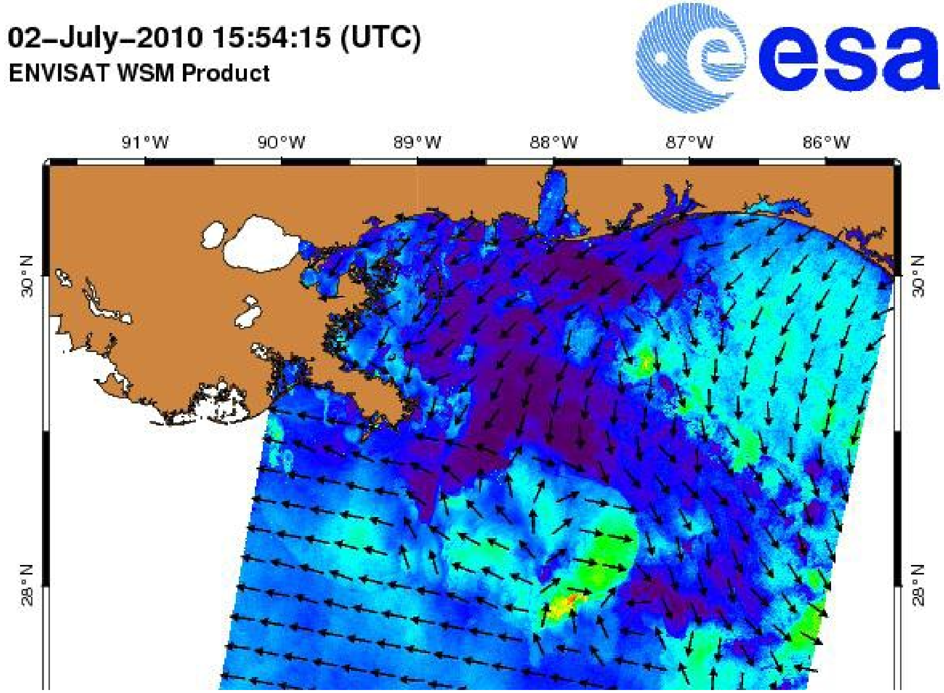


Doppler with all geophysical contributions

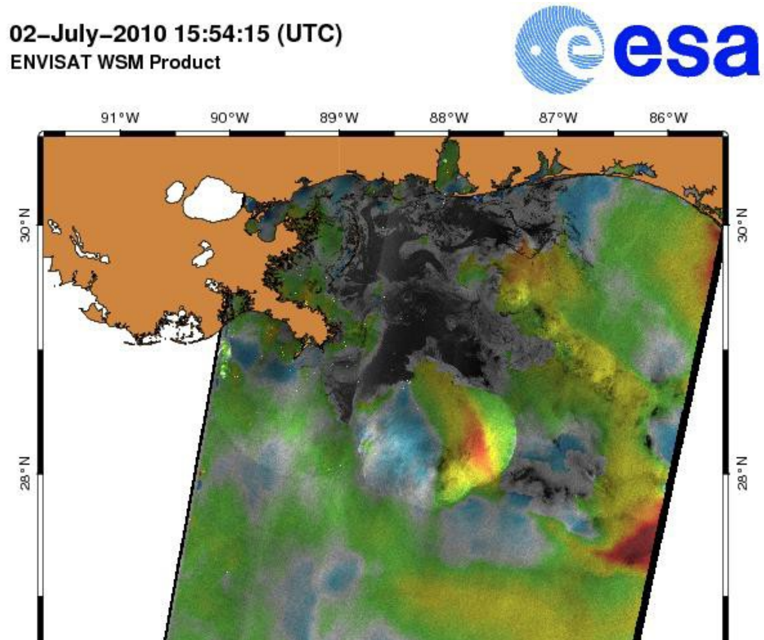


ENVISAT Experience : Doppler and Sea surface Wind from Wide Swath





Wind inversion where the Doppler information is **not** used



Wind inversion where the Doppler information is used

Content

- Doppler
  - Background
  - ENVISAT experience
  - **Conclusions & Perspectives**
- Cross-polarization
  - Cross-polarization and wind with RadarSat-2
  - Model & Understanding of the measurement
  - Conclusions & Perspectives

Conclusions

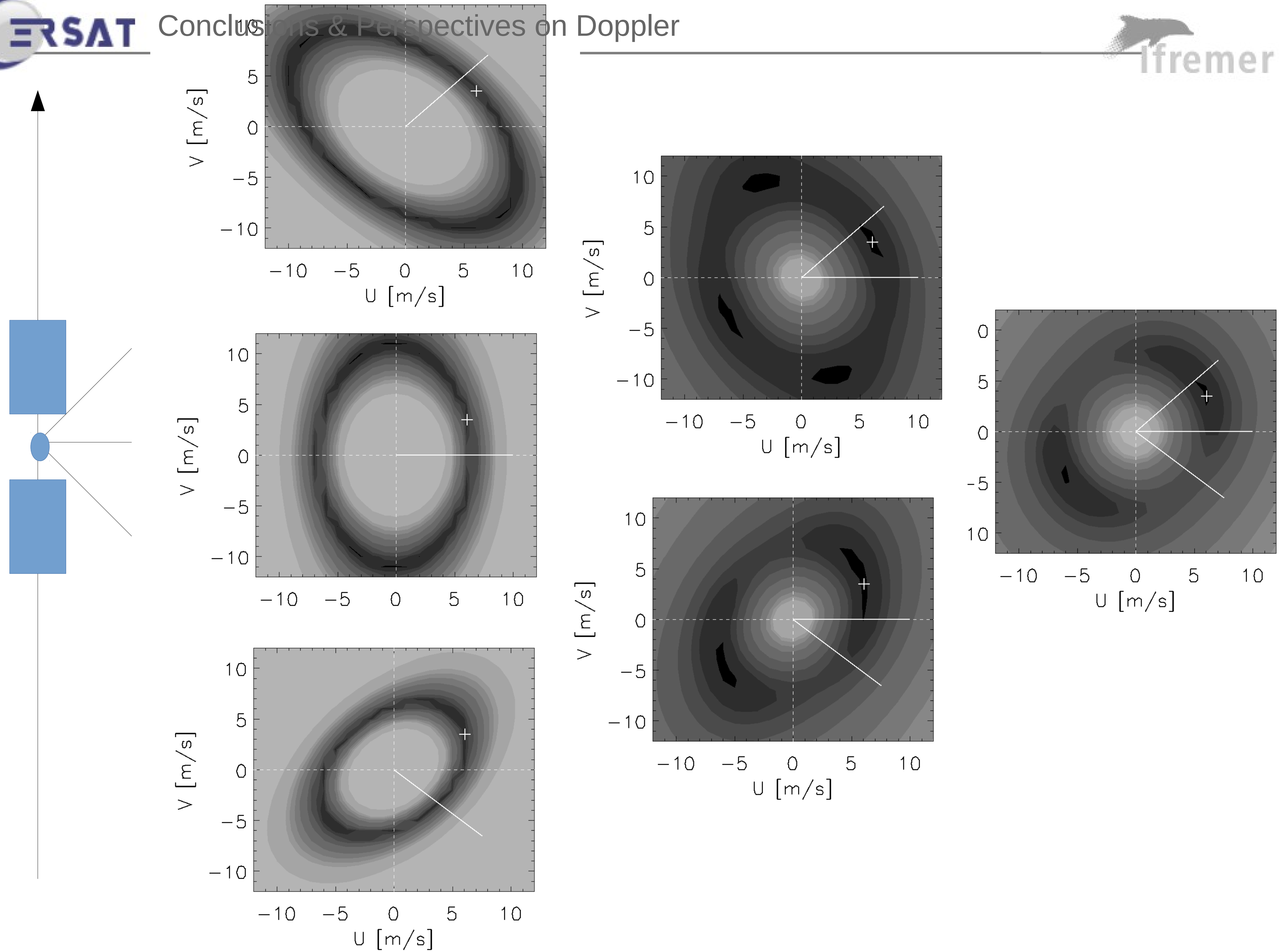
- Doppler is affected by both Sea state and Sea surface current
- Doppler response to sea state is higher in HH than in VV
- Doppler response to sea state decreases when incidence angle increases

- In cases where wind is dominating the Doppler contribution, Doppler can be used to constrain wind inversion. In particular for wind direction

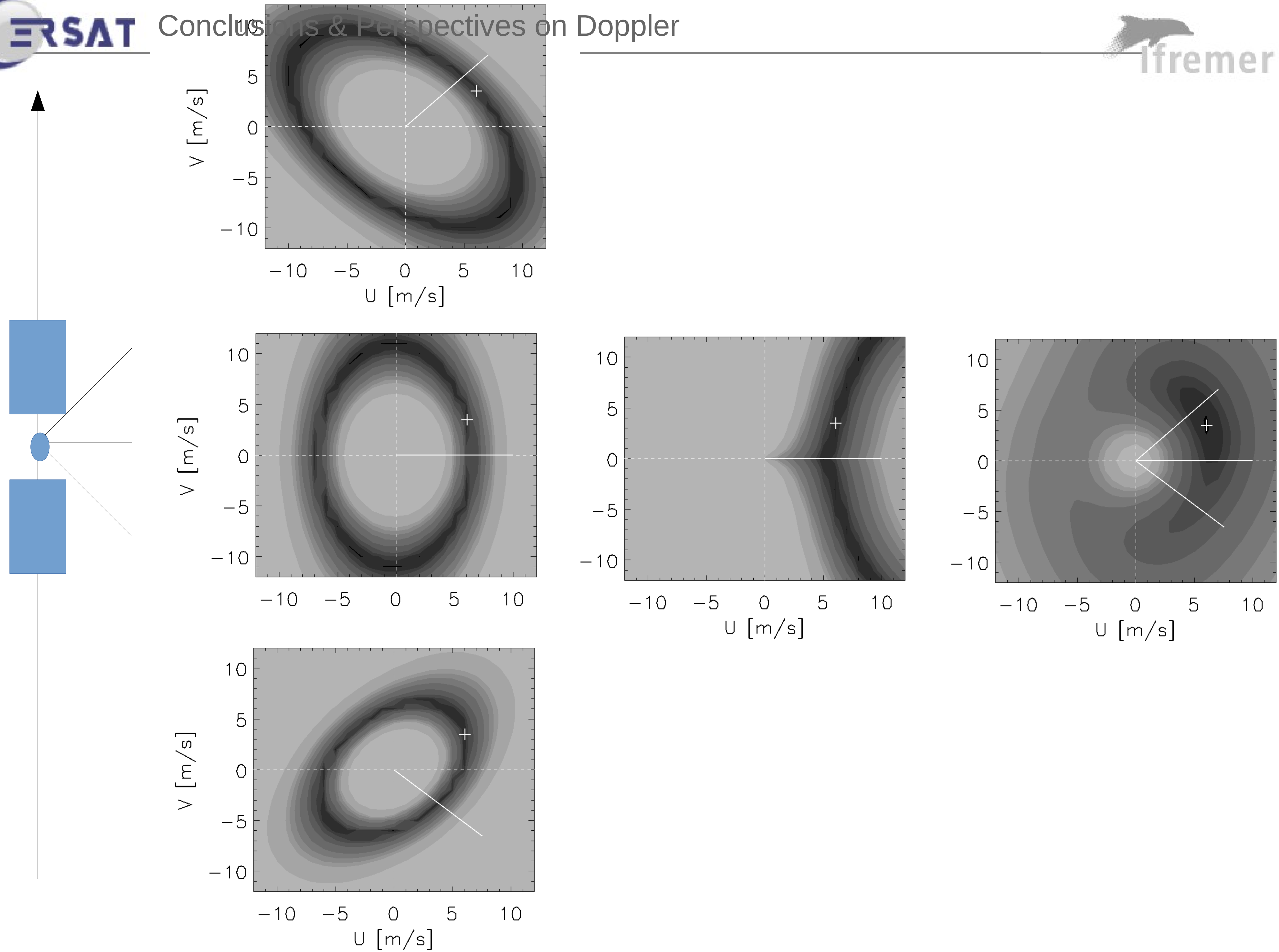
Perspectives

- Combination of Doppler and NRCS for wind retrieval from several antenna may be of interest

Conclusions & Perspectives on Doppler



Conclusions & Perspectives on Doppler



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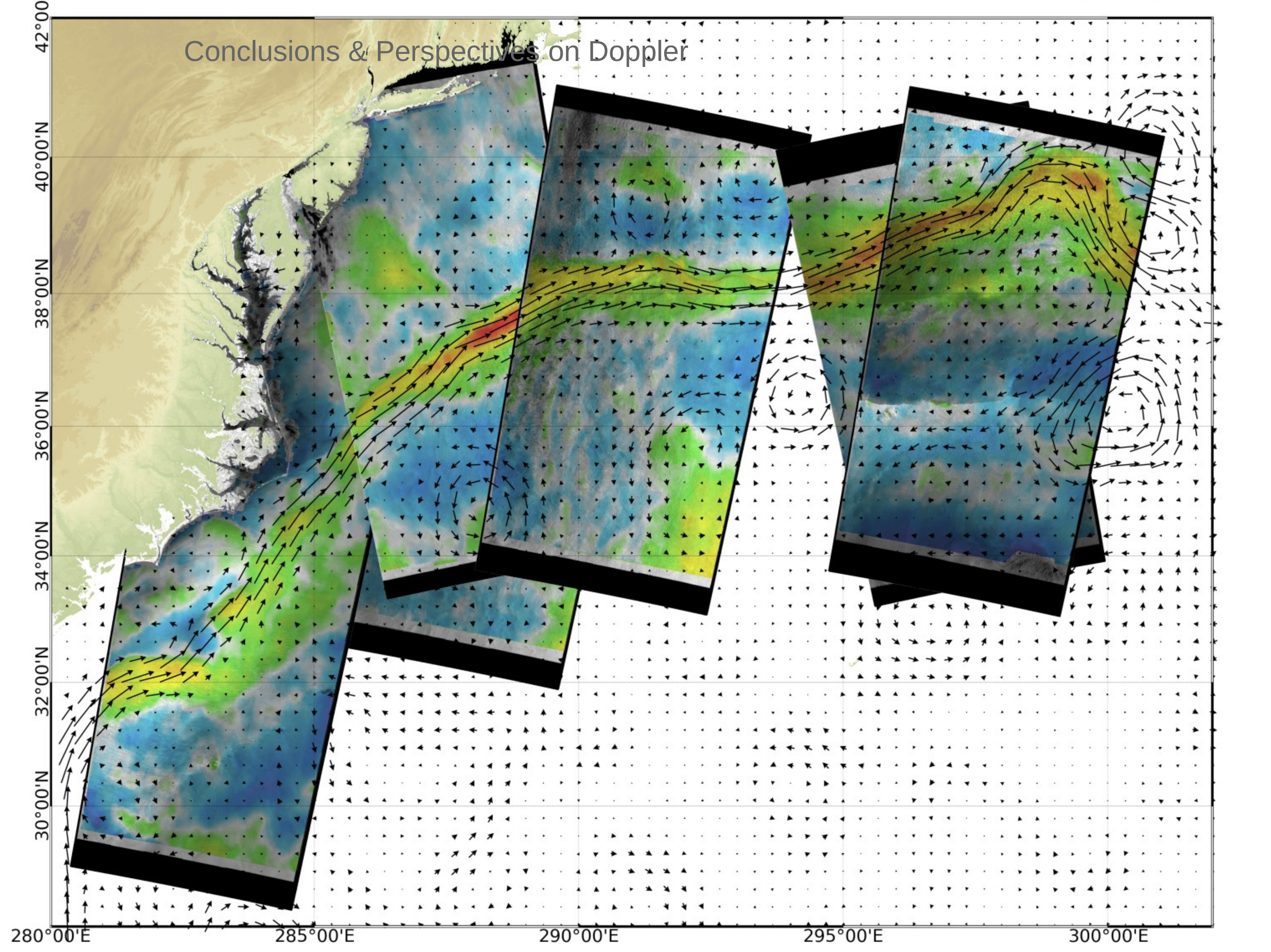
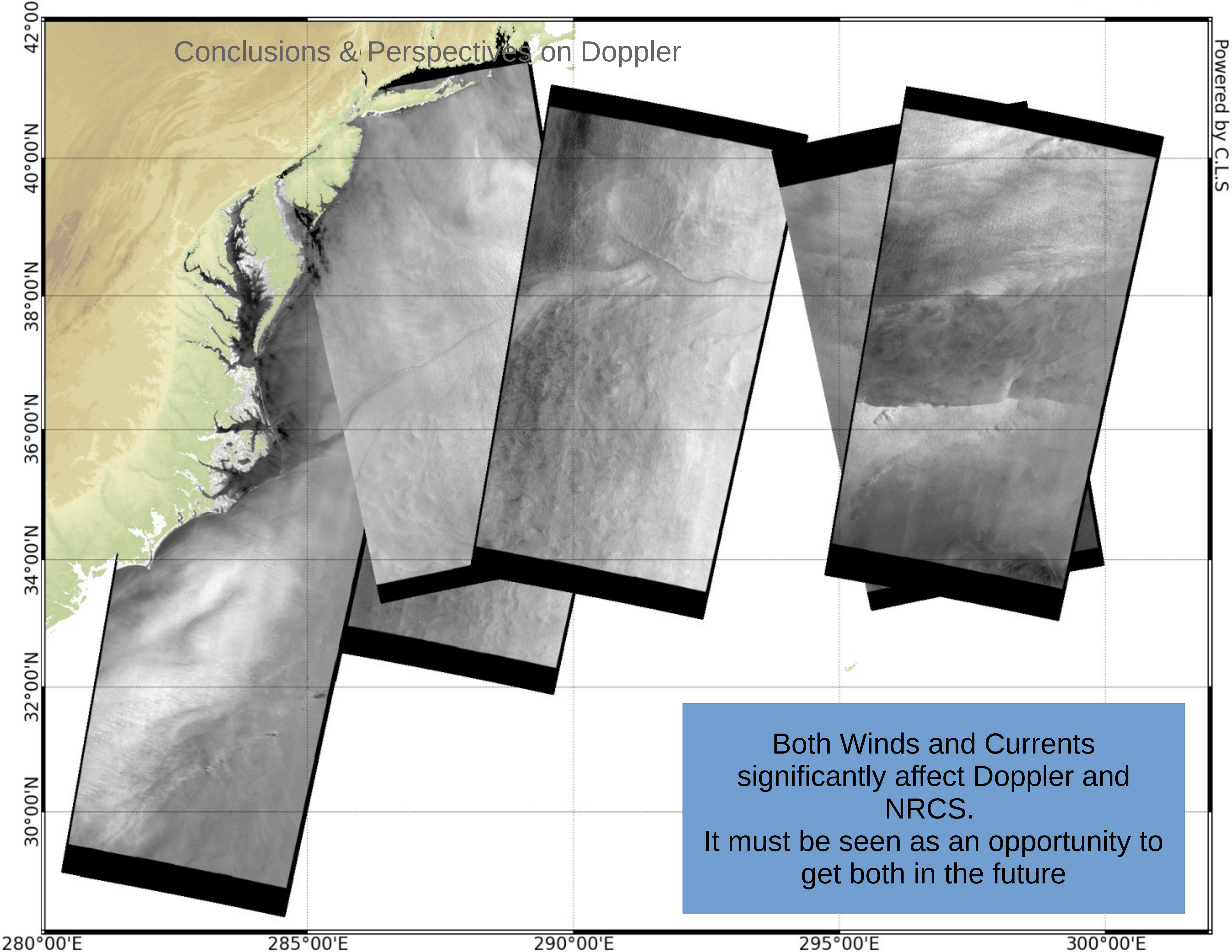
Perspectives

- Combination of Doppler and NRCS for wind retrieval from several antenna may be of interest
- Combination of Doppler and NRCS from several antenna(incidence/azimuth) may allow both wind & current retrieval at the same time.

