

# Structure function analysis of SAR imagery in PBL roll conditions and comparison with in situ observations

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Enhancing Knowledge of the Arabian Sea Marine  
environment through Science and Advanced Training (**EKAMSAT**)



# Summary

- The wind streak (WS) signal in SAR imagery is primarily induced by the along-roll perturbation wind
- Roll overturning mostly induces asymmetry in WS signal
  - Likely induced by sharp convergence/broad divergence
  - Phase difference between along-roll and across-roll maxima
  - Overturning locally enhances WS signal, but average effect ~10%
- Hint from early results agree with common roll interpretation:
  - WS tends to align closer to the surface wind as  $Ri$  becomes more unstable
  - Anisotropy in  $S_2$  (“WS energy”) increases as  $Ri$  becomes more unstable
    - Hypothesis:  $S_2$  Anisotropy is associated with micro-convection

# 2D Structure Function Analysis

- “Structure function analysis of SAR imagery reveals aspects of PBL roll dynamics”, Granero-Belinchon, et al. *Rem. Sens. Lett.*, **9**(13), 2022.
  - Research group from Ifremer
- Lagged correlations
  - 1<sup>st</sup>-order Autocorrelation Function (ACF)
  - 2<sup>nd</sup>-order ( $S_2$ ) is like variance (“energy”)
    - $S_2 = \text{VAR}(1-\text{ACF})$
  - 3<sup>rd</sup>-order ( $S_3$ ) is like skewness
    - $\text{Skew} = S_3/S_2^{3/2}$

# Astral/Ekamsat: Co-located SAR & Surface Data

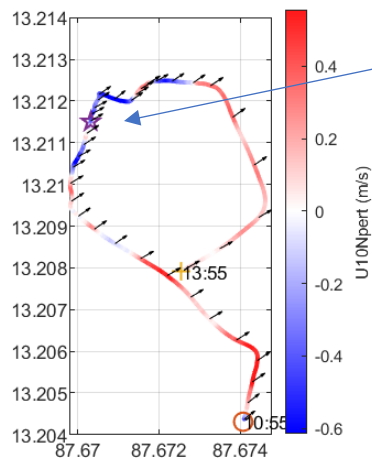
- Bay of Bengal, May-June, 2025
- Start with Wave Gliders
  - Array of 4 surrounding ship
    - Ida, Kelvin, Planck, WHOI43, roughly 15 km spacing
  - 1 Hz Meteorological data, ~1 m above surface
  - Sliding 10-minute running means across +/- 90 min windows → COARE v3
    - Sense of temporal variability (low)
    - U10N & Direction
    - Measure of stratification (Ri) as defined in Stopa et al. (2022)
    - Integral length scales
- Monsoon Conditions, relatively steady wind from south-west
  - Stopa et al. (2022): expect persistent PBL rolls

# Example: 11-minute Pair of Downwind Views

- 25 km SAR Tiles (sub-scenes) centered on WGs
  - Radar geometry (azimuth, range) 50 m spacing
- Preprocess:
  - De-spike top and bottom 1% (speckle)
  - Gentle wavelet filter: suppress sub-400 m variability
  - Subtract mean plane
- 1st at moderate incidence angle, 2nd at large incidence
  - Up/down views at high incidence are best for viewing rolls (Wang et al., 2020)
  - Signal to noise issue.
    - Roll modulation of NRCS largest at low incidence (Fine scale detail/SAR response)
    - C-band NRCS largest at low incidence (“scatterometer/coarse” response)
    - Best roll detection when modulation is easy to notice against background reflection
- Mean conditions nearly the same

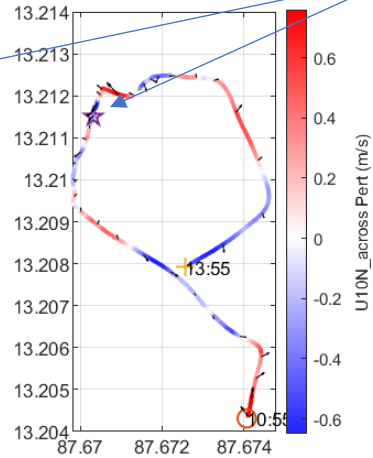
Ida\_20250602T122507

$U'_{along}$

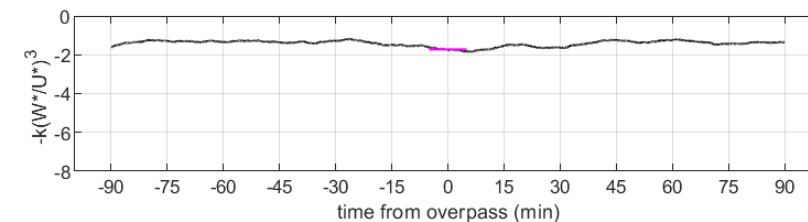
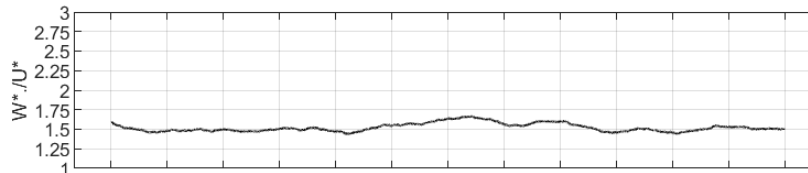
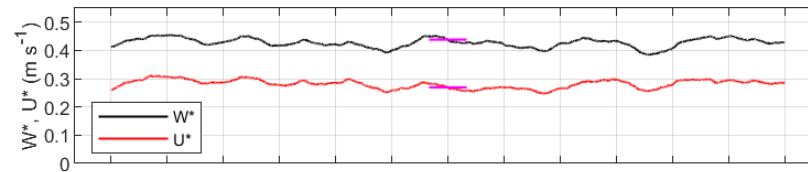