Conclusions & Perspectives on Doppler



Conclusions & Perspectives on Doppler



Both Winds and Currents significantly affect Doppler and NRCS.
It must be seen as an opportunity to get both in the future

Conclusions

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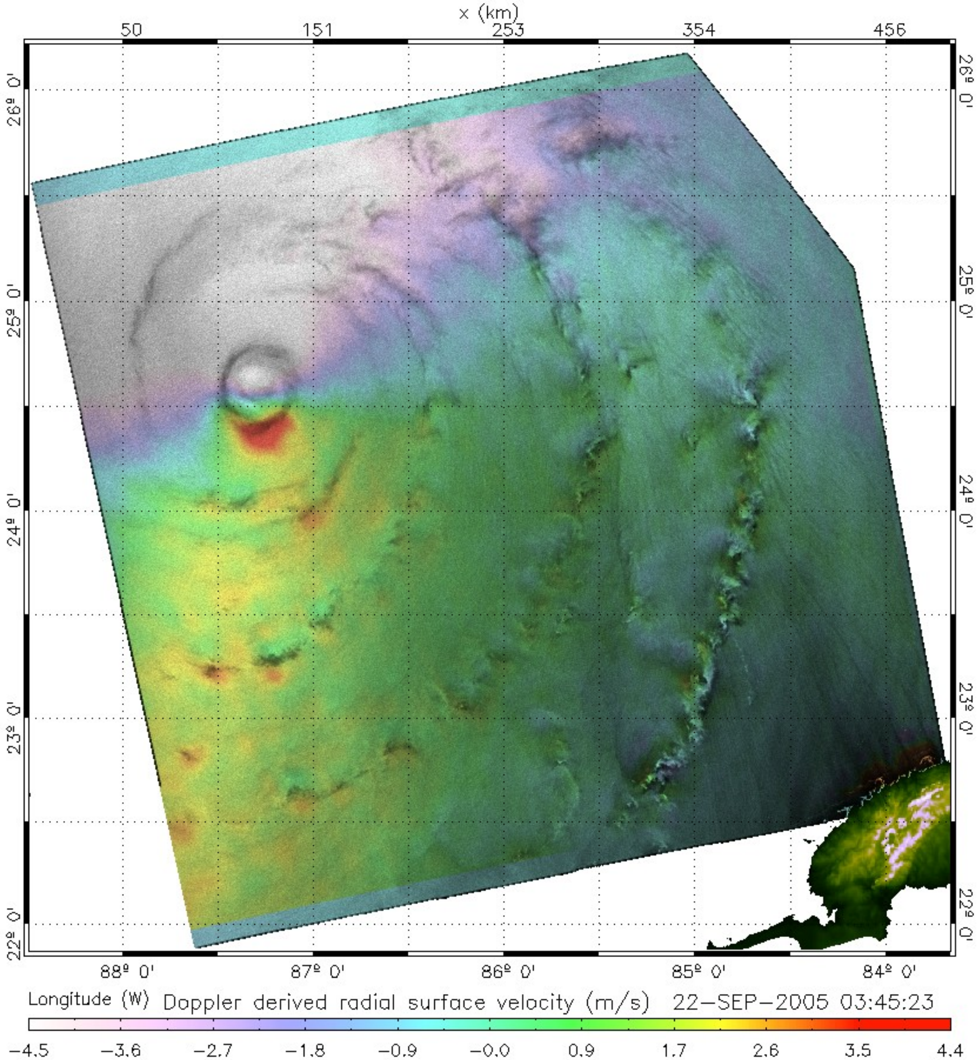
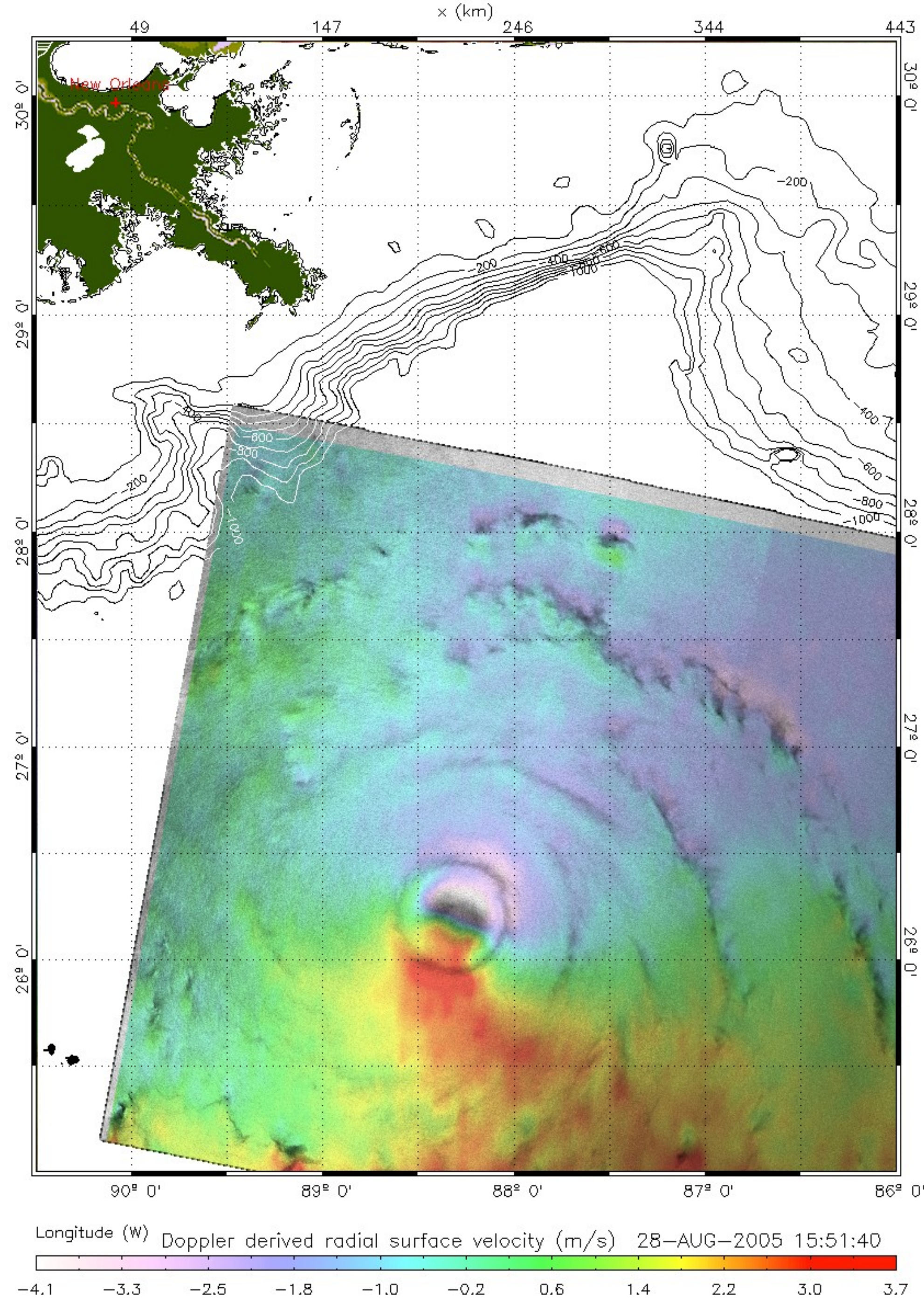
- Impact on waves on the Doppler

Conclusions & Perspectives on Doppler

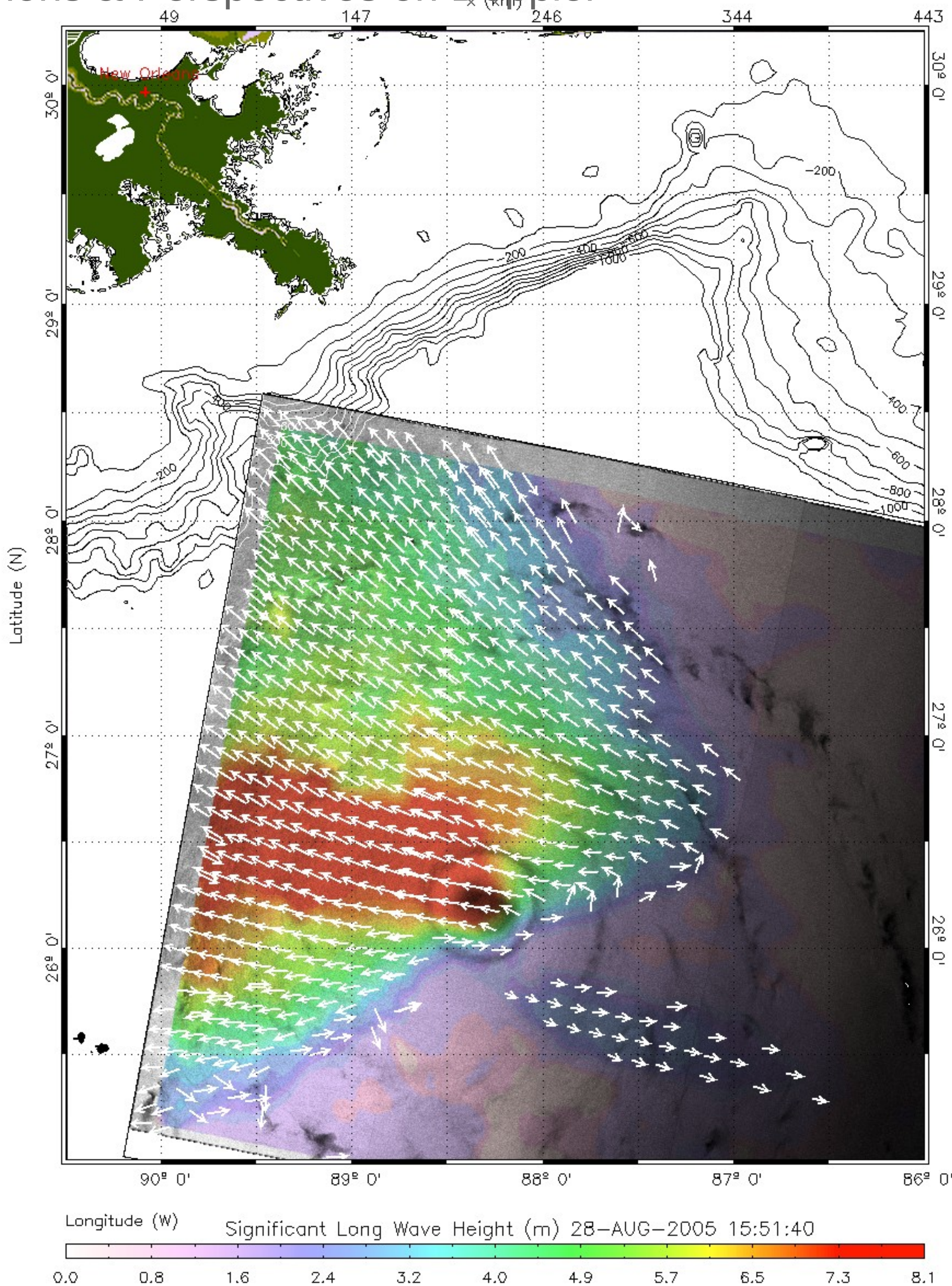


Hurricane Rita on September 22 2005 @ 03:45 UTC



Hurricane Katrina on August 28 2005 @ 15:50 UTC

Conclusions & Perspectives on Doppler



Conclusions

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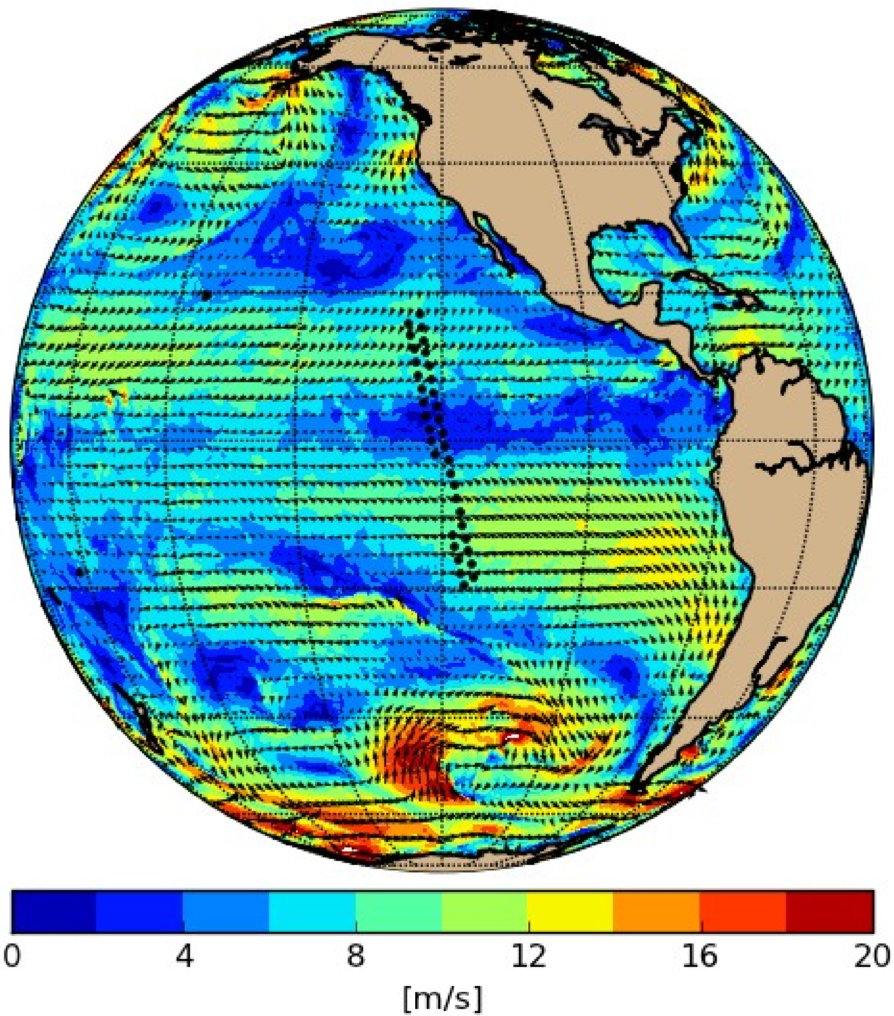
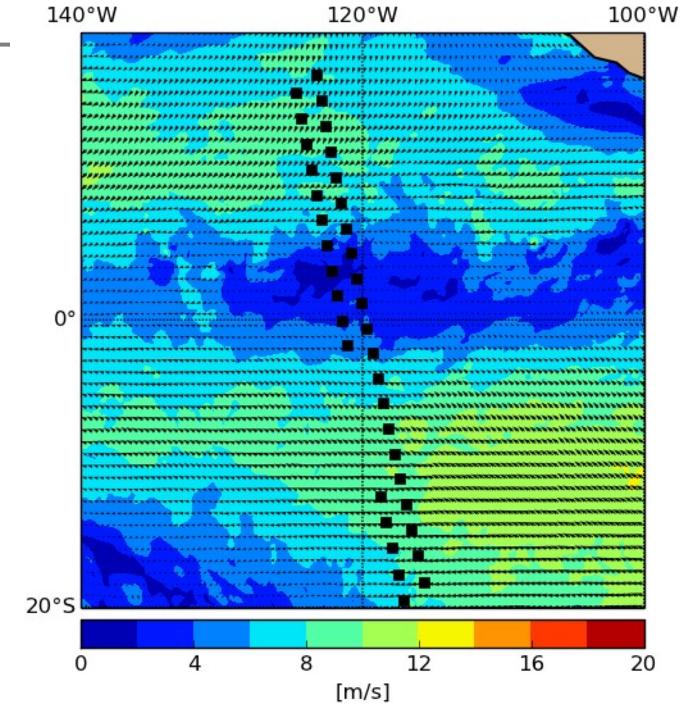
Perspectives

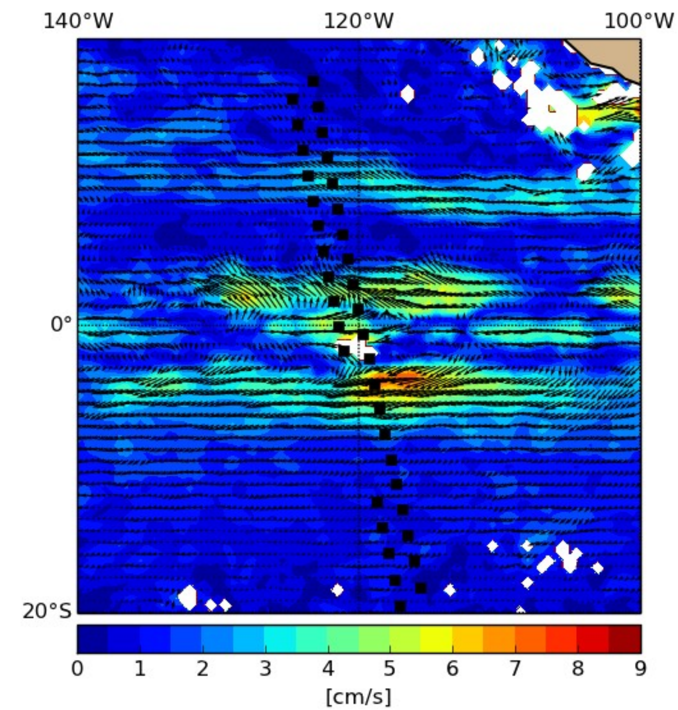
- Combination of Doppler and NRCS for wind retrieval from several antenna may be of interest
- Combination of Doppler and NRCS from several antenna(incidence/azimuth) may allow both wind & current retrieval at the same time.
- Impact on waves on the Doppler
- Sentinel-1 should allow better Doppler measurements (5 Hz on the Doppler centroid estimator) and pursue investigations

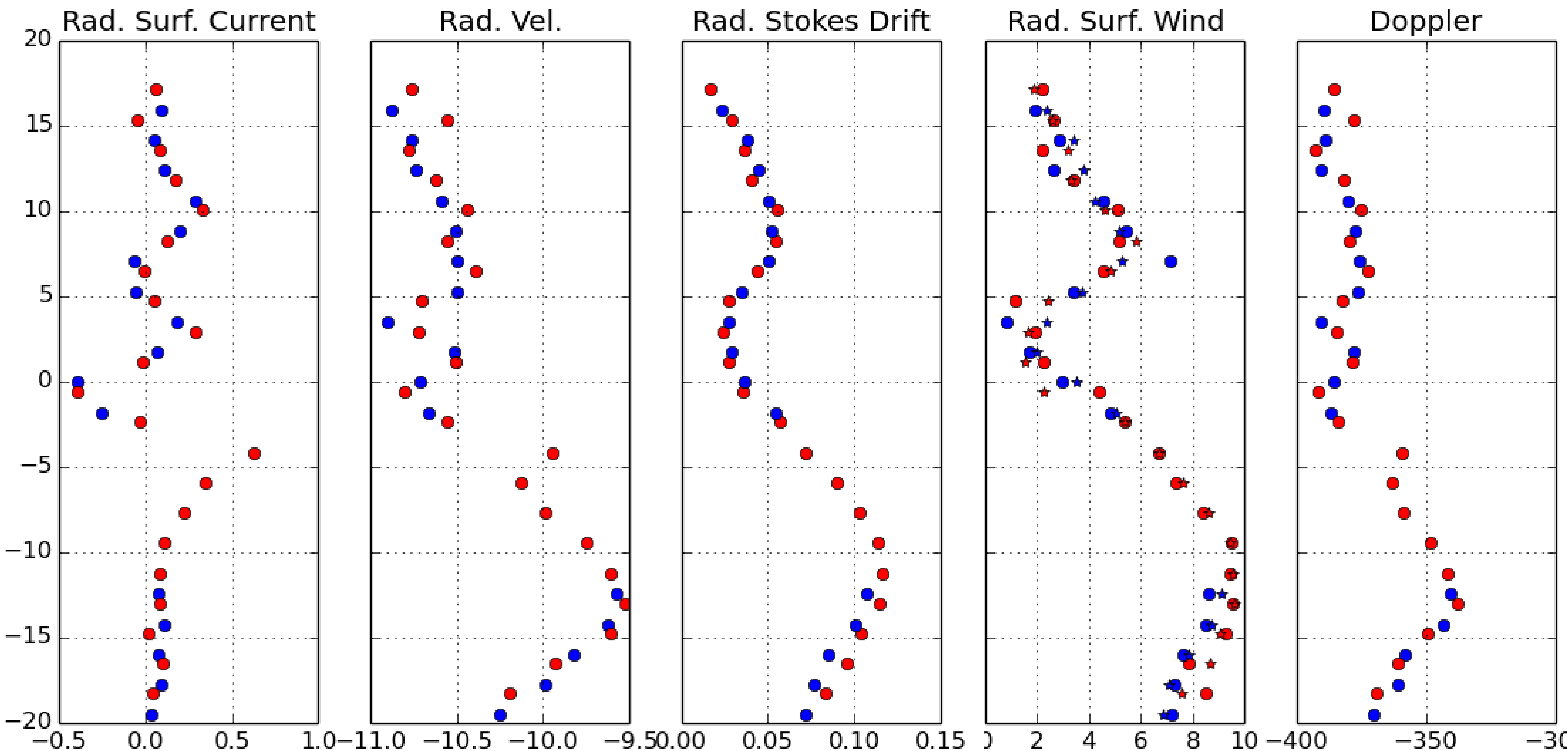
Conclusions & Perspectives on Doppler

12 April 2014 @ 02:11:23 – 02:21 :27







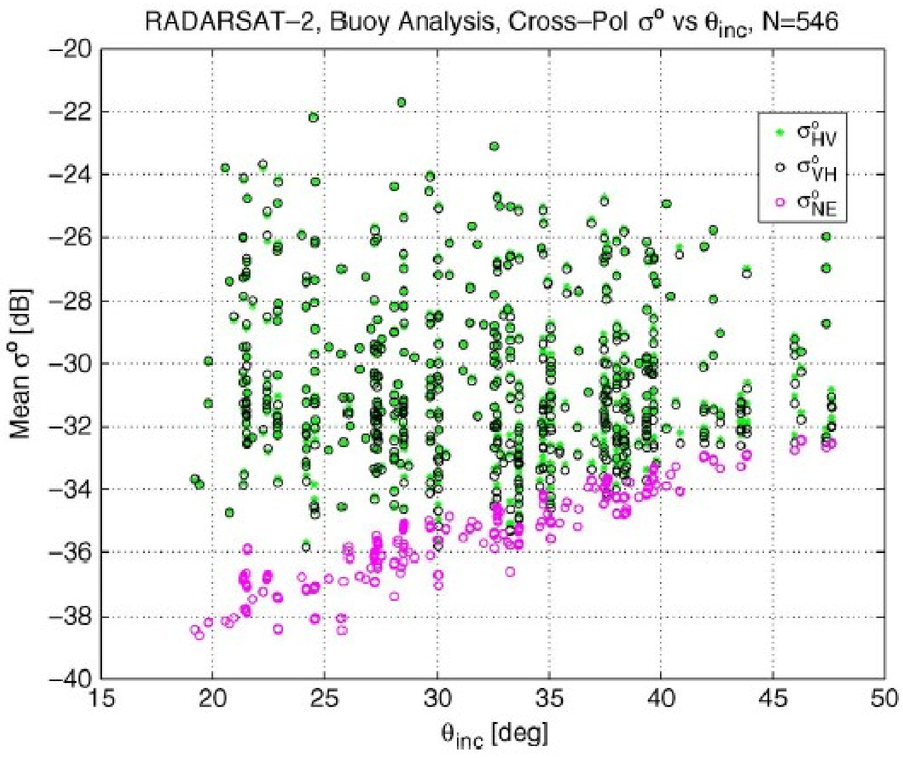

Rad. Surf. Current
Rad. Vel.
Rad. Stokes Drift
Rad. Surf. Wind
Doppler
20
15
10
5
0
−5
−10
−15
−20
−0.5
0.0
0.5
1.0
−11.0
−10.5
−10.0
−9.5
0.00
0.05
0.10
0.15
2
4
6
8
10
−400
−350

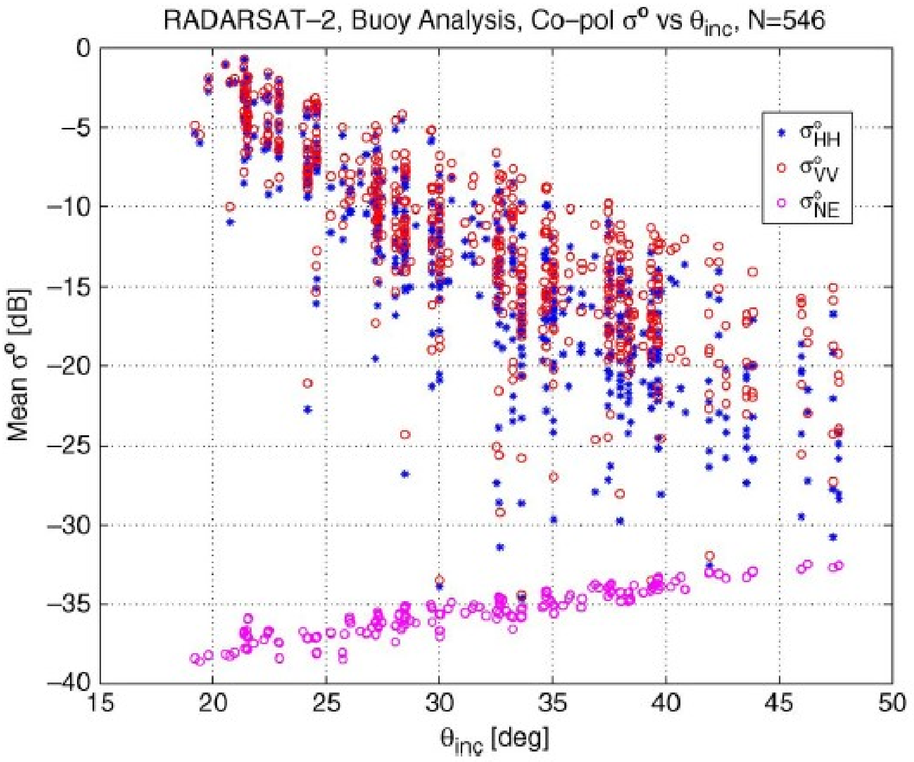
- Doppler
  - Background
  - ENVISAT experience
  - Conclusions & Perspectives
- Cross-polarization
  - **Cross-polarization and wind with RadarSat-2**
  - Model & Understanding of the measurement
  - Conclusions & Perspectives

- Based on RadarSat-2, Vachon et al., Hwang et al. and Zhang et al. have described the (N)RCS in cross-polarization at C-band with respect to incidence angle, wind speed and azimuth direction (i.e wind direction with respect to antenna look direction).

- Vachon, and J. Wolfe, 2011: C-band cross-polarization wind speed retrieval. IEEE Geosci. Remote Sens. Lett., 8, 456–459.
- Hwang, P. A., B. Zhang, and W. Perrie, 2010a: Depolarized radar return for breaking wave measurement and hurricane wind retrieval. Geophys. Res. Lett., 37, L01604, doi:10.1029/2009GL041780.
- Hwang, P. A., B. Zhang, J. V. Toporkov, and W. Perrie, 2010b: Comparison of composite Bragg theory and quad-polarization radar backscatter from RADARSAT-2: With applications to wave breaking and high wind retrieval. J. Geophys. Res., 115, C08019, doi:10.1029/2009JC005995
- Zhang, B., W. Perrie, and Y. He, 2011: Wind speed retrieval from RADARSAT-2 quad-polarization images using a new po-larization ratio model. J. Geophys. Res., 116, C08008, doi:10.1029/2010JC006522.
- Zhang, B., and W. Perrie, 2012: Cross-polarized synthetic aperture radar: A new potential technique for hurricanes. Bull. Amer. Meteor. Soc., 93, 531–541.
- Zhang, B., W. Perrie, P. W. Vachon, X. Li, W. G. Pichel, J. Guo, and Y. He, 2012: Ocean vector winds retrieval from C-band fully polari-metric SAR measurements. IEEE Trans. Geosci. Remote Sens., 50, 4252–4261.
- Zhang, B., W. Perrie, Zhang, J., Uhlhorn, E. and He, Y. , 2014 : High-Resolution Hurricane Vectors Winds from C-Band Dual-Polarization SAR Observations
- G.-J. van Zadelhoff, A. Stoffelen, P. W. Vachon, J. Wolfe, J. Horstmann, and M. Belmonte Rivas 2014: Retrieving hurricane wind speeds using cross-polarization C-band measurements, Atmos. Meas. Tech., 7, 437–449.
- Horstmann et al., IOVWST Meeting, Brest, June 2014

- Major findings can be summarized as followed :
  - Very low RCS values (with respect to co-pol values)
  - No incidence angle dependence





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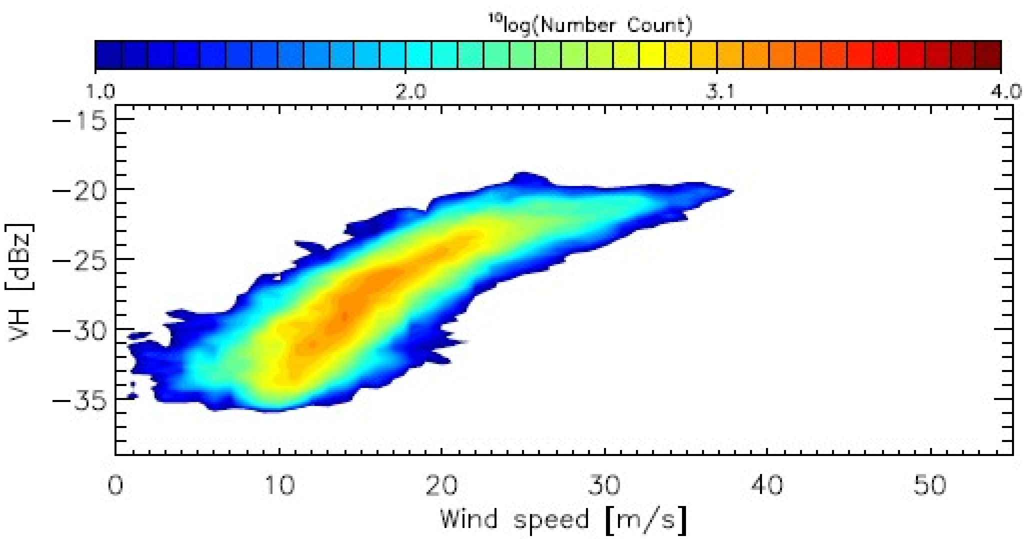
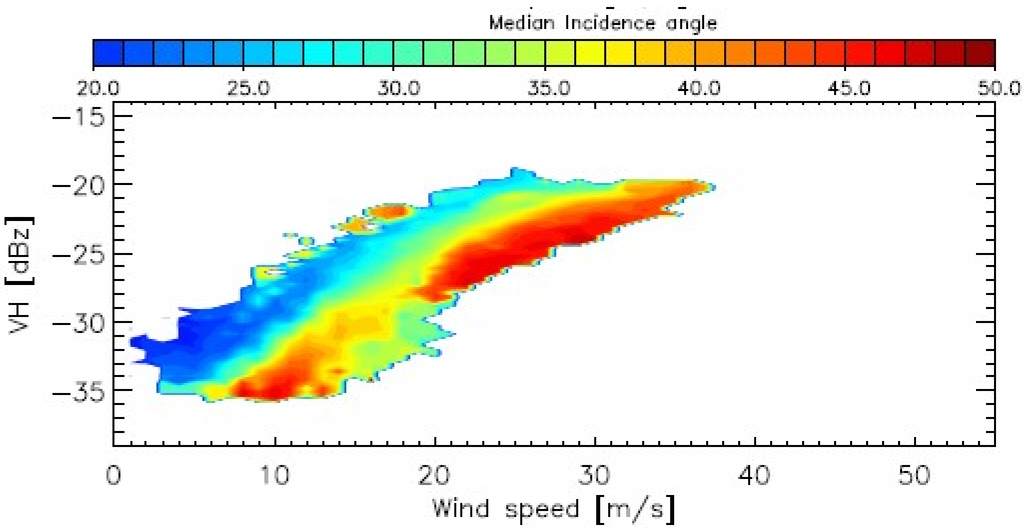
- Major findings can be summarized as followed :
  - Very low RCS values (with respect to co-pol values)
  - **Small** incidence angle dependence (for moderate winds)





G.-J. van Zadelhoff, A. Stoffelen, P. W. Vachon, J. Wolfe, J. Horstmann, and M. Belmonte Rivas 2014: Retrieving hurricane wind speeds using cross-polarization C-band measurements, Atmos. Meas. Tech., 7, 437–449.

- Major findings can be summarized as followed :
  - Very low RCS values
  - Small incidence angle dependence (for moderate winds)
  - Small azimuth direction dependency (not modelled so far)

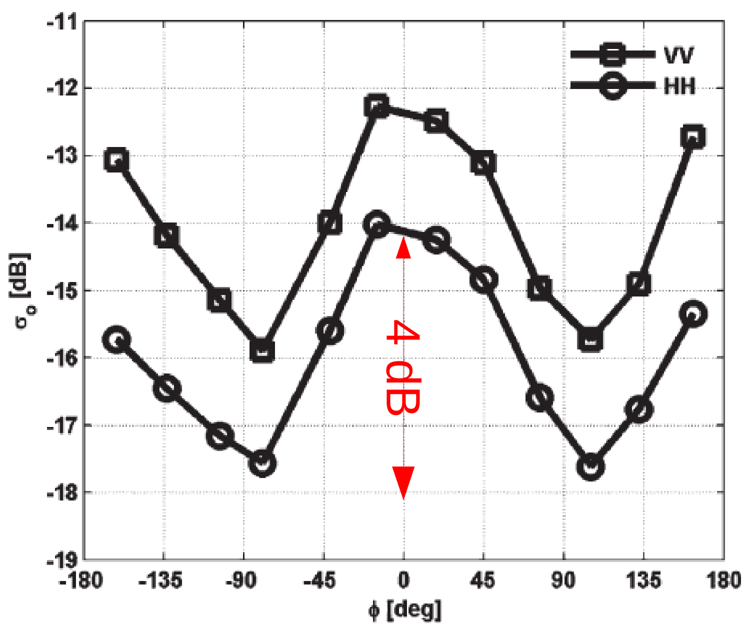


Fig. 3. RADARSAT-2 measured NRCS in VV and HH polarizations versus relative wind direction. The average wind speed and incidence angle are 10 m/s and 35°, respectively.

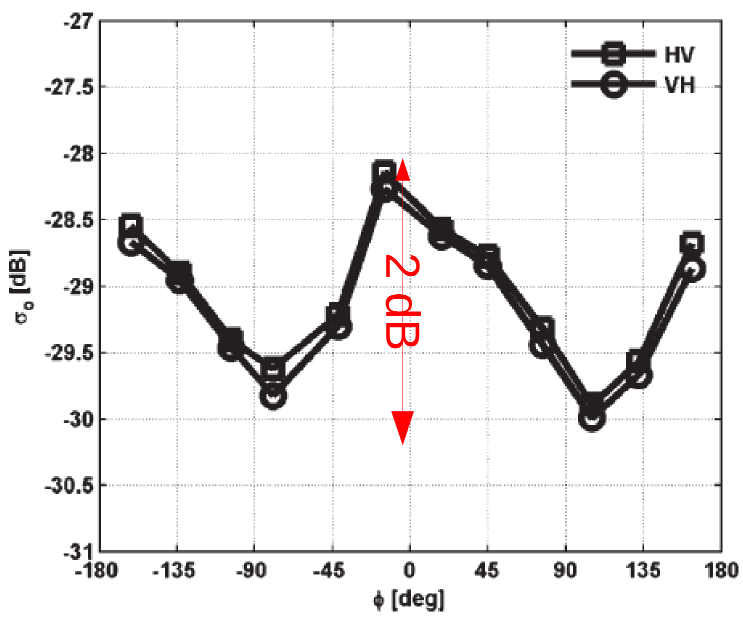
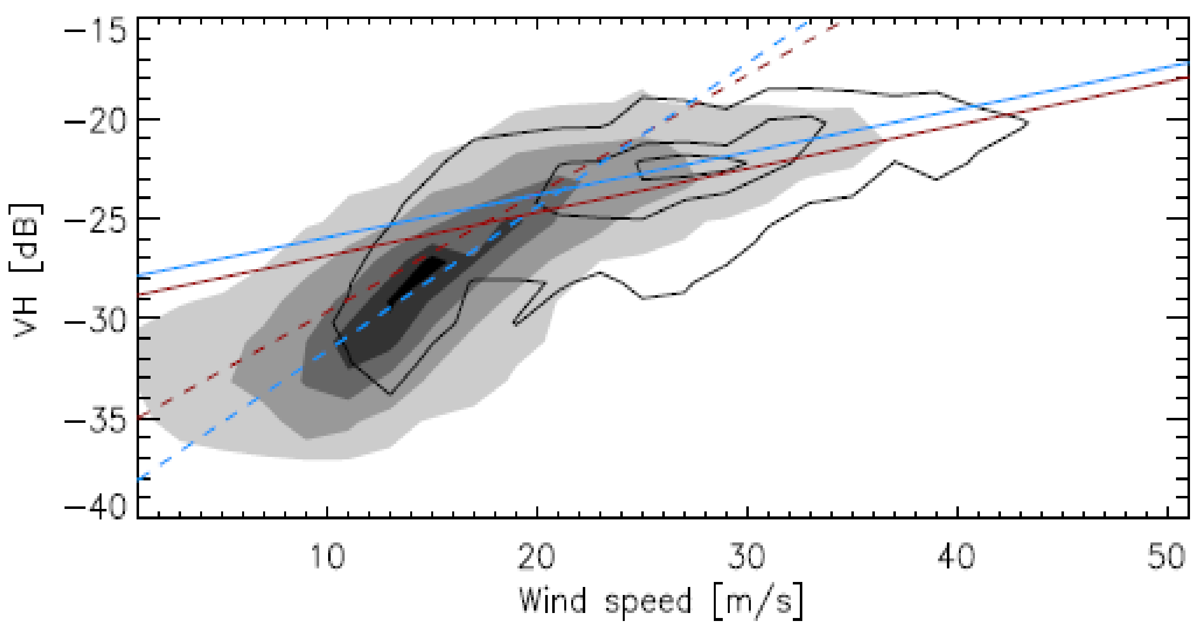


Fig. 4. RADARSAT-2 measured NRCS in HV and VH polarization versus relative wind direction. The average wind speed and incidence angle are 10 m/s and 35°, respectively.