Overpass

$U'_{across}$

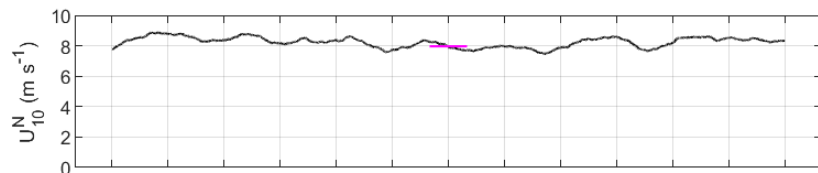


Ida\_20250602T122507

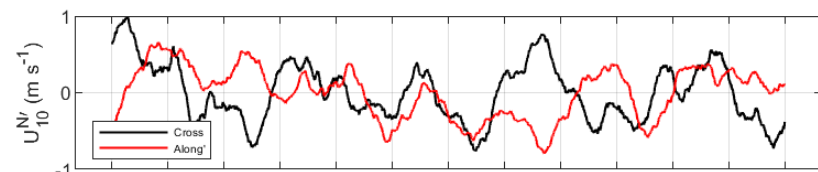


$\frac{z_i}{L}$

Ida\_20250602T122507

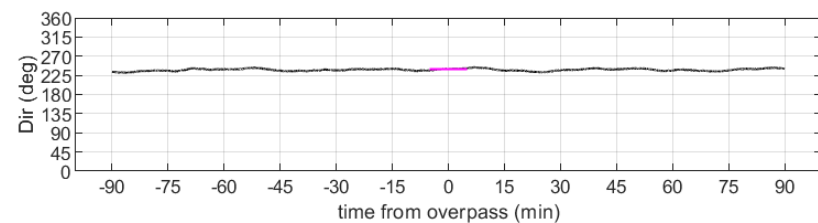


$U_{10}^N$



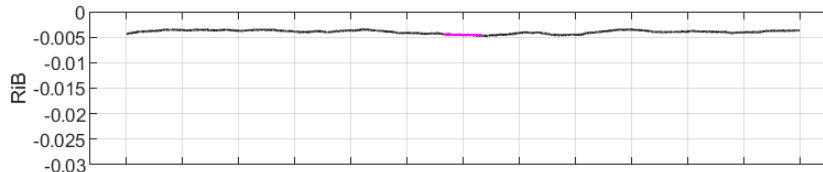
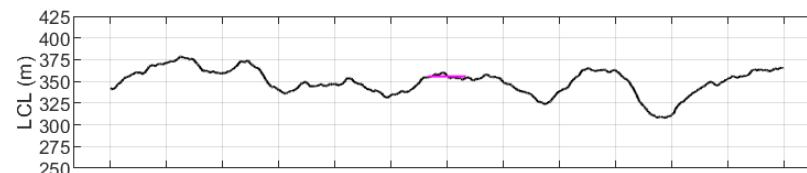
$U'_{along}$

$U'_{across}$

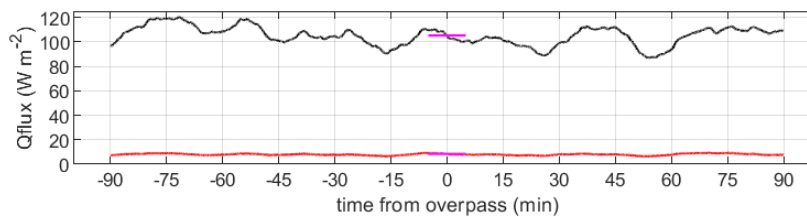


$Dir$

Ida\_20250602T122507



Ri



At SAR overpass 20250602T1225 (2<sup>nd</sup> image)

Wave Glider	U10N	DIR	Qflx	Bflx	LCL	RiB	Wstar	Ustar
Ida (87.672, 13.208)	8.0	240	105.1	8.4	355.7	-0.0046	0.439	0.269
Kelvin (87.542, 13.208)	8.4	231	112.4	9.5	354.7	-0.0043	0.456	0.291
WHOI 43 (86.607, 13.145)	7.0	239	88.9	7.0	342.5	-0.0057	0.407	0.227