Zhang, B., W. Perrie, P. W. Vachon, X. Li, W. G. Pichel, J. Guo, and Y. He, 2012: Ocean vector winds retrieval from C-band fully polari-metric SAR measurements. IEEE Trans. Geosci. Remote Sens., 50, 4252–4261.

- Major findings can be summarized as followed :
  - Very low RCS values (up to lower than for VV)
  - Small incidence angle dependence (for moderate wind)
  - No azimuth direction dependency
  - No RCS saturation for high winds



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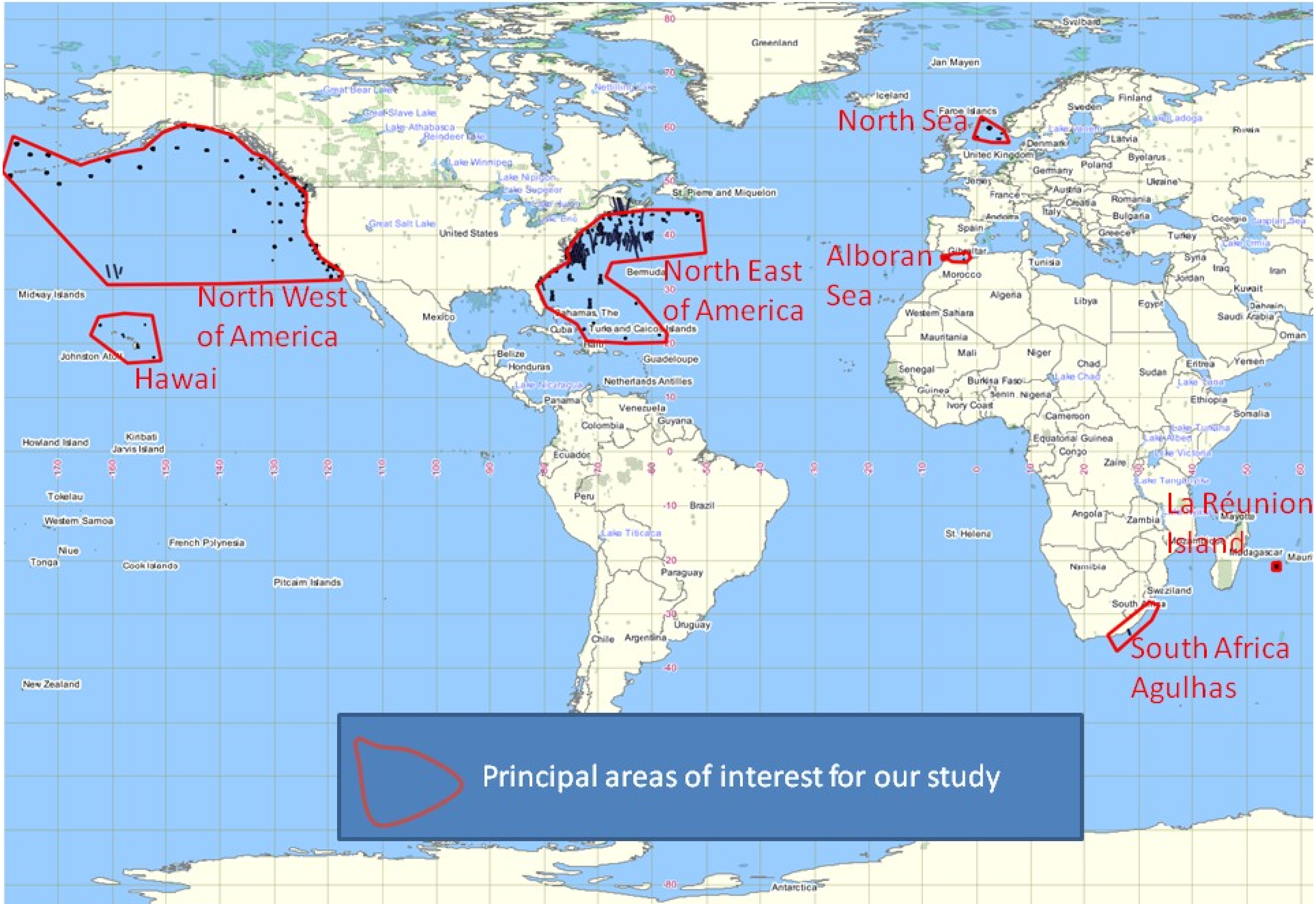
Exemple of interesting areas where acquisitions has been made



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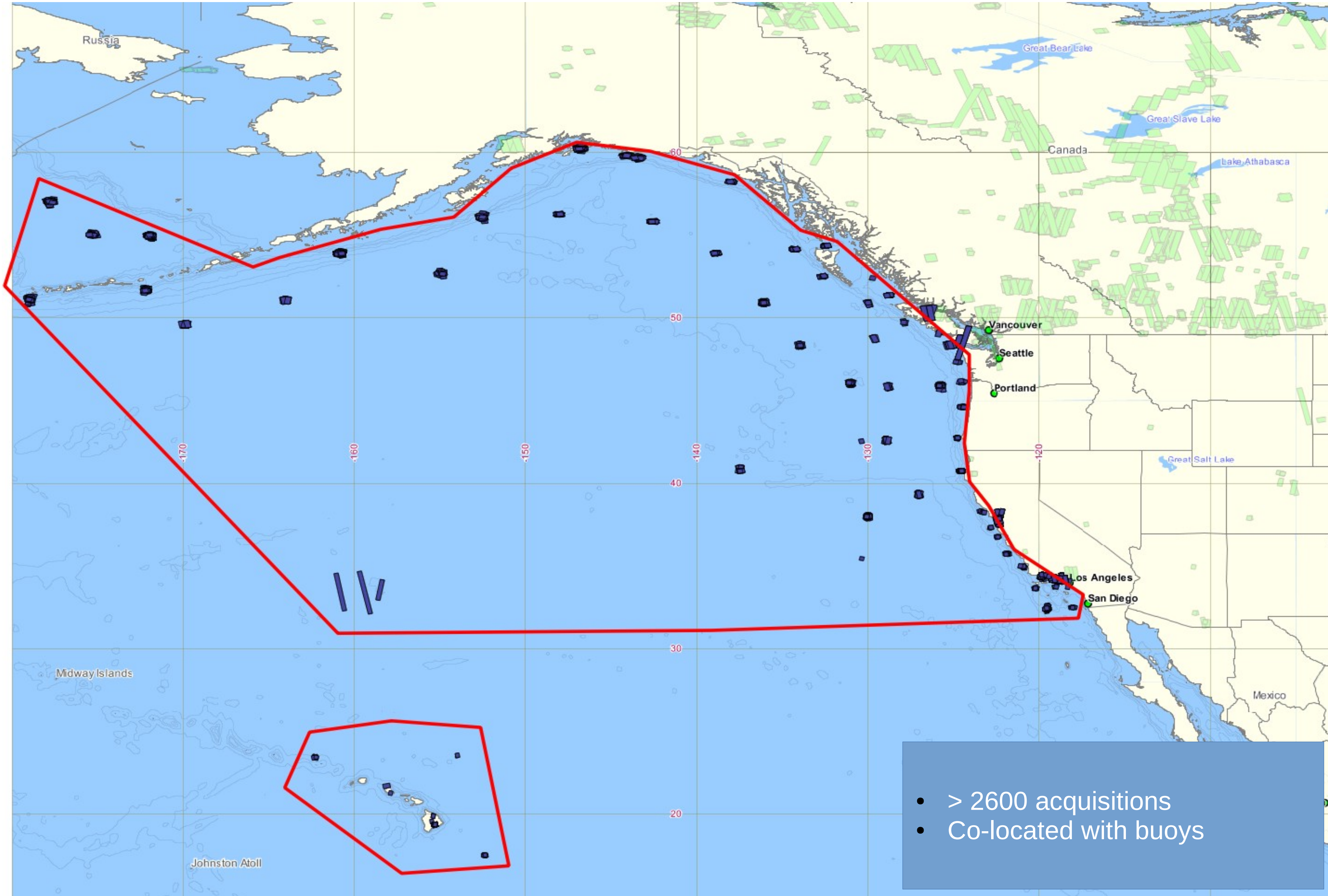
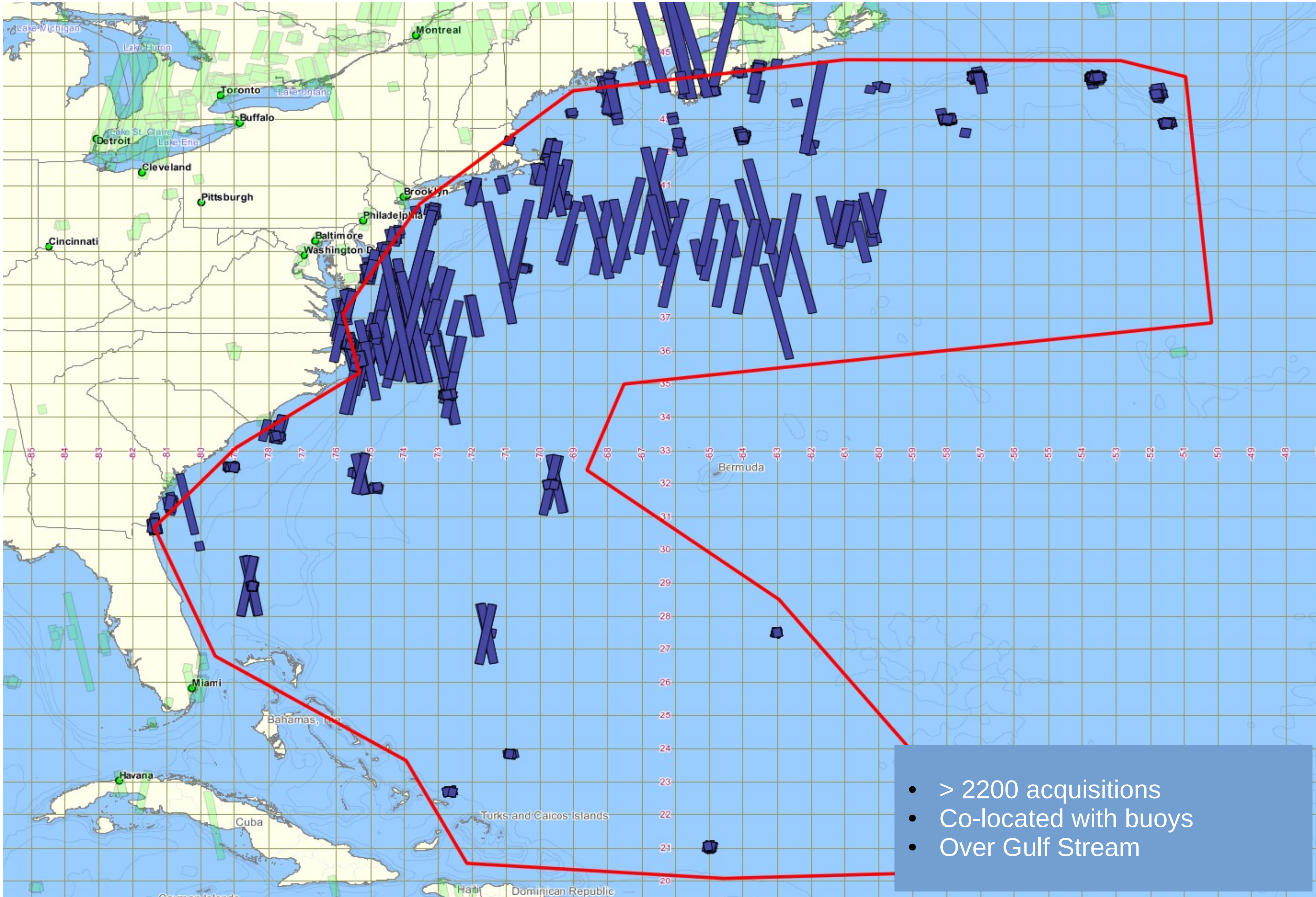


- > 2600 acquisitions
- Co-located with buoys

Cross-polarization: Cross-polarization & Wind with RadarSat-2

Exemple of interesting areas where acquisitions has been made



- > 2200 acquisitions
- Co-located with buoys
- Over Gulf Stream

- Doppler
  - Background
  - ENVISAT experience
  - Conclusions & Perspectives
- Cross-polarization
  - Cross-polarization and wind with RadarSat-2
  - **Model & Understanding of the measurement**
  - Conclusions & Perspectives

- Do we have the basics (VV & HH) ?

VV and HH polarized signal are affected by several surface properties:

- Polarizing short wind waves ~ 5 cm

- Non-polarized contribution
(steep scatters and wave breaking)

$$\sigma_0^{pp} = \sigma_{br}^{pp} + \sigma_{wb},$$

Polarization Difference, PD, short Bragg waves :

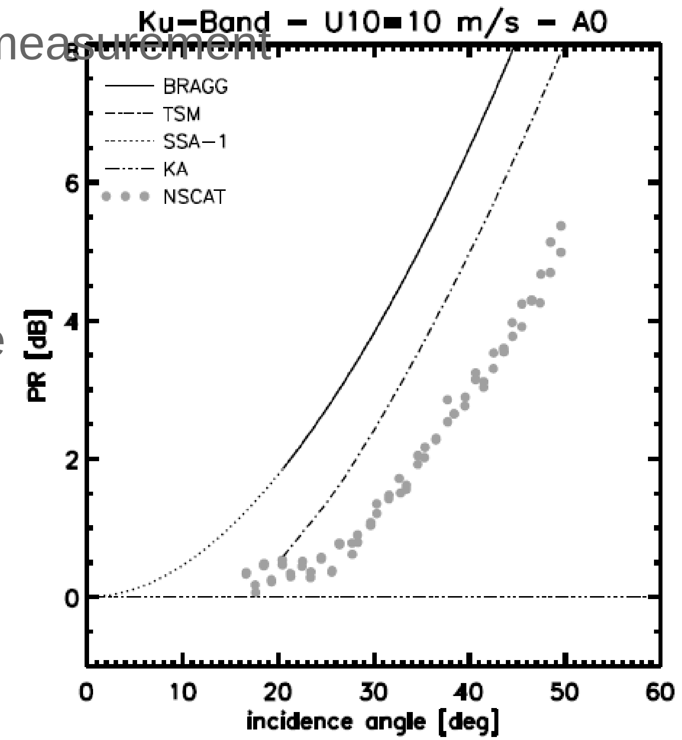
$$\Delta\sigma_0 \equiv \sigma_0^{vv} - \sigma_0^{hh} = \sigma_{0B}^{vv} - \sigma_{0B}^{hh}$$

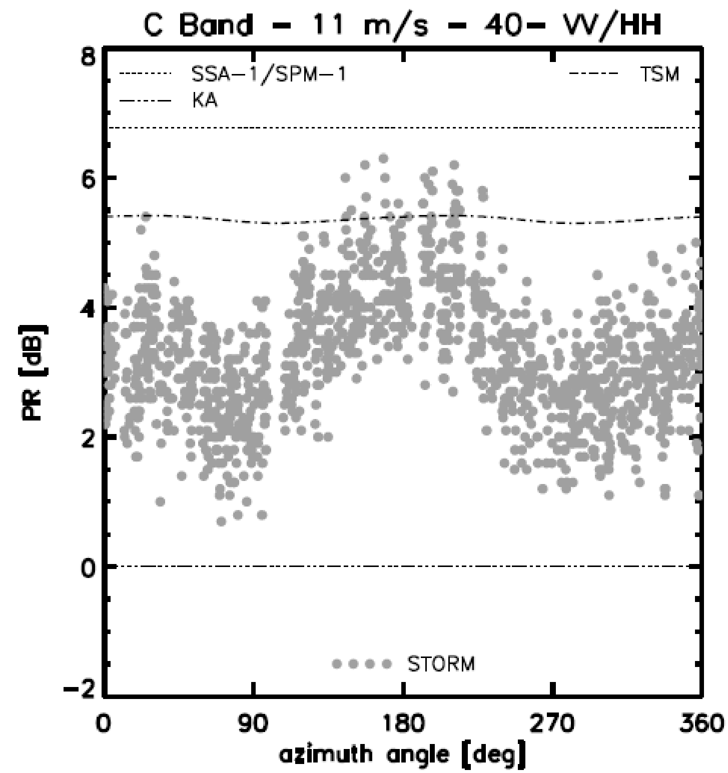
NP contribution from breaking waves :

$$\sigma_{wb} = \sigma_0^{vv} - \Delta\sigma_0/(1-p_B)$$

where $p_B = \sigma_{0B}^{hh}/\sigma_{0B}^{vv}$ is PR for Bragg scattering

Standard EM models are not able to properly reproduce both VV and HH NRCS with respect to :
- incidence angle
- azimuth angle





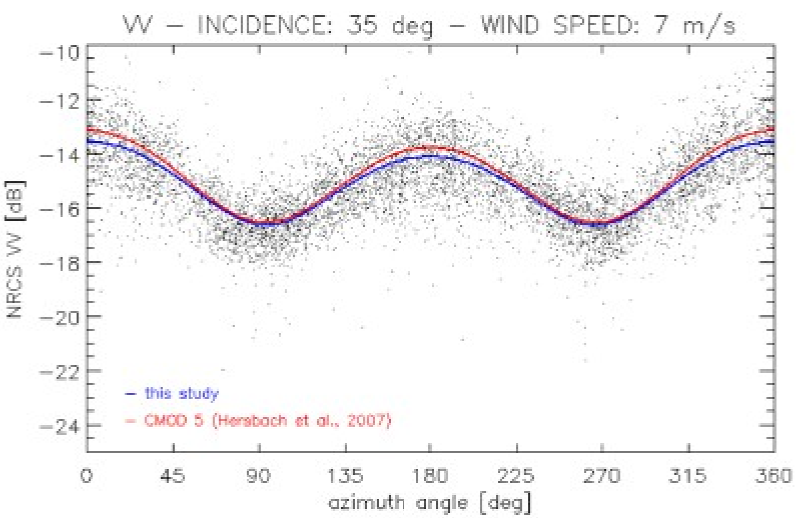
Cross-polarization: Model & Understanding of the measurement

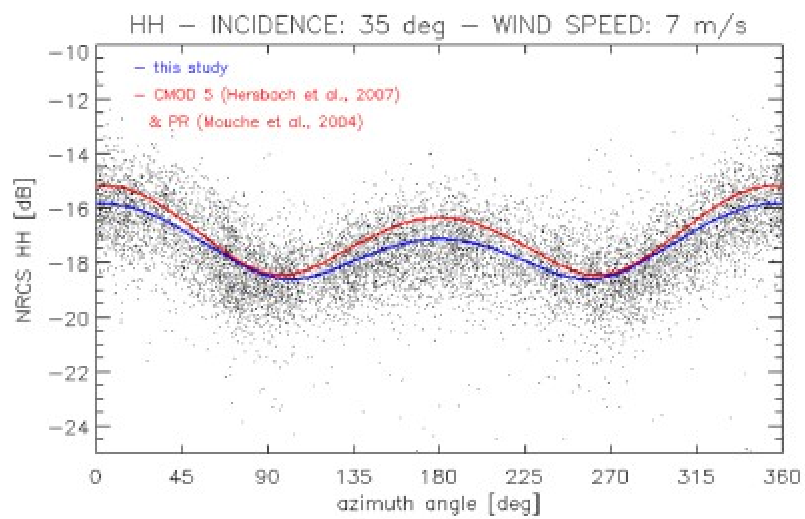
Massive colocations between

- Radar parameters from ASAR in both VV & HH co-polarisation
  Incidence angles, look angle, NRCS and doppler
- Wind speed and direction from ASCAT

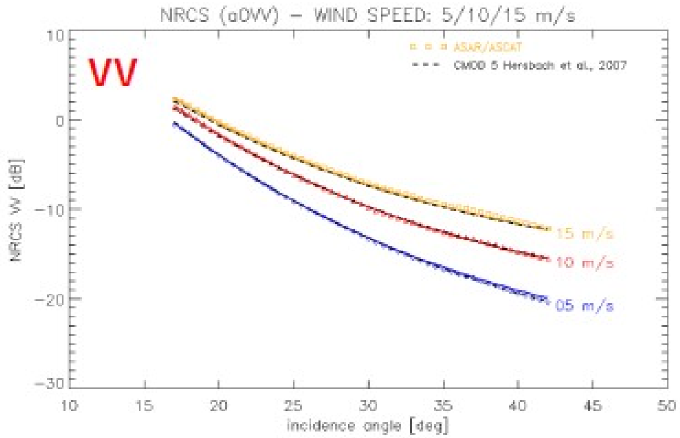
Collocations are done in areas where sea surface current signature are expected to be negligible (European waters)

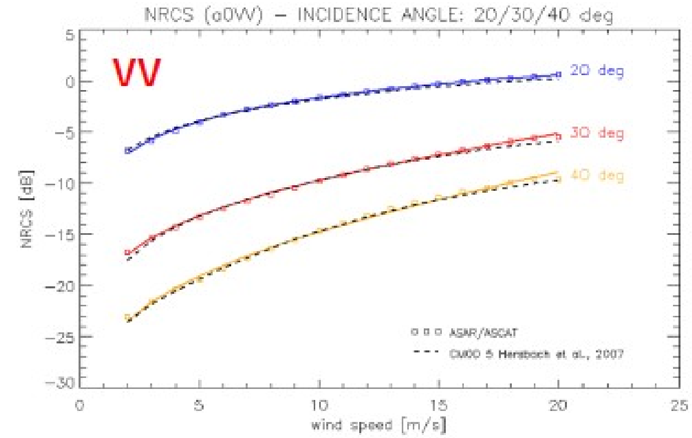
Collocation time is less than 1 hour

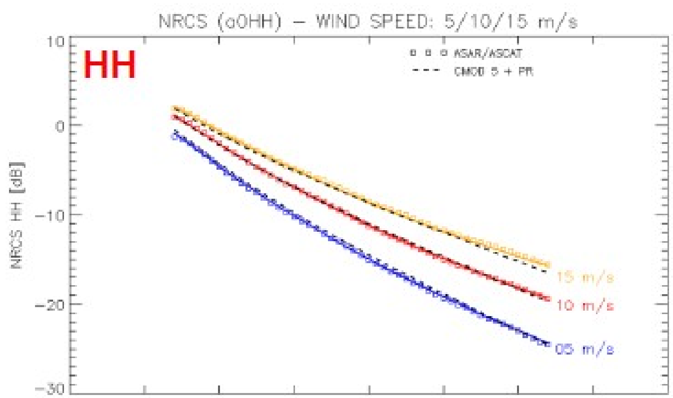


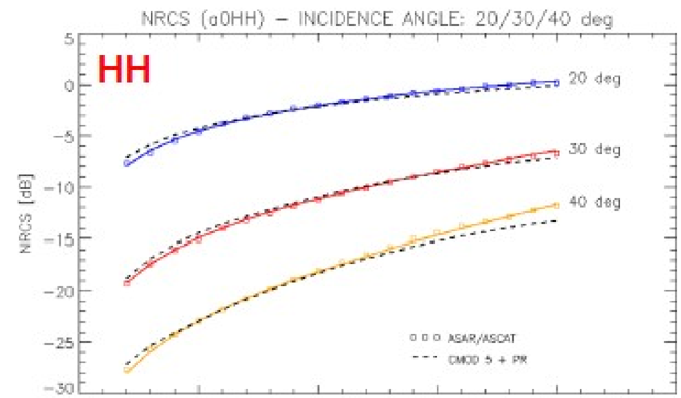


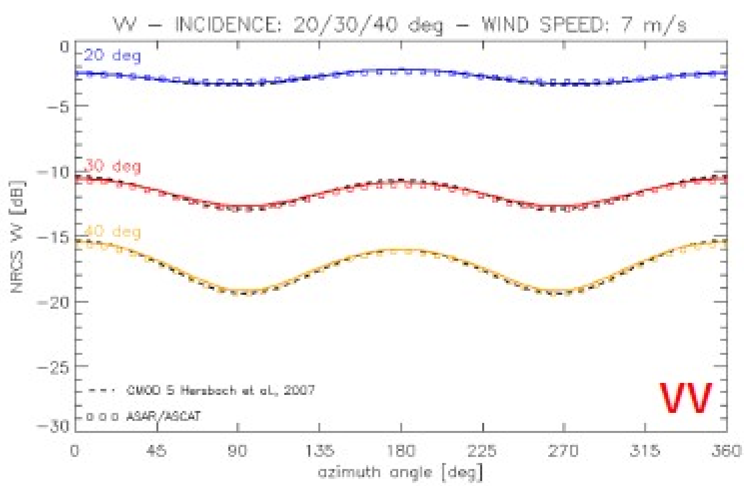
Cross-polarization: Model & Understanding of the measurement

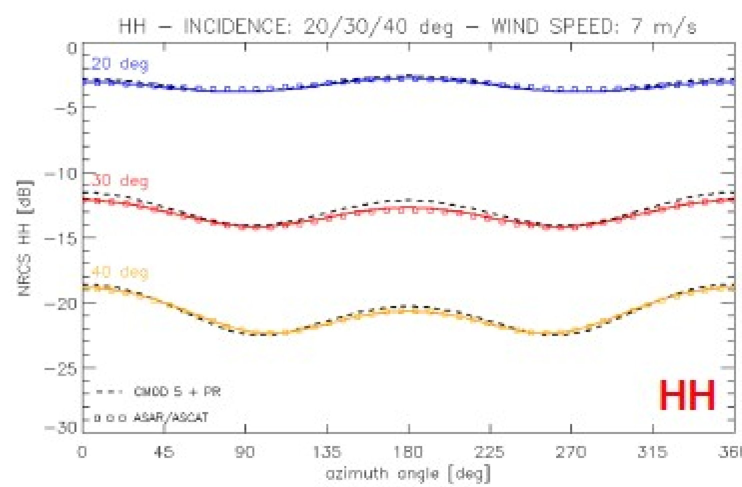




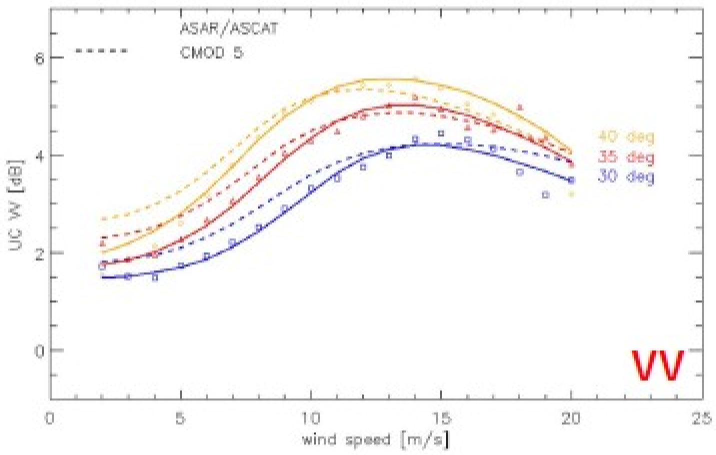


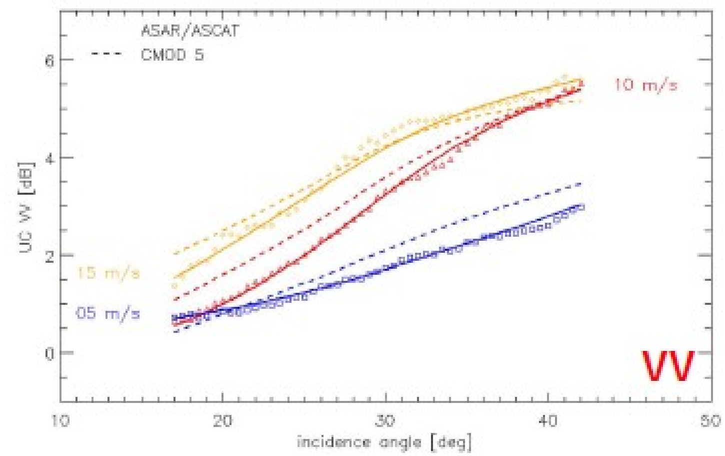


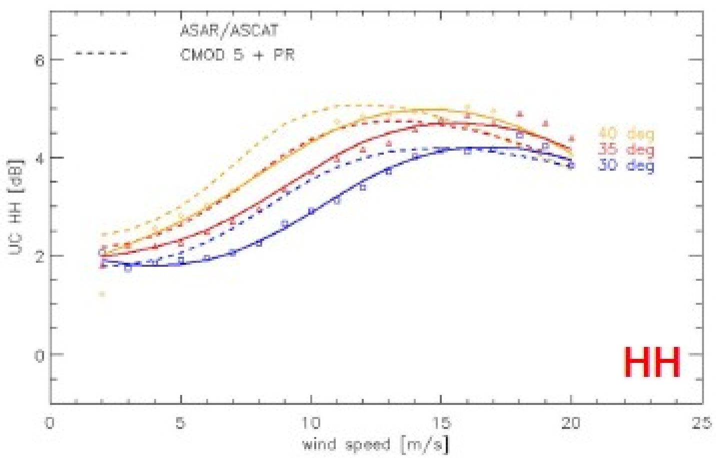


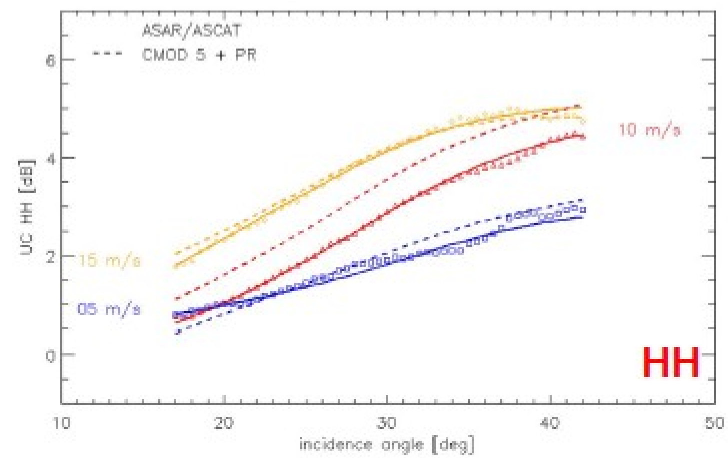


Cross-polarization: Model & Understanding of the measurement



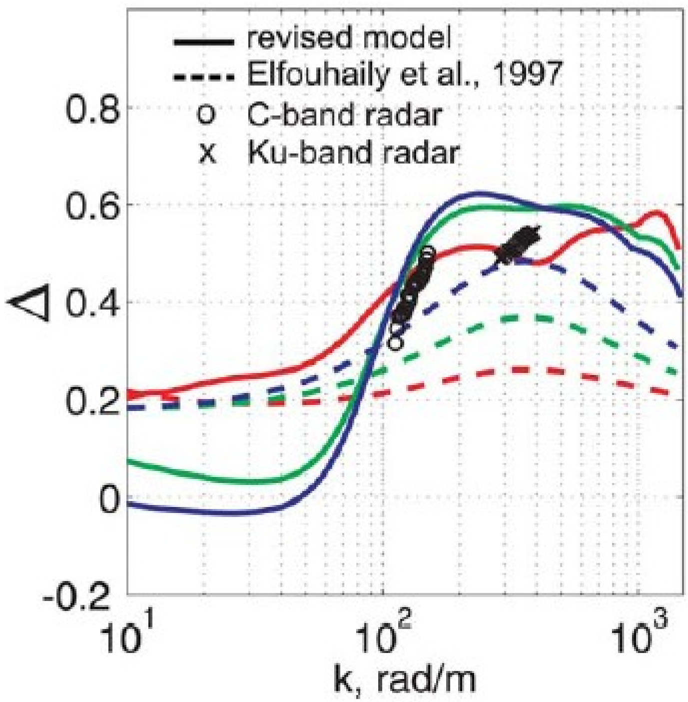




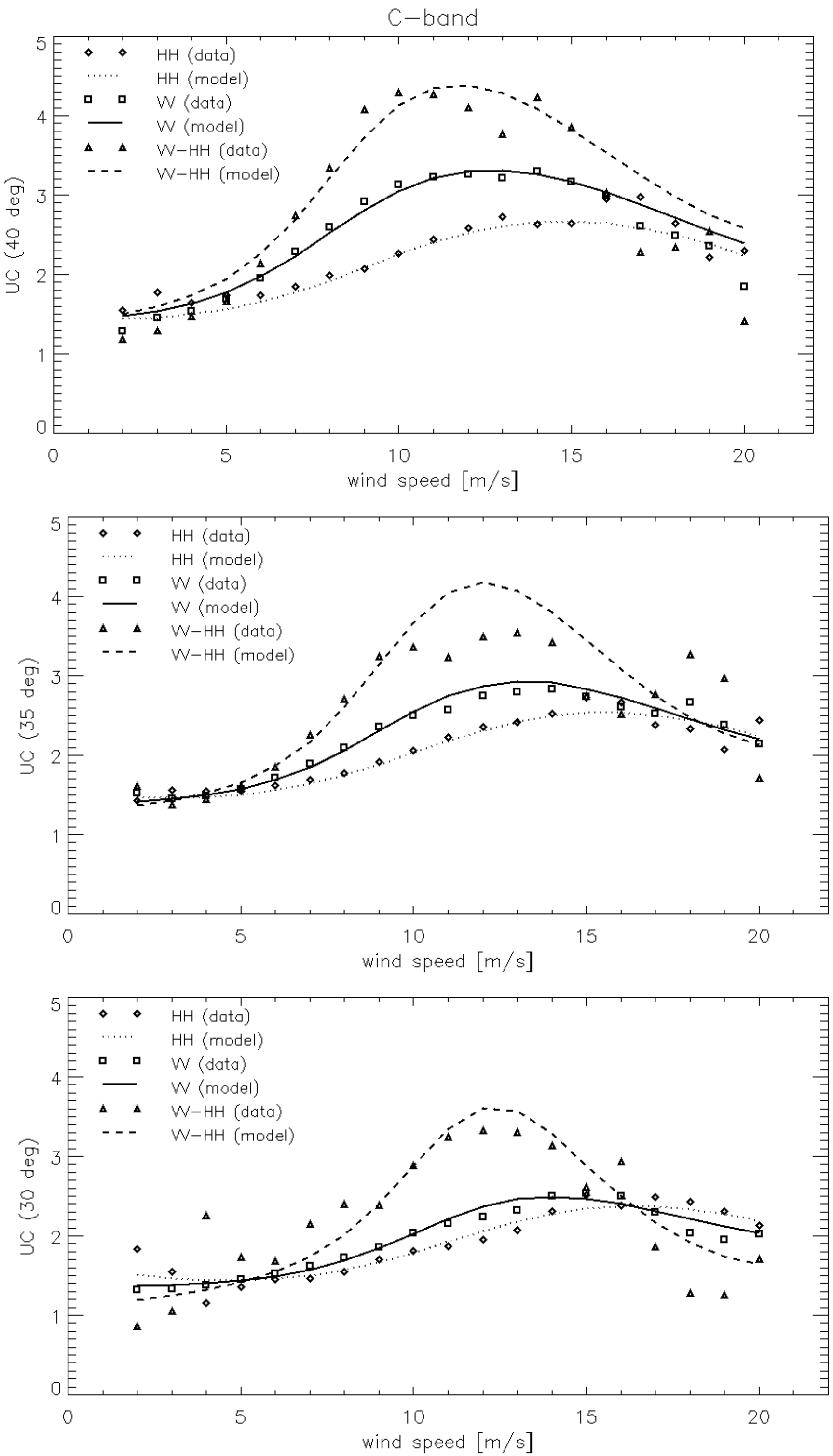


$$\Delta\sigma = \sigma_{br}^{vv} - \sigma_{br}^{hh} = \left(G_{vv}^2 - G_{hh}^2\right) B(\mathbf{k}_{br}),$$

$$B(k,\varphi) = B_0(k)[1 + \Delta\cos(2(\varphi - \varphi_0))]/\pi,$$

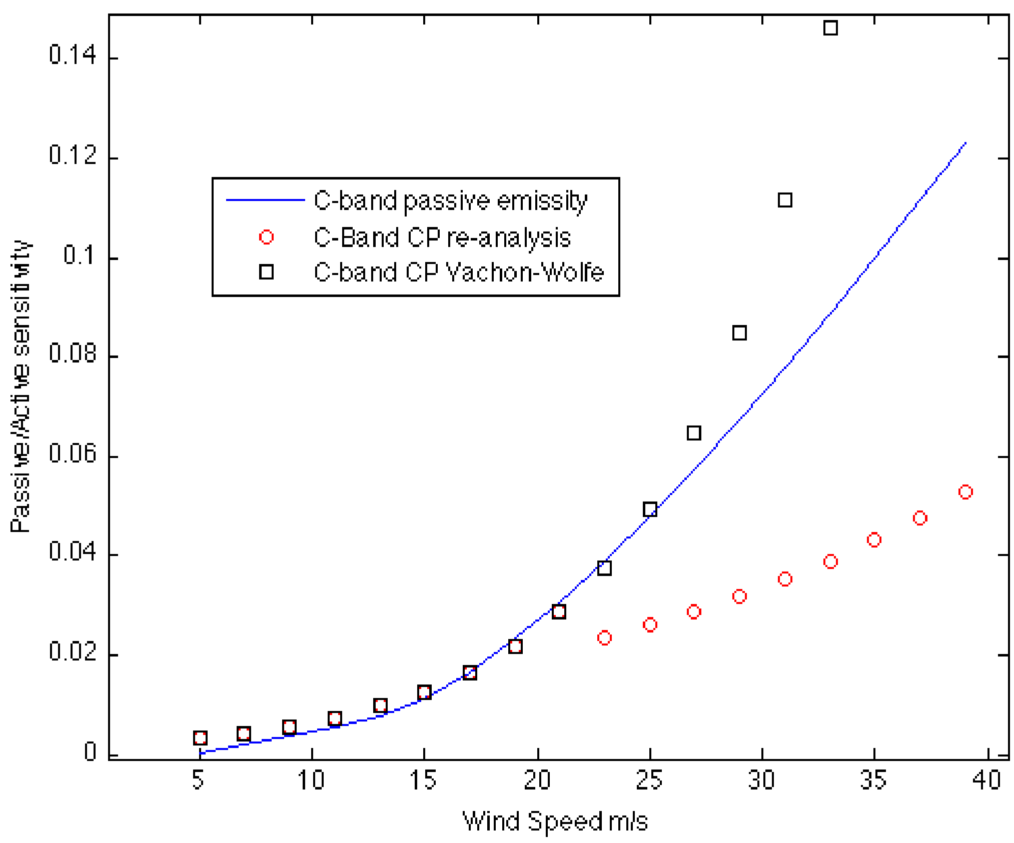


- Directionnality of the wave spectrum with respect to wavenumber from Dual polarization measurement is in agreement with wave spectrum derived from optic measurements by Yurovskaya et al., JGR 2013
- Significant differences with Elfouhaily et al, JGR 1997 are found