2025-06-02 12:25

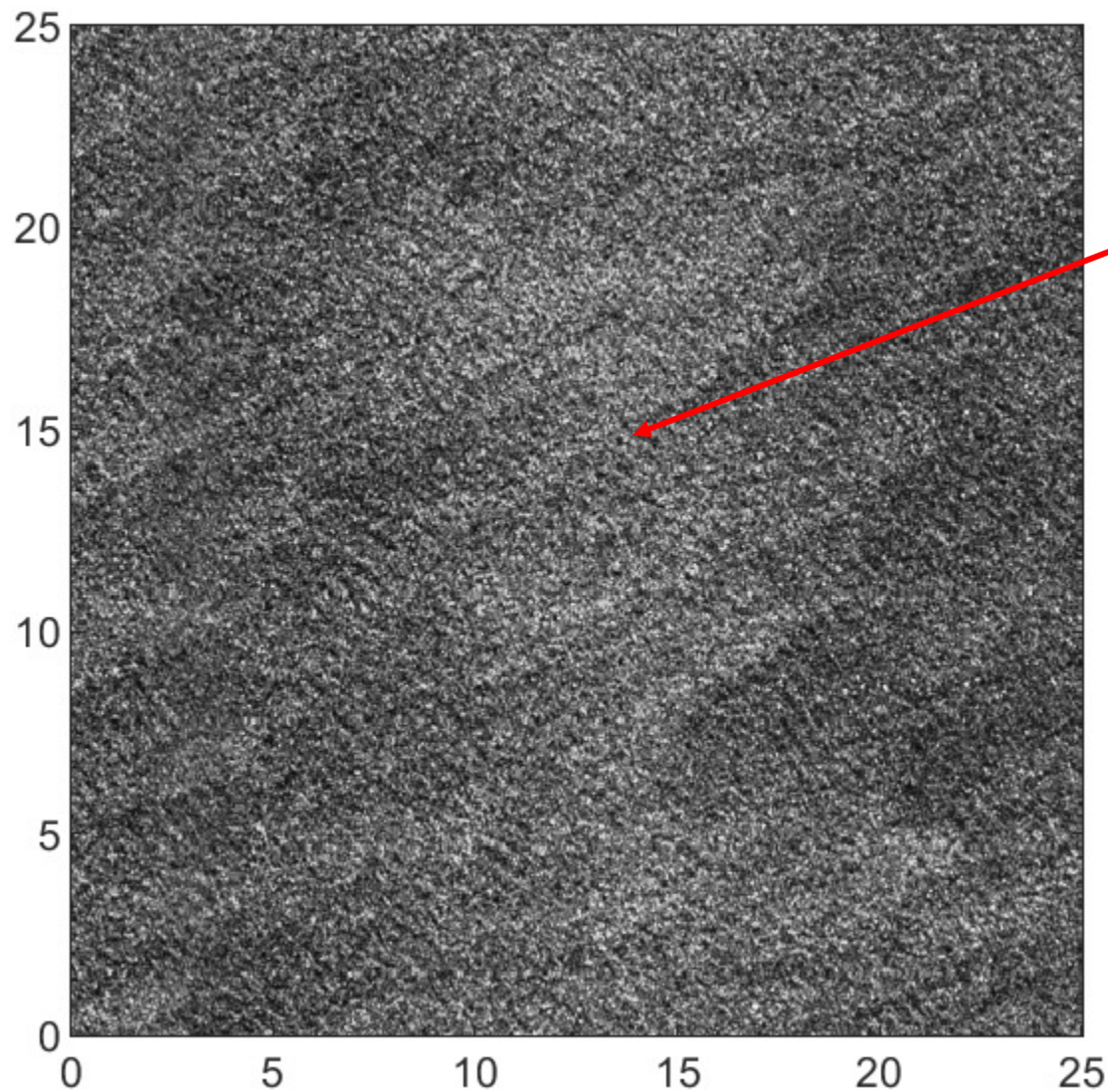
20250602T1214

Moderate incidence

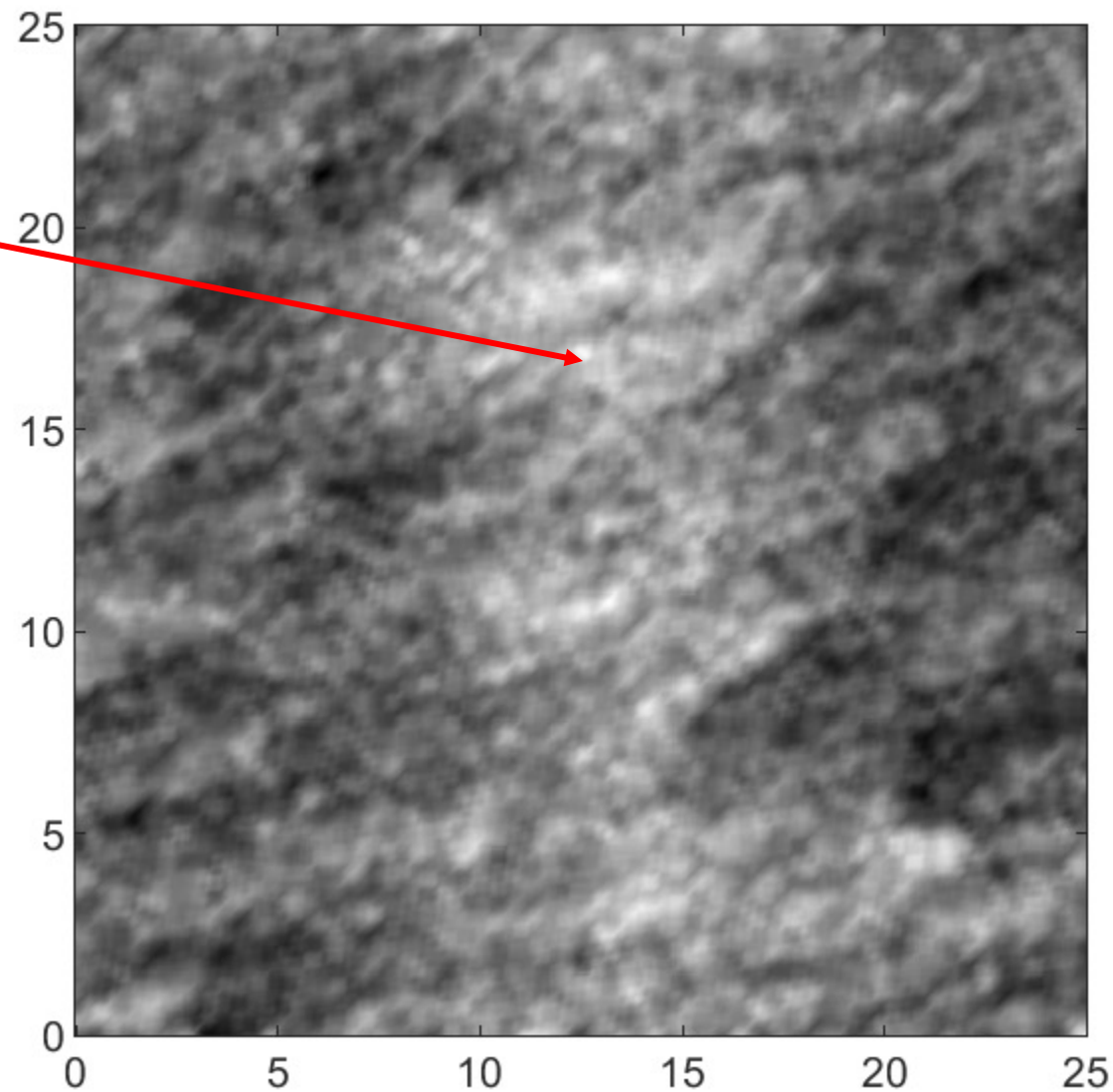
WG IDA: U10N = 8 m/s, 237°, Ri = -0.0043

PAZ1: X-band (3 cm), VV, ASC,  $\theta = 35.5^\circ$ , Pixel Size 16  $\rightarrow$  50 m

Stationary Wavelet Filter: Suppress, but not eliminate variance below 400 m



"UA"  
blob



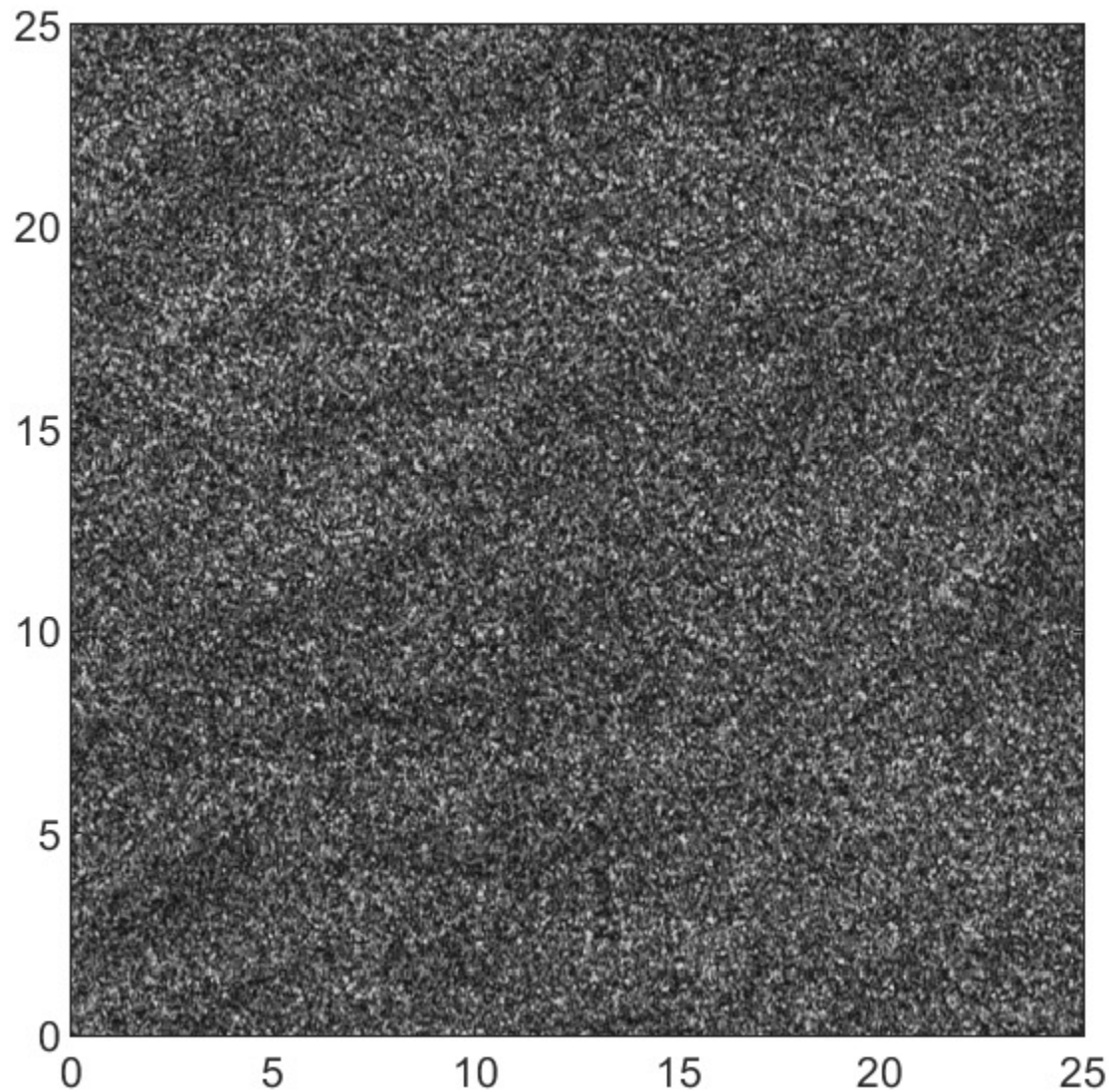
20250602T1225 (+11 min)