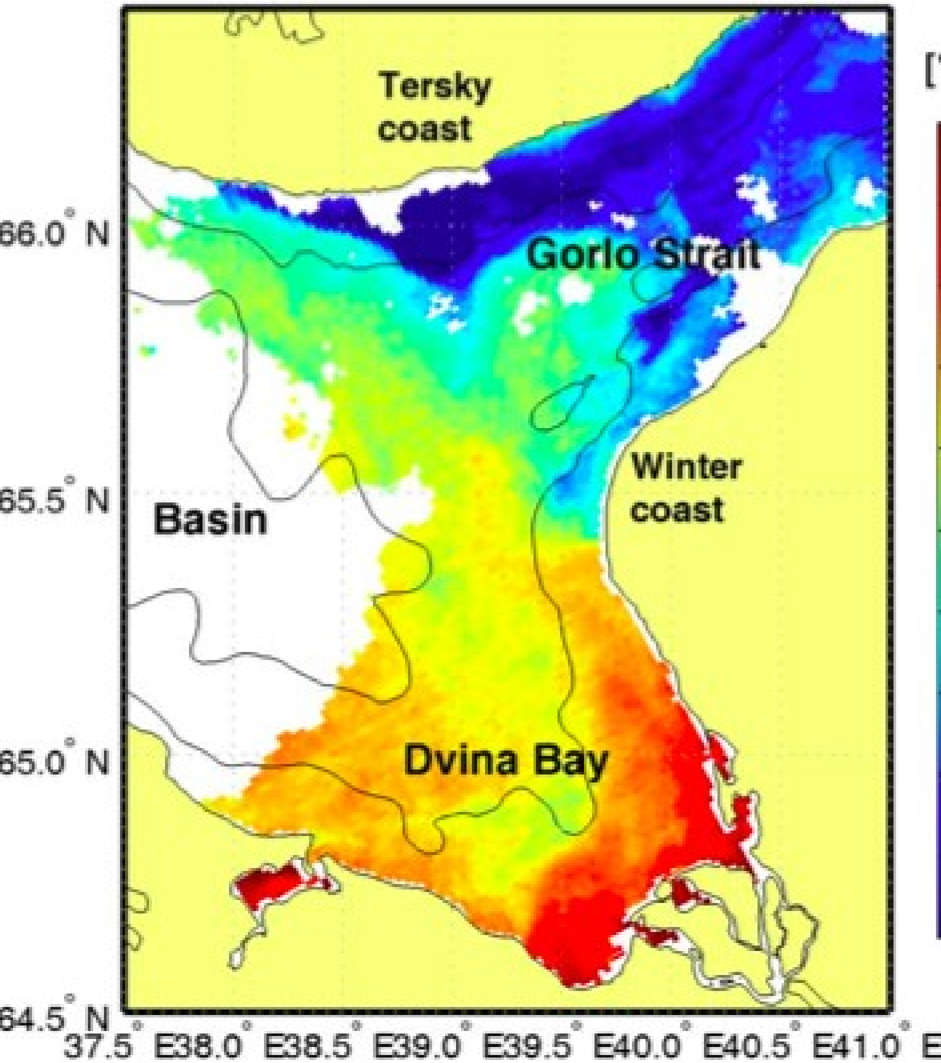
$$\Delta\sigma = \sigma_{br}^{vv} - \sigma_{br}^{hh} = \left(G_{vv}^2 - G_{hh}^2\right) B(\mathbf{k}_{br}),$$

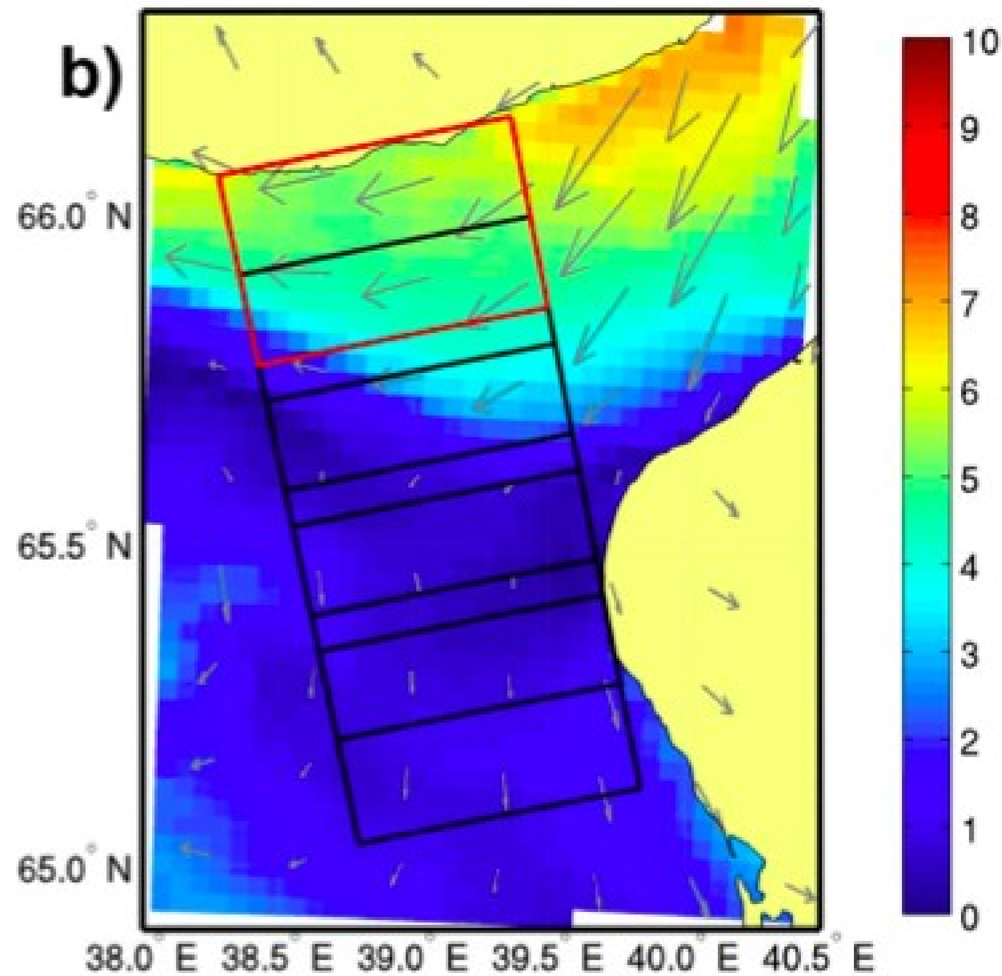
- As for Ku, Sensitivty to wind direction is more import in VV-HH is than in VV and HH



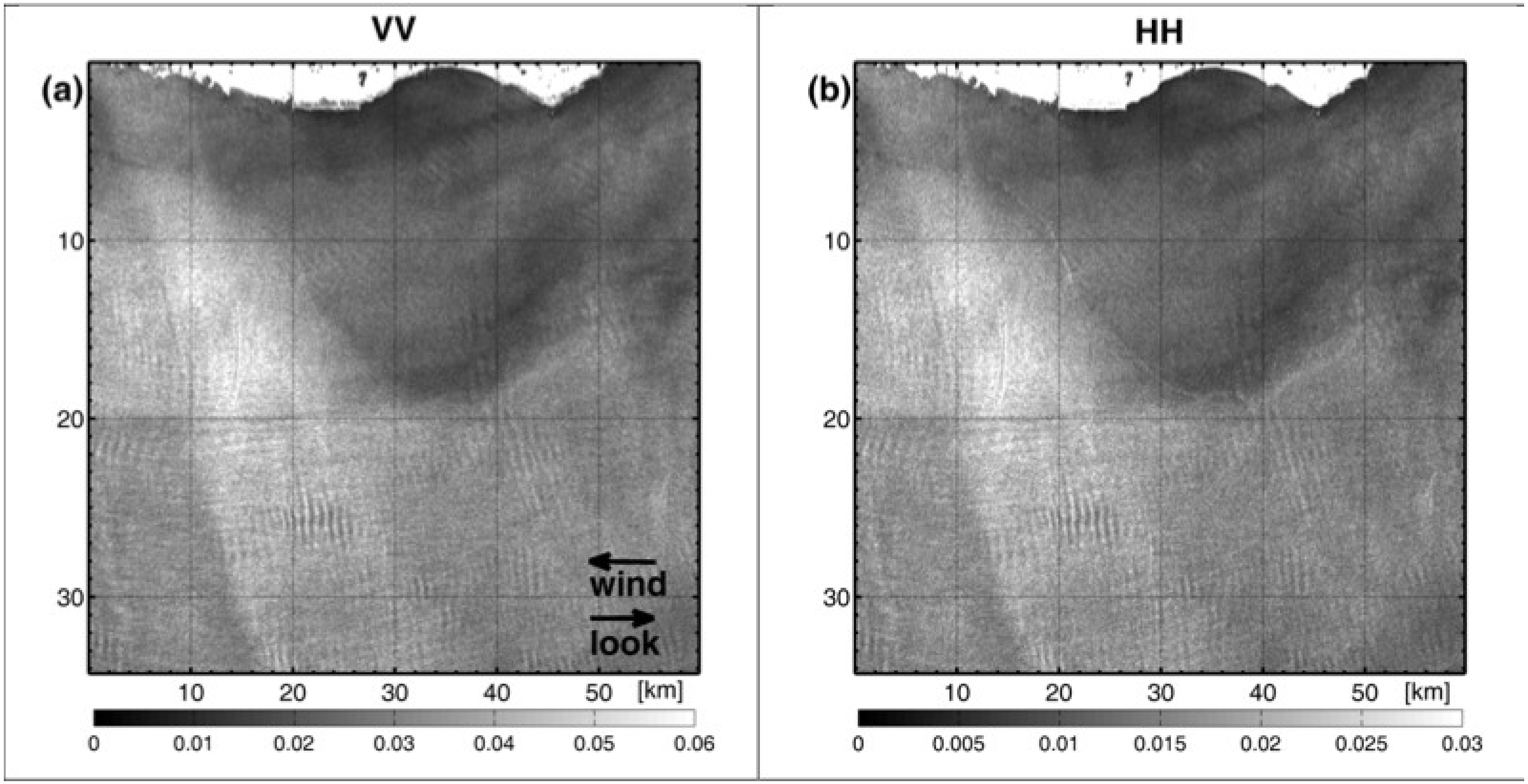
Consistency between C-band active CP measurement and excess of emissivity as measured by C-Band radiometer (SFMR) which is known to be foam sensitive. At high winds, volume scattering explains the non-saturation of the CP signal

RadarSat-2 case study





Atmospheric front and Oceanographic front are present on the image

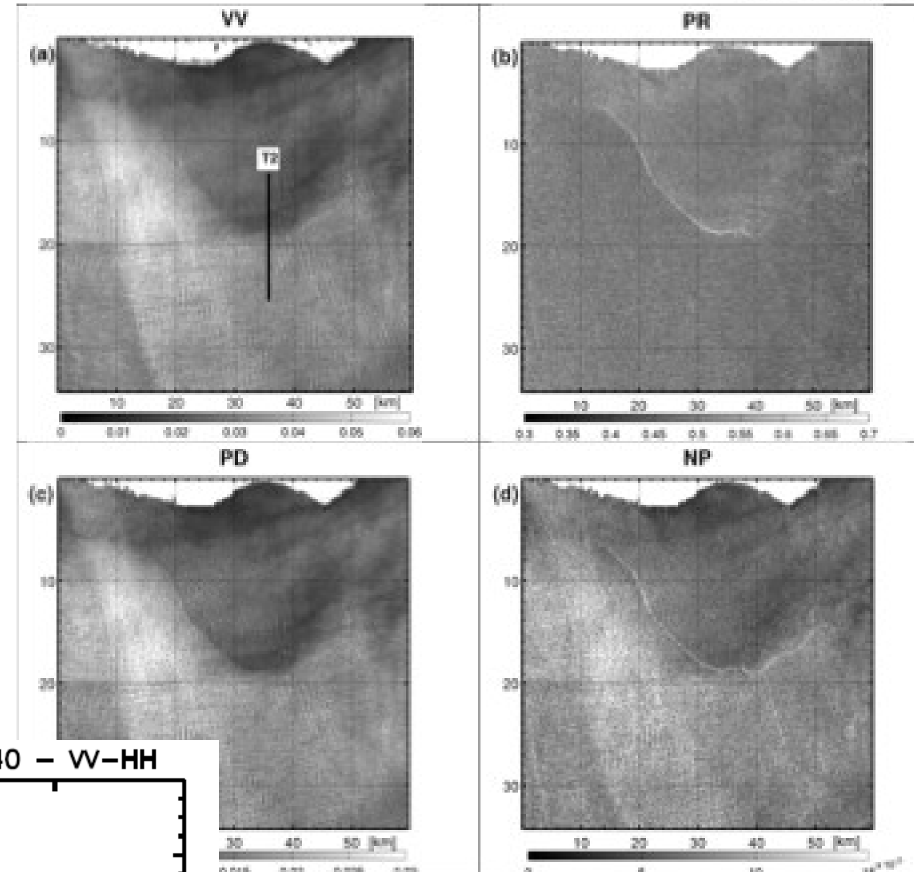


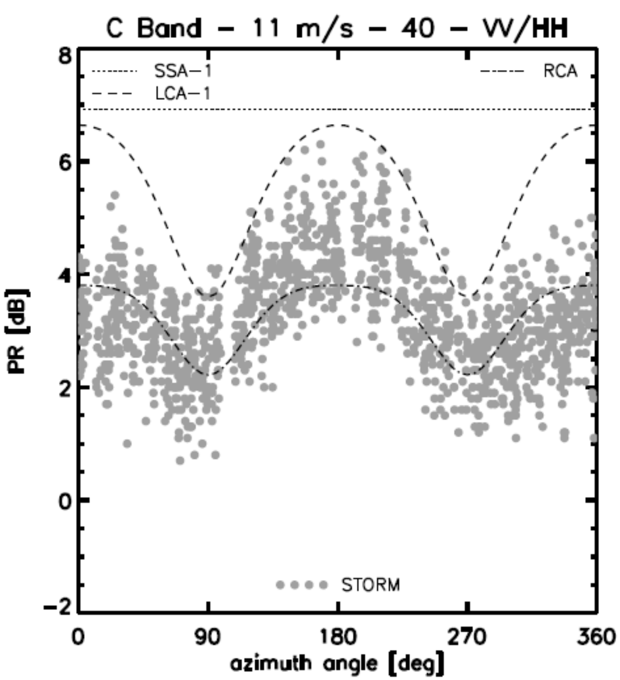
VV and HH are very close with the same signature of the backround sea state.
As expected HH seems to be more sensitive to non-polarized signature associated with breaking waves

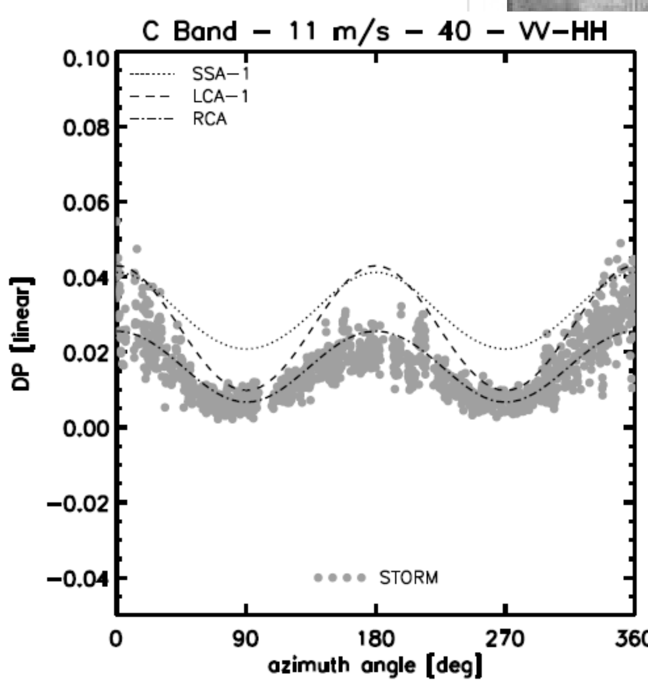
Cross-polarization: Understanding of the measurement & Modeling

PR filters out background component of the signal and is very sensitive to oceanic front signature.

PD filters out oceanic front signature associated with non-polarized contribution.