Large incidence

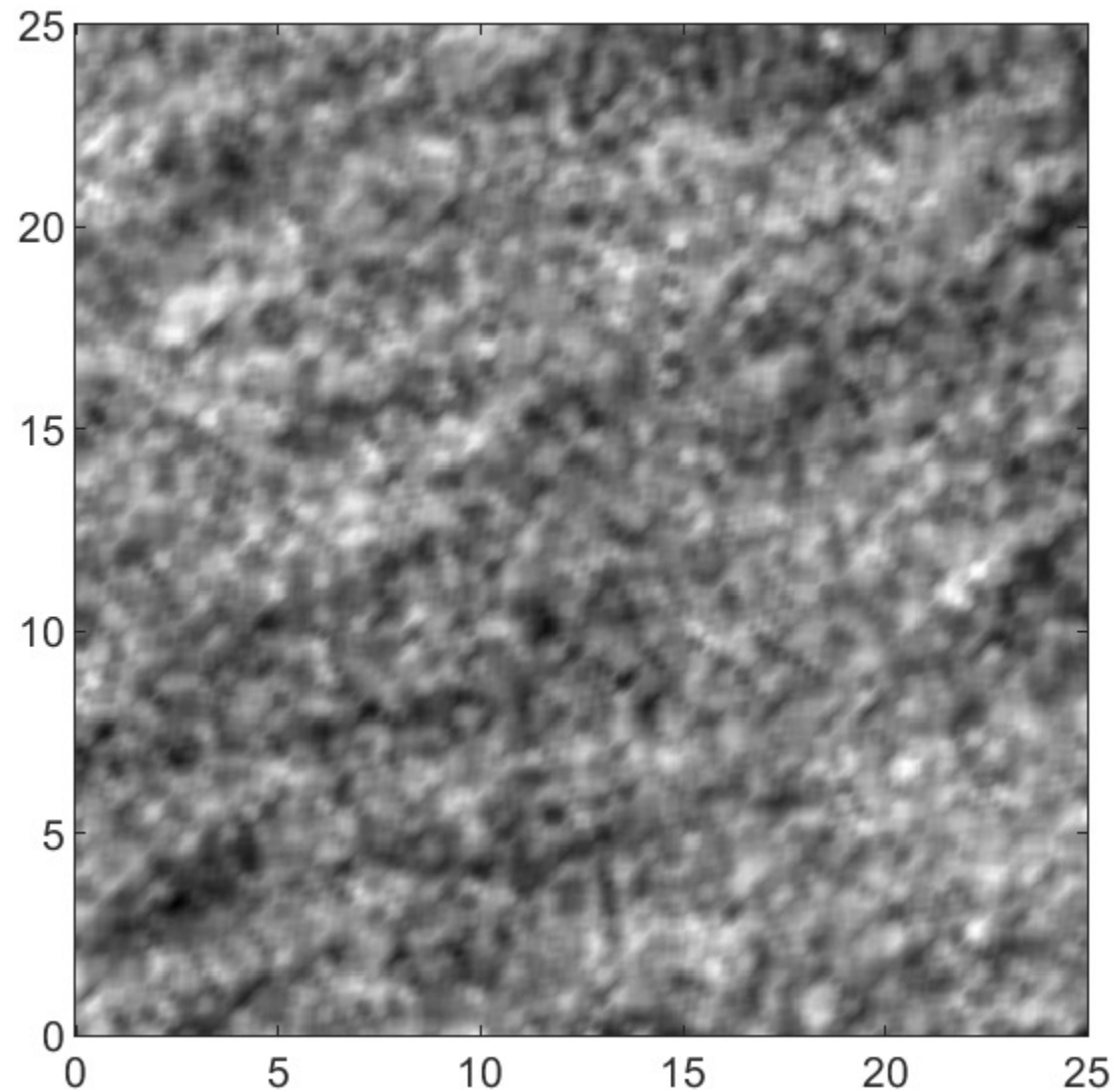
WG IDA: U10N = 8 m/s, 240°, Ri = -0.0046