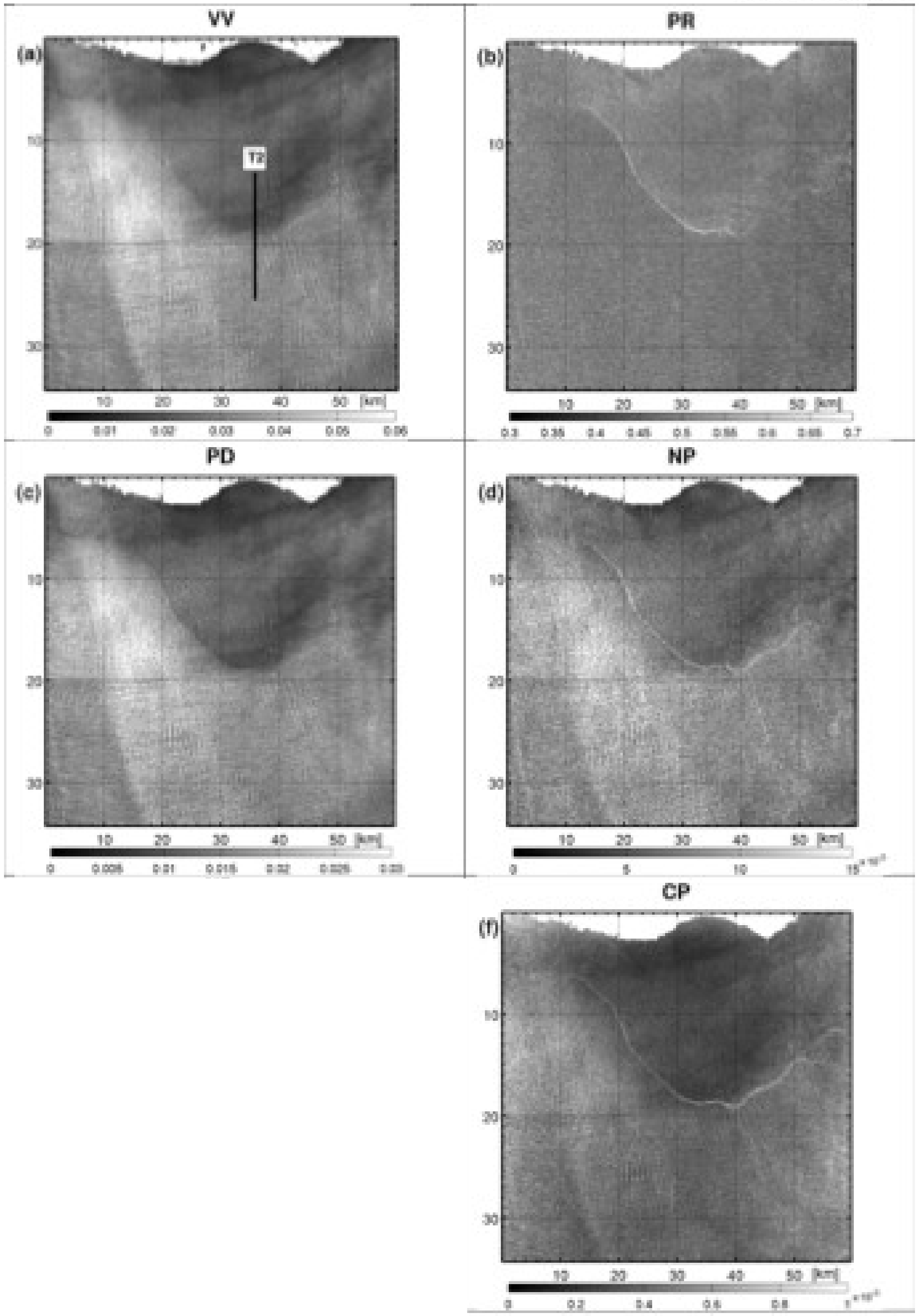


Cross-polarization: Understanding of the measurement & Modeling

For moderate wind speeds CP (VH) measurements reflect these different contributions:

- Polarizing short wind waves ~ 5 cm (background)

- Non-polarized contribution (steep scatterers and wave breaking)

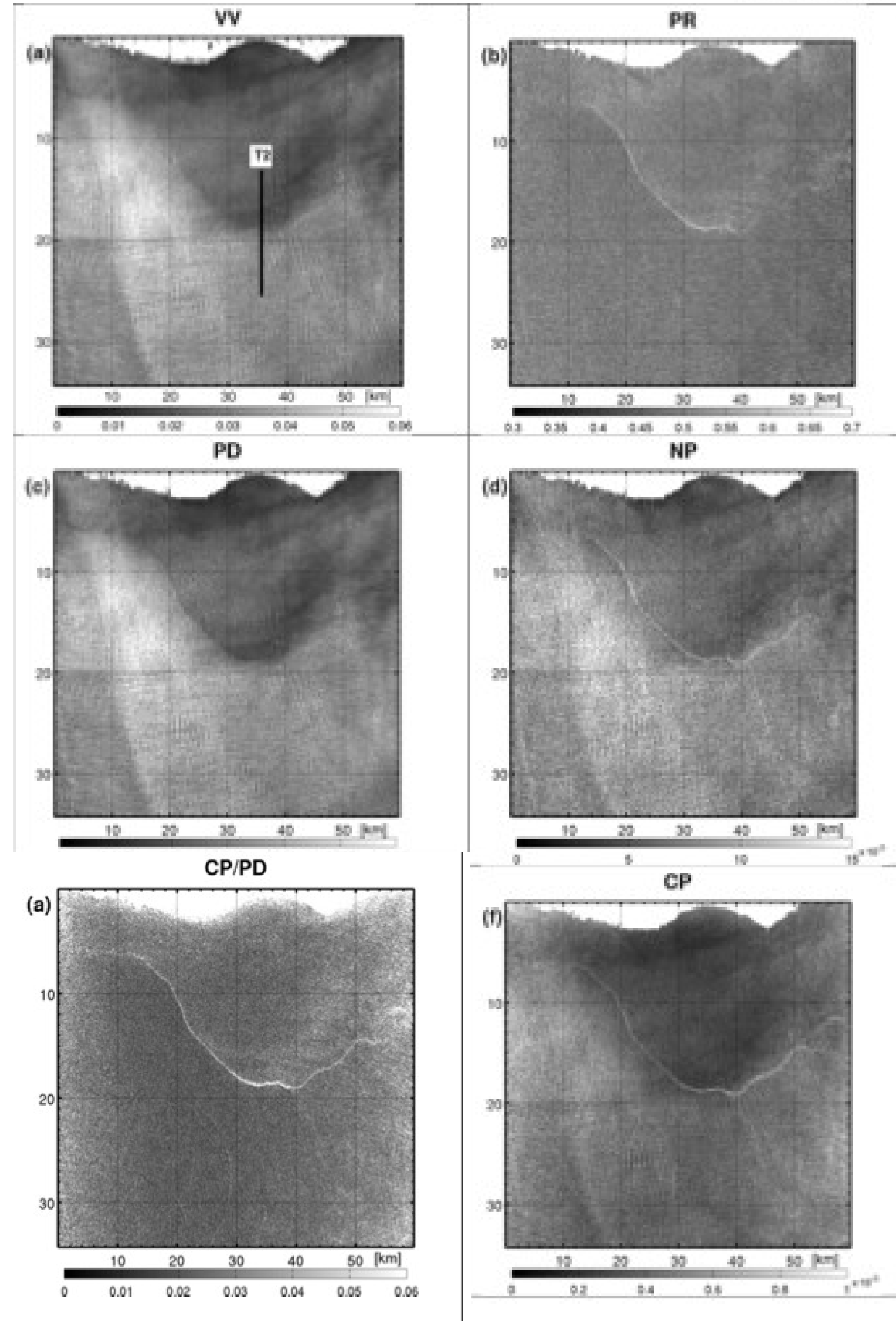


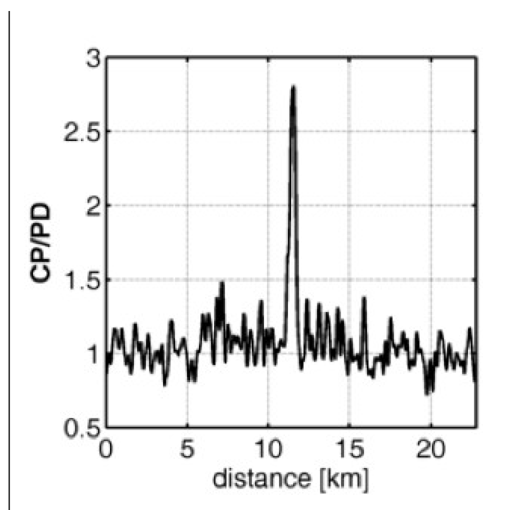
For moderate wind speeds CP (VH) measurements reflect these different contributions:

- Polarizing short wind waves ~ 5 cm (background)

- Non-polarized contribution (steep scatterers and wave breaking)

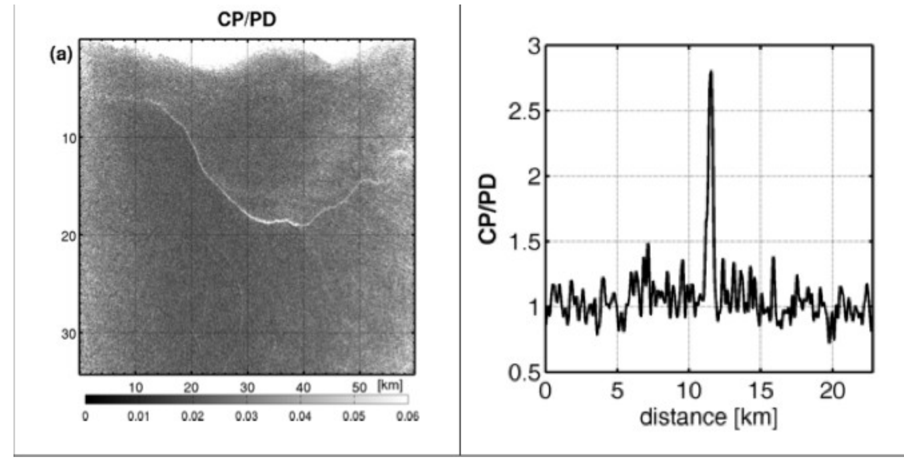
Background contribution can be removed by combining CP and PD.

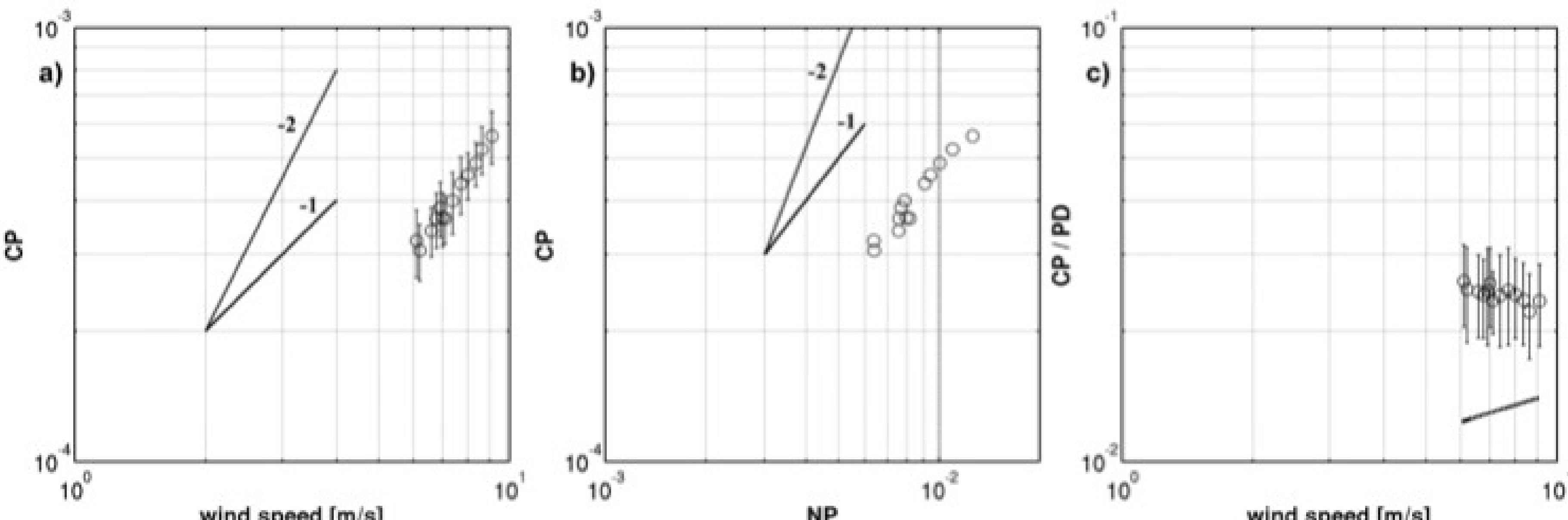




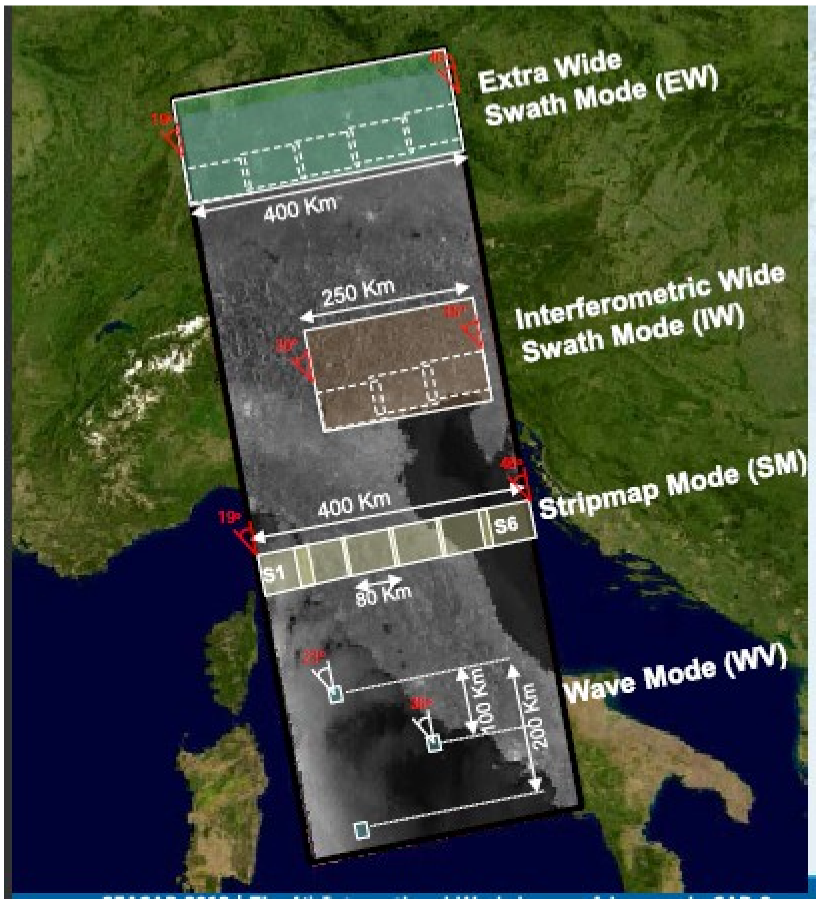
Cross-polarization: Understanding of the measurement & Modeling

$$\frac{\sigma_0^{vh}}{\Delta\sigma_0} = \frac{\left|G_{vv} - G_{hh}\right|^2}{\left|G_{vv}\right|^2 - \left|G_{hh}\right|^2} \frac{s_n^2}{\sin^2\theta},$$





Sentinel–1 Product Family



- 4 exclusive operational modes.

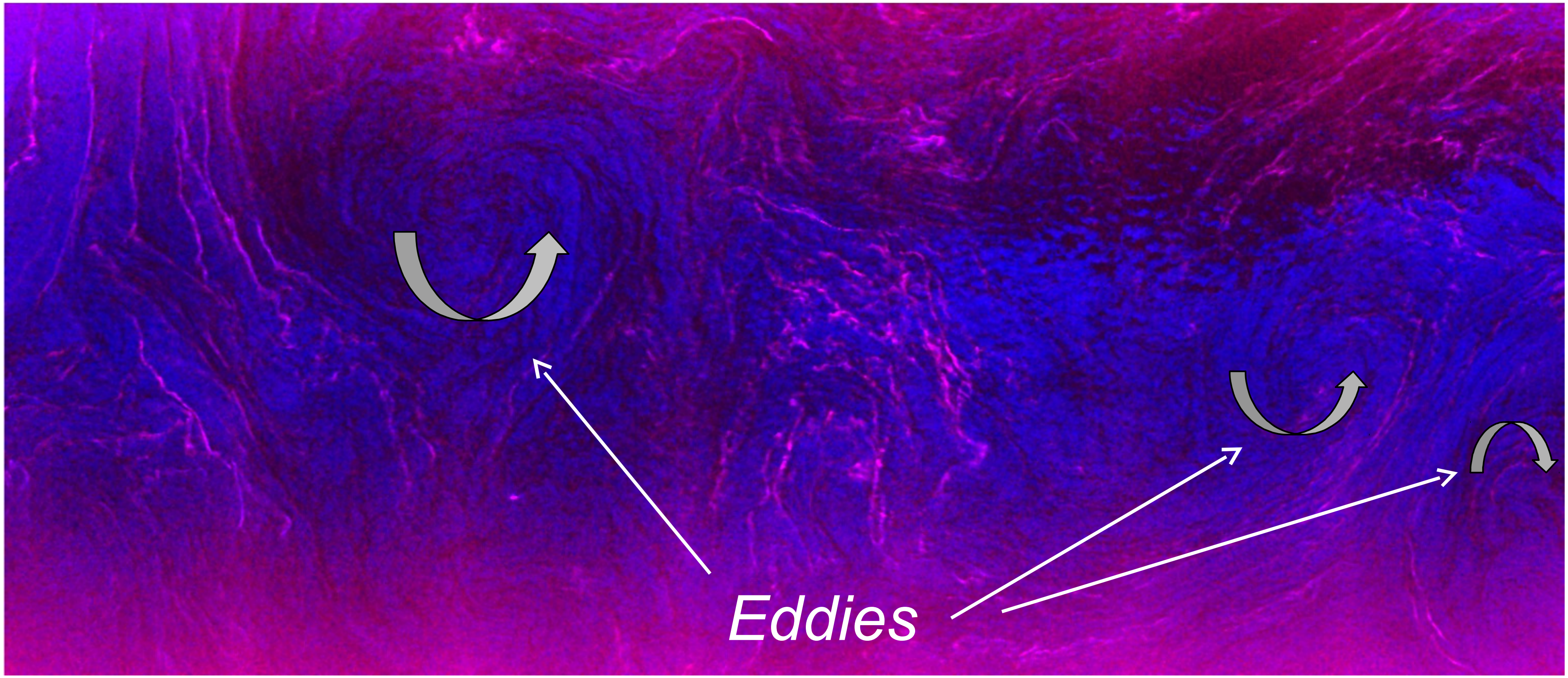
Mode Rates	Acquisition Mode
High Bit Rate (HBR)	IW
	EW
	SM (S1->S6)
Low Bit Rate (LBR)	WV

- Polarisation schemes for IW, EW and SM:
  - single polarisation: HH or VV
  - dual polarisation: HH+HV or VV+VH

- Single polarization VV (or HH), for WV

Incidence angles : 20-46 degrees
NESZ : ~-28 dB

First Analysis of IW Dual Pol acquisition : polarization composition (VV Blue/VH Red)
for breaking wave detection (pink filaments) at the ocean fronts boundaries.