RSAT-2: C-band (5 cm), VV, ASC,  $\theta = 46.7^\circ$ , Pixel Size 50 m

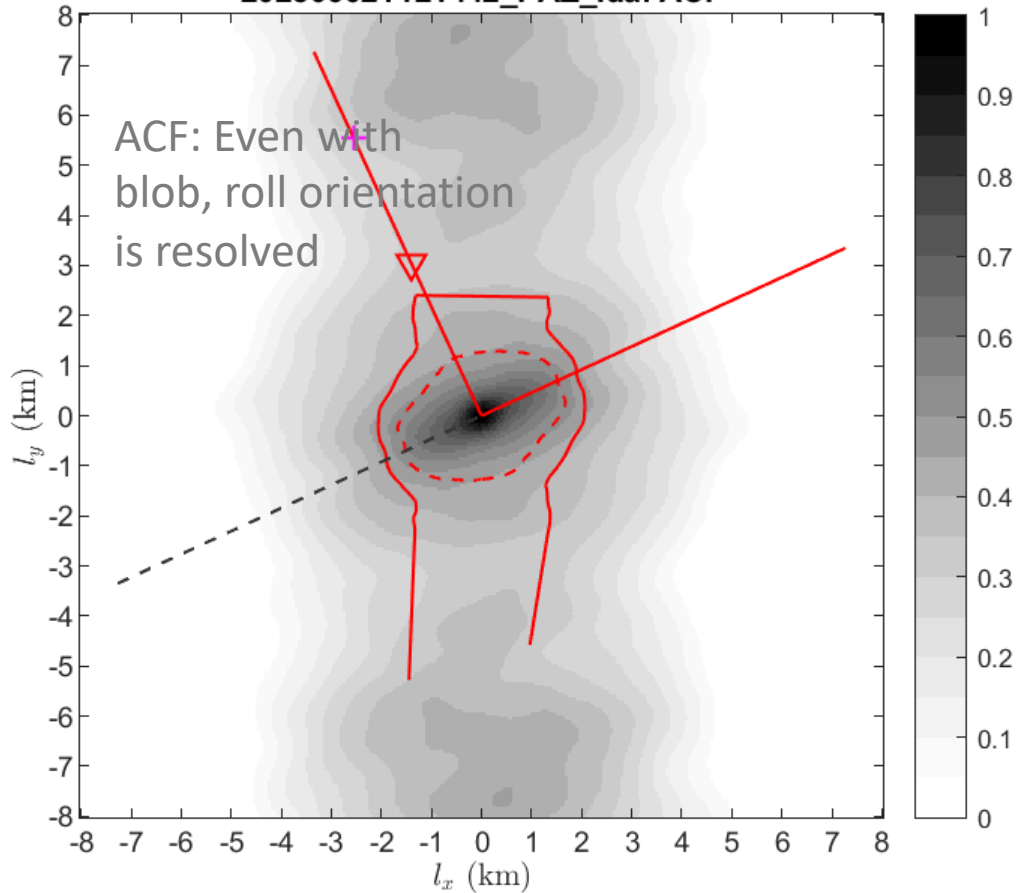
Stationary Wavelet Filter: Suppress, but not eliminate variance below 400 m



“UA”  
gone



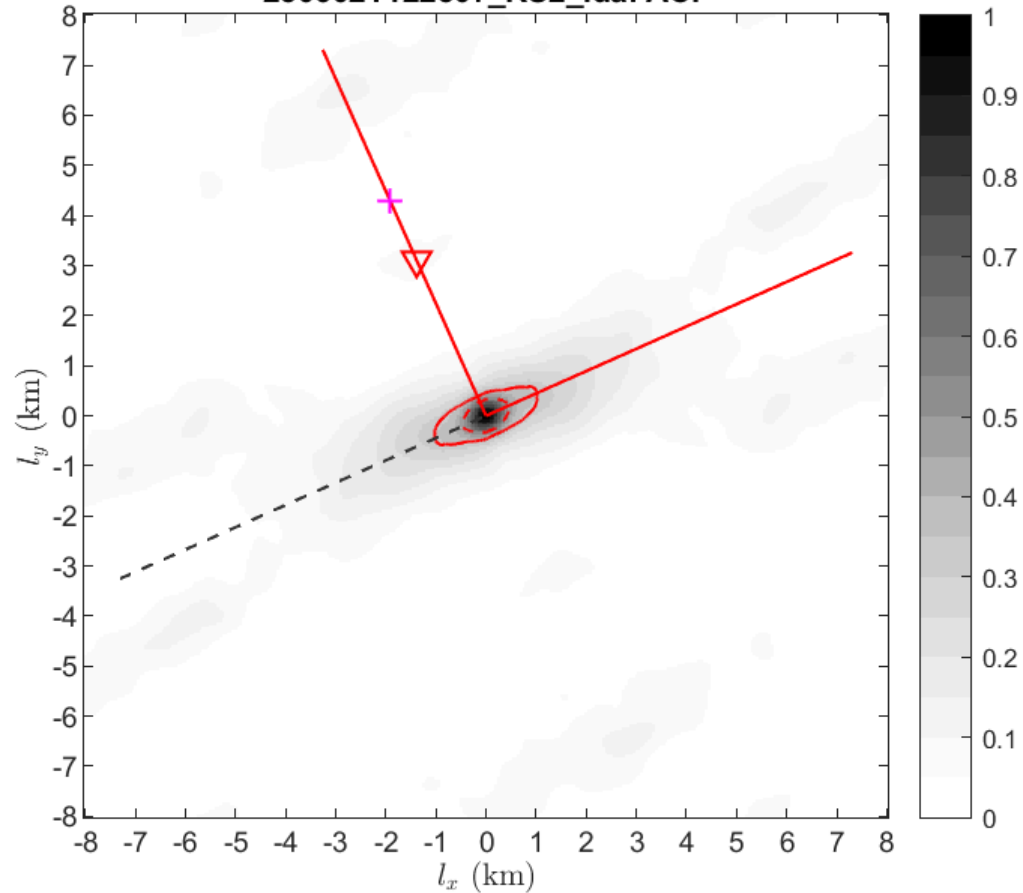
20250602T121442\_PAZ\_Ida: ACF



ACF: Even with blob, roll orientation is resolved

Note effect of "UA" blob on integral length scales

250602T122507\_RS2\_Ida: ACF



Dashed black line is ACF-calculated roll orientation  $27.7^\circ$  in image coordinates

Dashed red line is integral length scale (Integral of ACF from 1 to  $\exp(-1)$ )

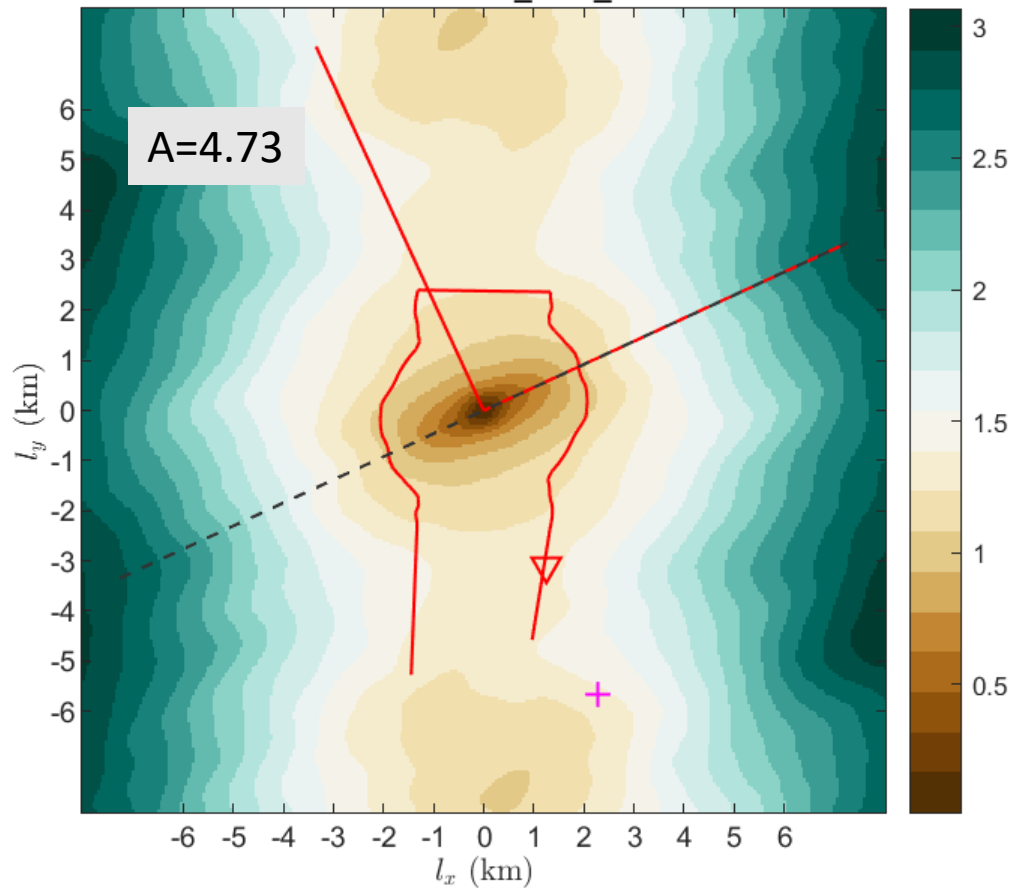
Red triangle is ACF-estimated wavelength (3.4 km)

Dashed black line is ACF-calculated roll orientation  $24.0^\circ$  in image coordinates

Dashed red line is integral length scale (Integral of ACF from 1 to  $\exp(-1)$ )

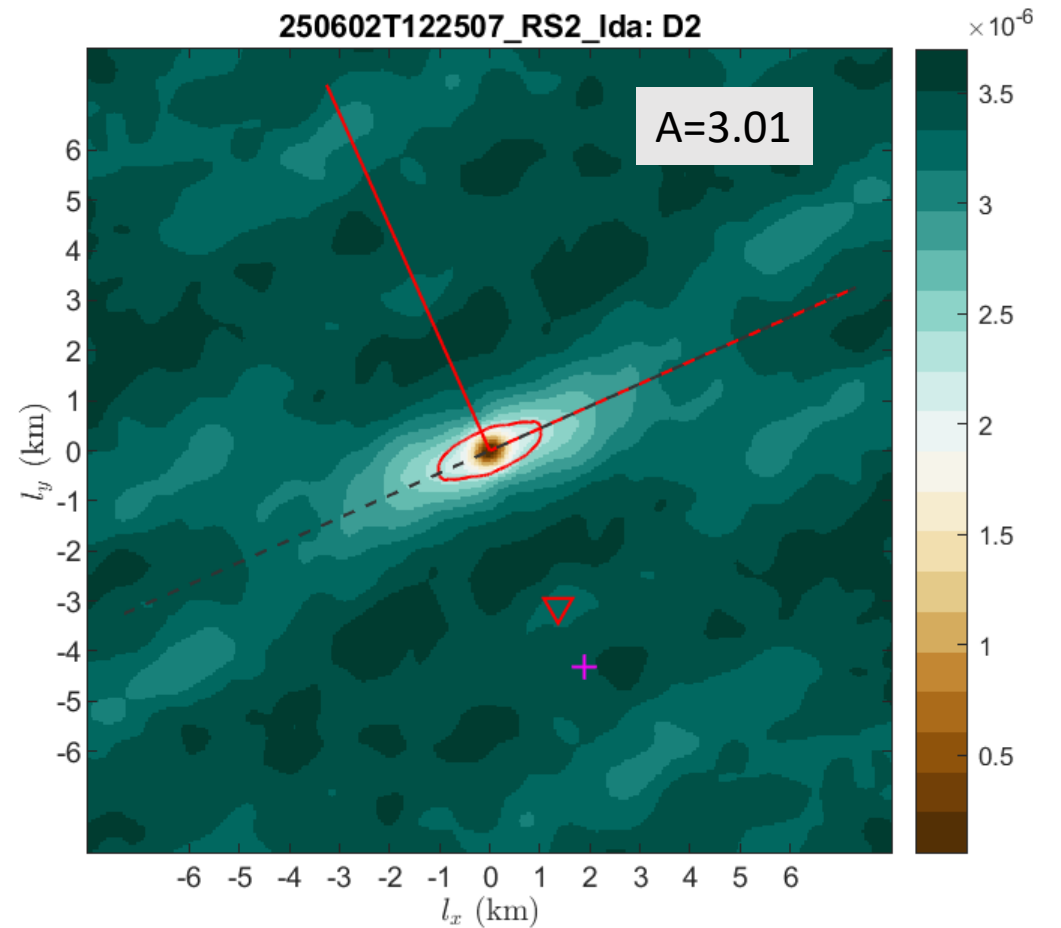
Red triangle is ACF-estimated wavelength (3.4 km)

20250602T121442\_PAZ\_Ida: D2



$S_2$ : “Energy”