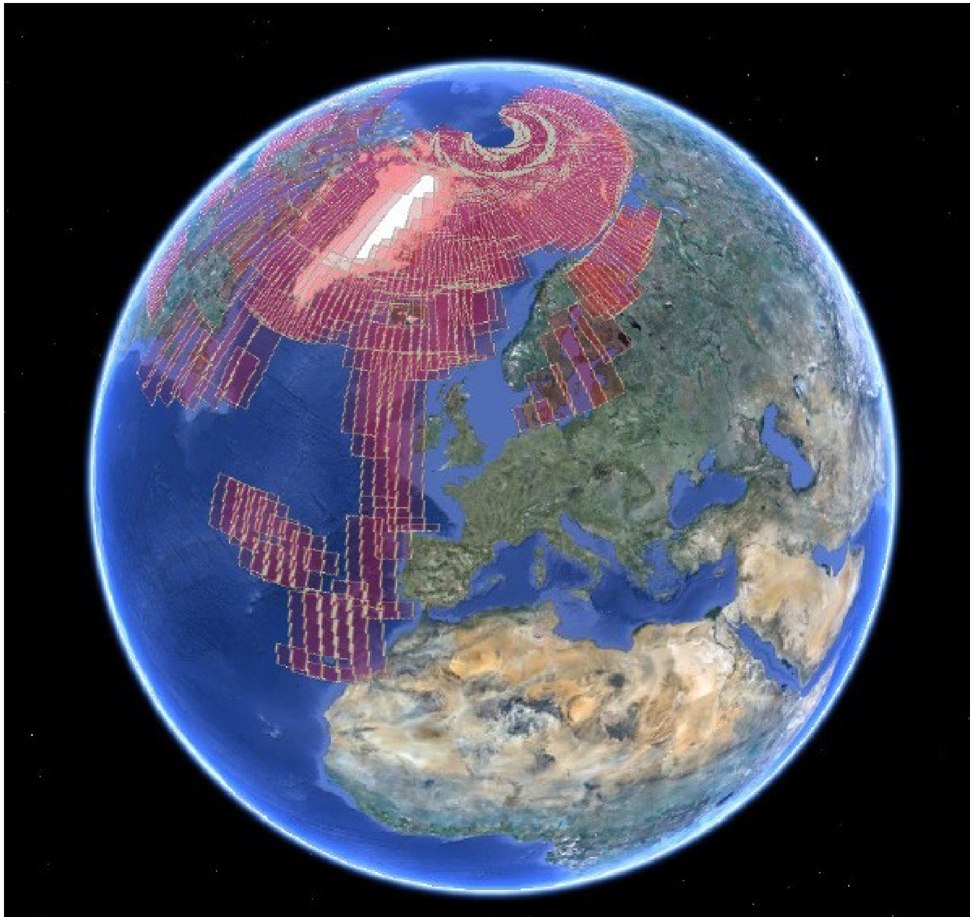
Courtesy of F. Collard, Ocean Data Lab

High Level Operation Plan

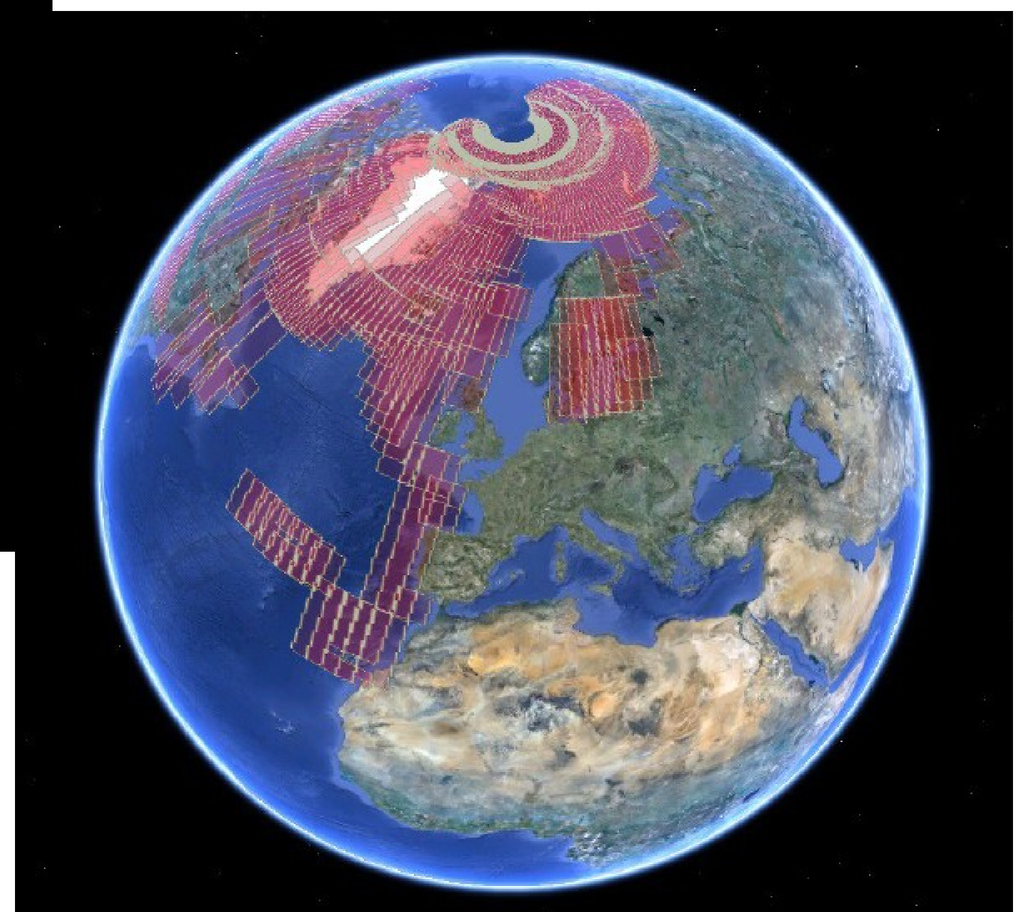
- Set up for the first 6 months after the 3 months of the comissioning phase.
  (draft available on ESA website)
- Driven by GMEs services, national services, ESA and EU members
- A new version including the routine phase is being writting by P. Potin.
- Duty cycle : S-1 is capable of operating up to a total of 25 min per orbit in any combination of IW, EW or SM modes and up to the rest of the orbit in Wave Mode.
- General basic Acquisition rules
  - Wave Mode continuously operated over the ocean with blower priority w.r.t. other modes
  - IW or EW modes operated over predefined areas :
    - Over land : IW
    - Over Oceans, seas and polar areas : IW or EW
  - If possible, single polarization is adopted to give priority to the coverage extent

Example of Acquisition S-1 Plan (1/2)

Europe and European Waters
EWS mode



Ascending and Descending orbits
Over a 12-days repeat cycle (January).



EWS VV+VH is selected for western Europe (orbits not crossing coasts) for

- Oil spill monitoring
- Wind measurements

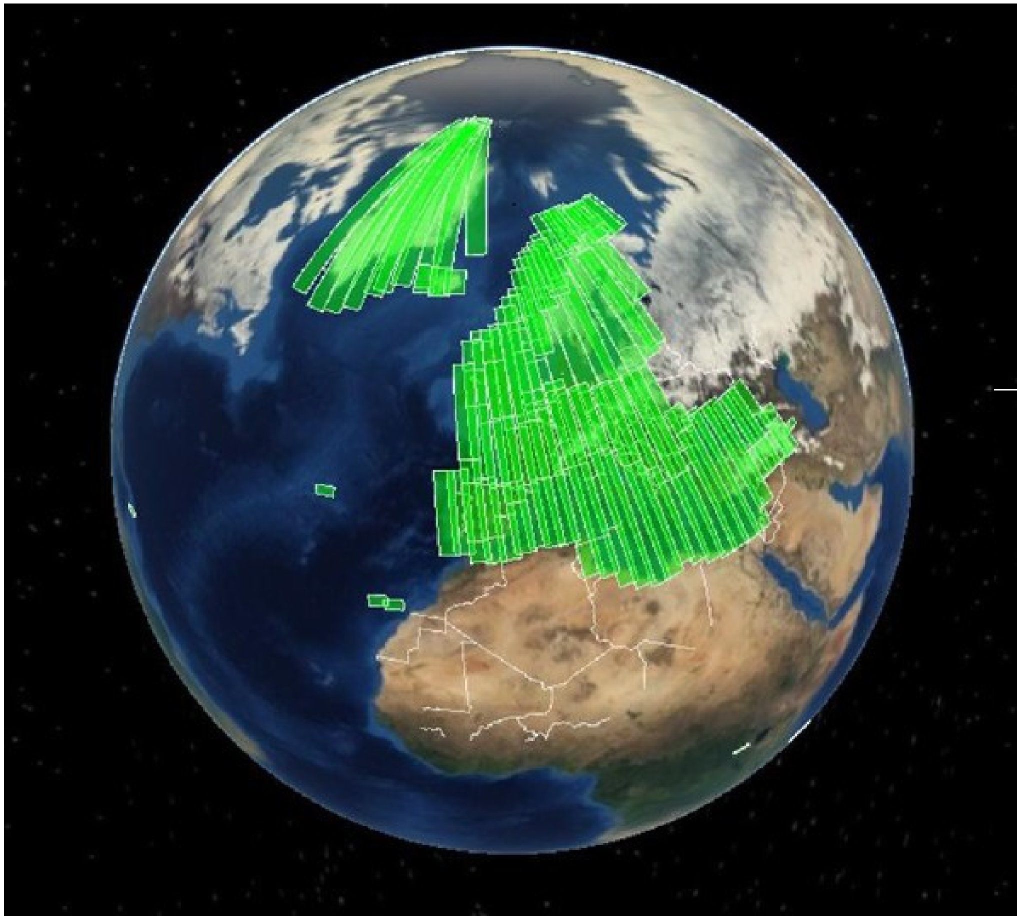
EWS HH+HV

- for sea ice monitoring

Example of Acquisition S-1 Plan (2/2)

Europe and European Waters
IWS mode

Ascending and Descending orbits
Over a 12-days repeat cycle (January).



IWS VV is selected for western Europe (orbits crossing coasts) for

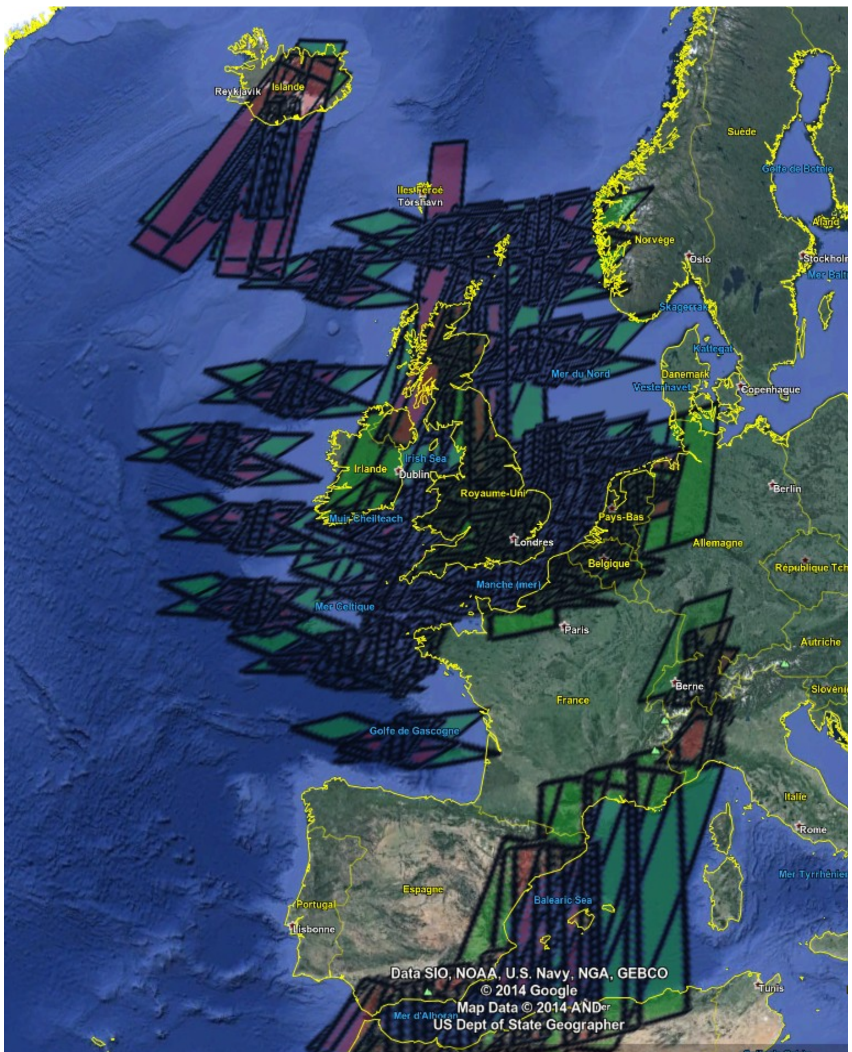
- Land applications
- Oil spill monitoring
- Wind measurements

IWS HH over Greenland

Cross-polarization: Sentinel-1 A Opportunity

Cal/val Plan (1/2)

- Cal/Val activities are a good opportunity to get acquisitions modes independent from GMES constraints that may be more interesting for algorithms developments and science applications



- Wind over European Buoys, Iceland (SM, IW, EW)

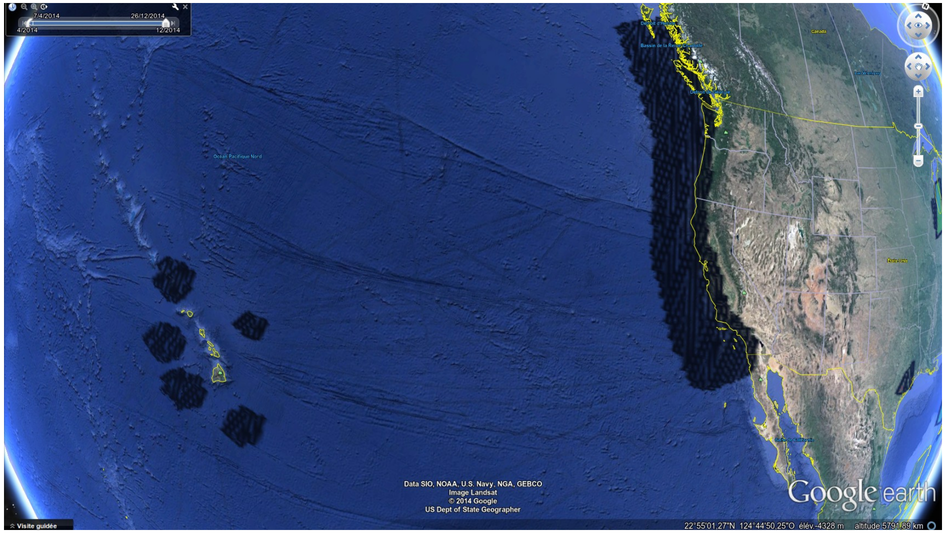
- Waves over Iroise Sea (SM)

- Wind & Doppler over Mediterranean Sea (IW and EW)

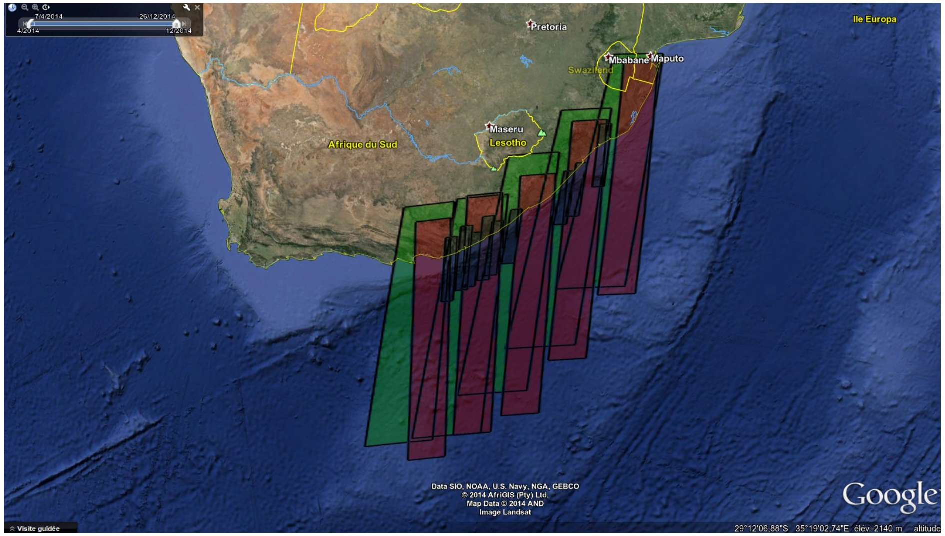
- Doppler in North-East of UK

Cal/val Plan (2/2)

- Less conflicts in areas not concerned by GMES services. Agulhas, Florida Strait, California coasts, Hawai, are ideal natural sites very interesting to improve our understanding of the measure



- Waves over Hawaii Buoys (SM)
- Waves & current signature near California coast (SM)



- Doppler over Agulhas current (EW, IW & SM)

- Waves (SM)

in a linear horizontal- and vertical-polarization base can be expressed as

$$S = \begin{bmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{bmatrix} \tag{3}$$

where S_{HV} is the scattering element of horizontal-transmitting and vertical-receiving polarization, and the other three elements are similarly defined. Each scattering matrix element is a complex number with its amplitude and phase indicating the strength of scattering signals and phase delay. The square of the absolute magnitude of each scattering matrix element represents the radar backscatter for each polarization. In addition to co- and cross-polarized backscatter measurements, fully polarimetric SAR can also acquire the correlation between different polarized backscatter measurements. The correlation between VV and VH polarization channels is denoted by PCC, i.e.,

$$\rho_{\mathrm{VVVH}} = \frac{\langle S_{\mathrm{VV}} \cdot S^*_{\mathrm{VH}} \rangle}{\sqrt{\langle |S_{\mathrm{VV}}|^2 \rangle \langle |S_{VH}|^2 \rangle}}. \tag{4}$$

This is a complex number that indicates the degree of correlation and relative phase angle (phase difference) of VV and VH polarized backscatter signals.

To analyze the symmetric characteristics of PCC with respect to wind direction, we first fixed the radar incidence angle and the wind speed as 35° and 10 m/s and thus obtained a small data set. Alternate examples, such as 25° and 15 m/s, would give similar results. The data set consists of PSMEs (S_{HH}, S_{HV}, S_{VH}, and S_{VV}) and NRCS (σ^o_{HH}, σ^o_{HV}, σ^o_{VH}, and σ^o_{VV}) in quad-polarizations. Subsequently, we combine collocated PSME with (4) to estimate PCC. Both NRCS in co- and cross-polarizations are shown to have even symmetry with respect to the wind direction in Figs. 3 and 4. We can also observe the upwind-to-downwind asymmetry of the NRCS

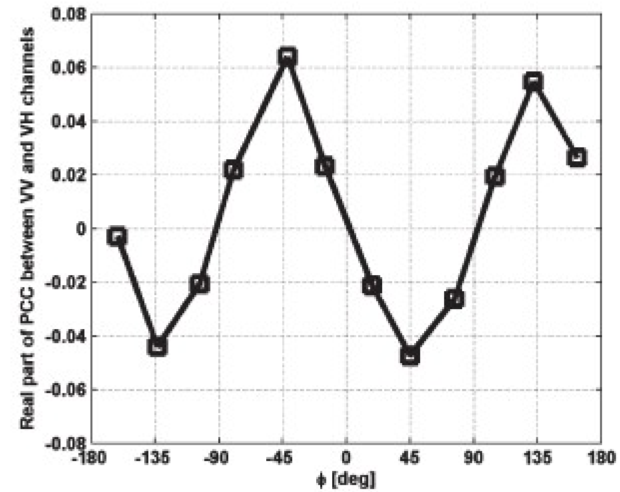


Fig. 5. RADARSAT-2 measured real part of the PCC between VV and VH channels versus relative wind direction. The average wind speed and incidence angle are 10 m/s and 35°, respectively.