250602T122507\_RS2\_Ida: D2

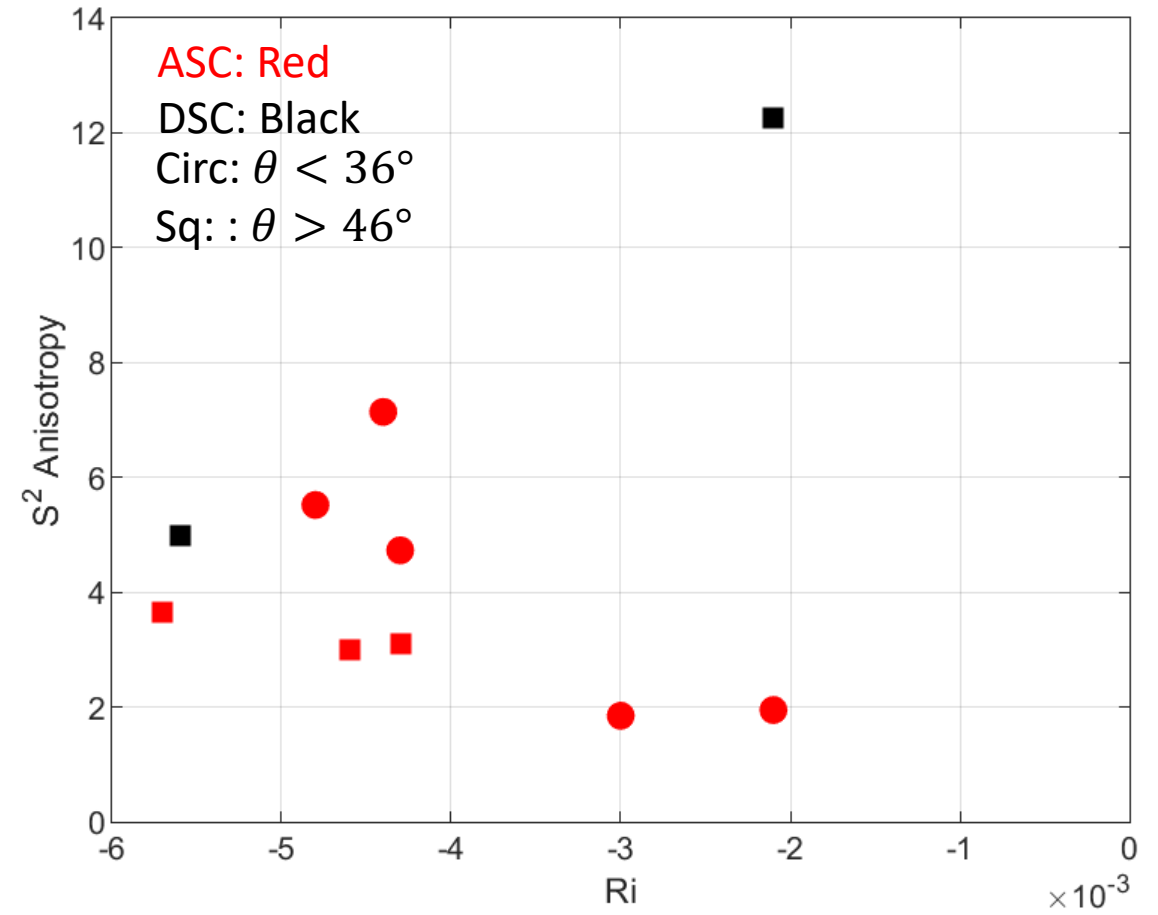
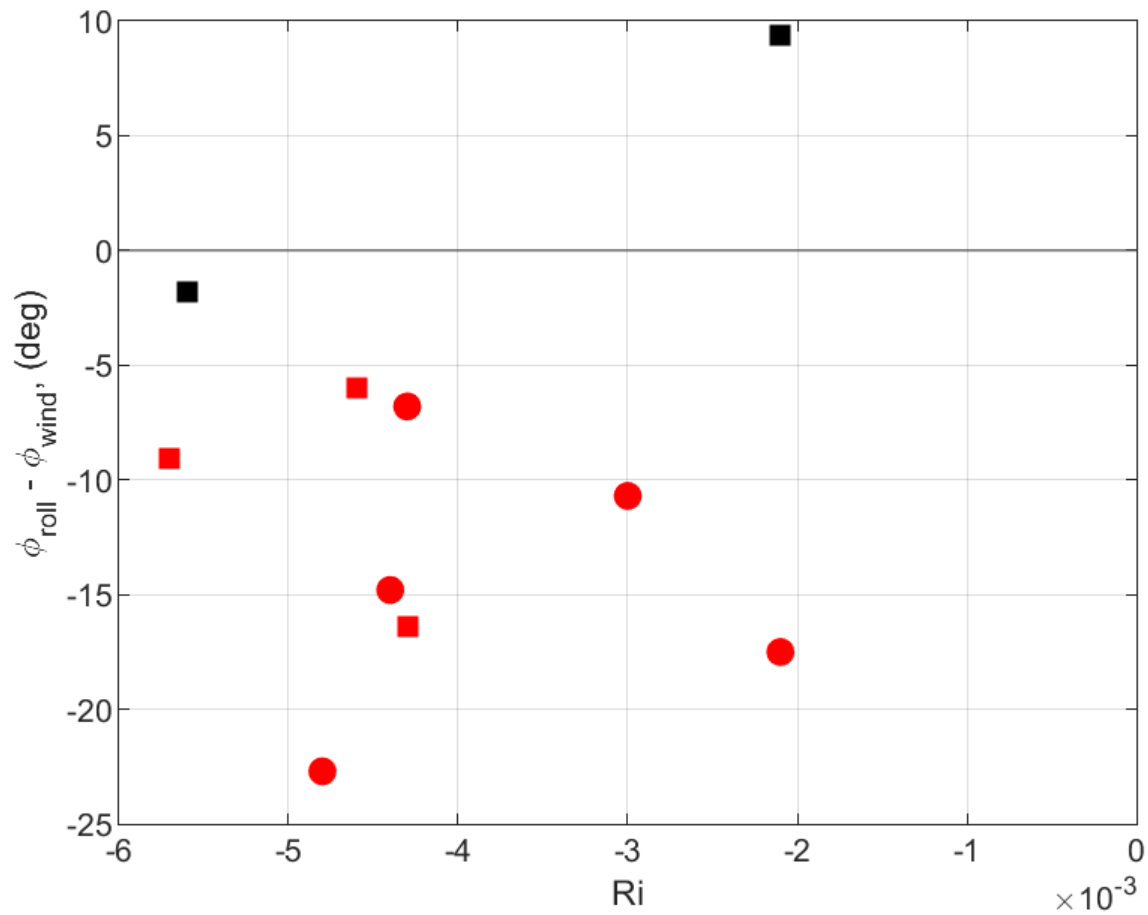


$$J = \begin{bmatrix} \overline{\left(\frac{\partial S_2}{\partial x}\right)^2} & \overline{\left(\frac{\partial S_2}{\partial x}\right)\left(\frac{\partial S_2}{\partial y}\right)} \\ \overline{\left(\frac{\partial S_2}{\partial y}\right)\left(\frac{\partial S_2}{\partial x}\right)} & \overline{\left(\frac{\partial S_2}{\partial y}\right)^2} \end{bmatrix}$$

- Solve E-value problem for  $J$  (masked for scale regime)
  - Small e-value,  $e_1$ , corresponds to stable (roll) axis
  - Large e-value,  $e_2$ , corresponds to unstable (transverse) axis
- Define  $S_2$  anisotropy:  $A = \frac{e_2}{e_1}$  (E.V. (1) ~ ACF direction)
- Search for largest  $A$  in PBL roll regime (~400 to 4000 m)
- EV(1) ~ parallel to roll axis

$J$  is “moment of inertia” tensor for  $S_2$

**SAR roll signal “energy” associated with local surface wind**

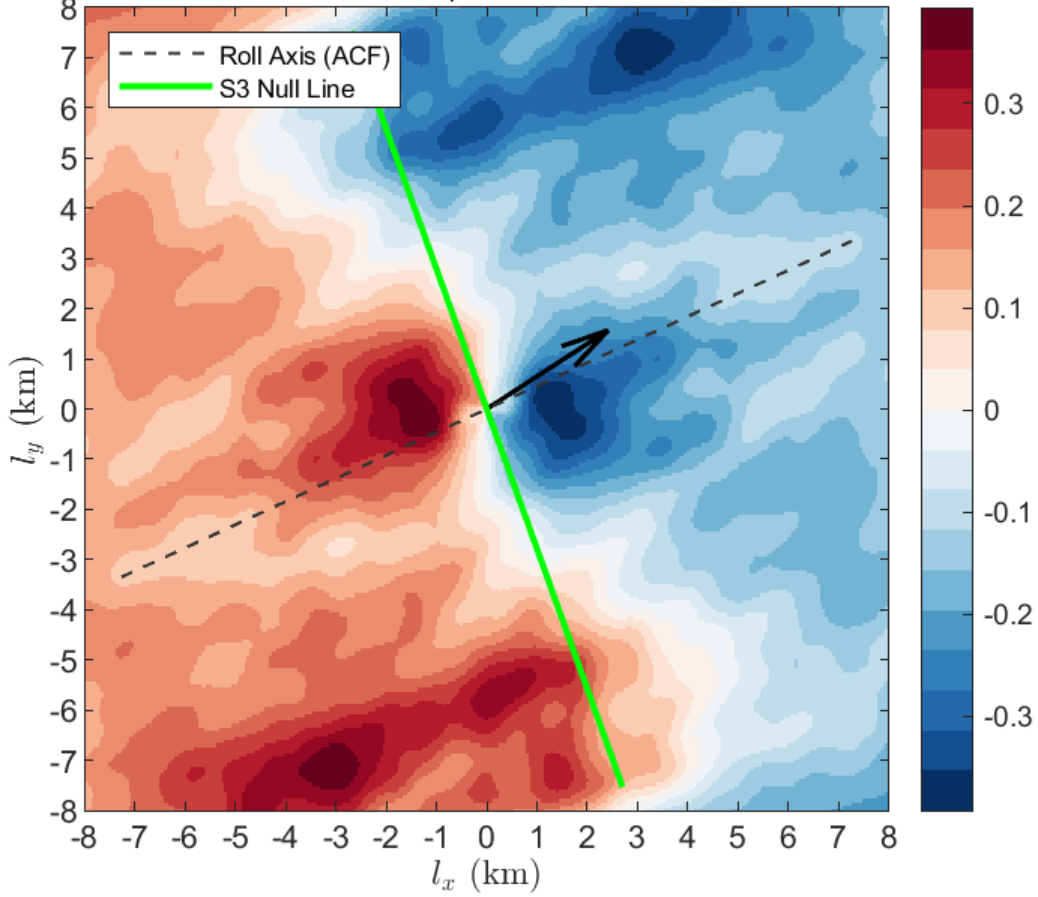


Too few cases analyzed so far to determine actual trends, but,

(a) Roll axis hints at aligning more closely to surface wind with increasingly unstable stratification

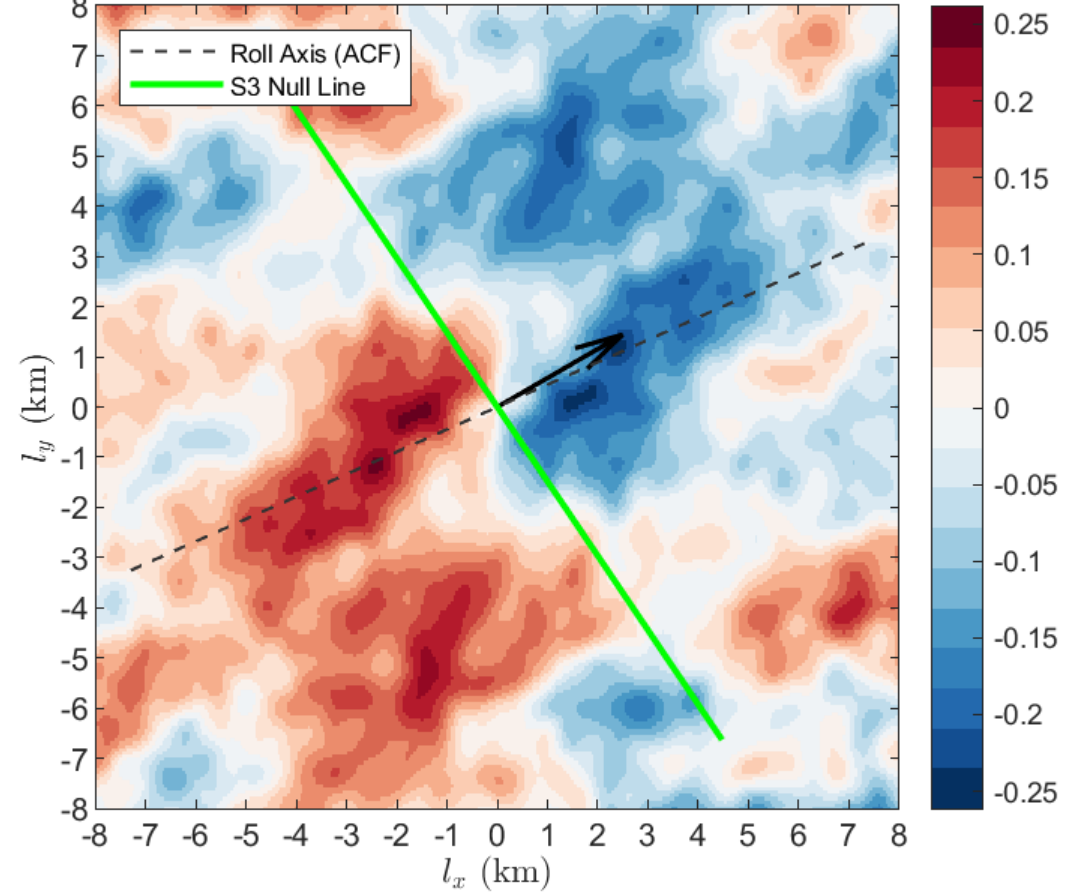
(b) Anisotropy hints at increasing with increasingly unstable stratification. **Hypothesis:** Anisotropy is associated with an increasing cellular contribution (toward mixed rolls and cells).

S3skew: ASC; Ri= -0.0043;  $\gamma=10.2^\circ$ ;  $\delta = -5.0^\circ$ ; wind-roll = 8.3 $^\circ$



## Skewness

S3skew: ASC; Ri= -0.0046;  $\gamma=15.6^\circ$ ;  $\delta = 10.0^\circ$ ; wind-roll = 6.0 $^\circ$



Null Axis: minimum skewness closest to roll axis + 90 $^\circ$ . Roughly separates positive from negative skewness. Upwind tends to be positive.

Normalized by  $S2^{3/2}$

Although peaks are  $\sim 25\%$ ,  
Averages near 10%

**Overtuning contributes, but along-roll dominates**

**(1) HYPOTHESIS: NON-ORTHOGONALITY OF NULL AXIS ASSOCIATED WITH PHASE DIFFERENCE BETWEEN ALONG/ACROSS ROLL PERTURBATION**

**(2) HYPOTHESIS: ROLL OVERTURNING CONTRIBUTION: SHARP CONVERGENCE VS. BROAD DIVERGENCE**

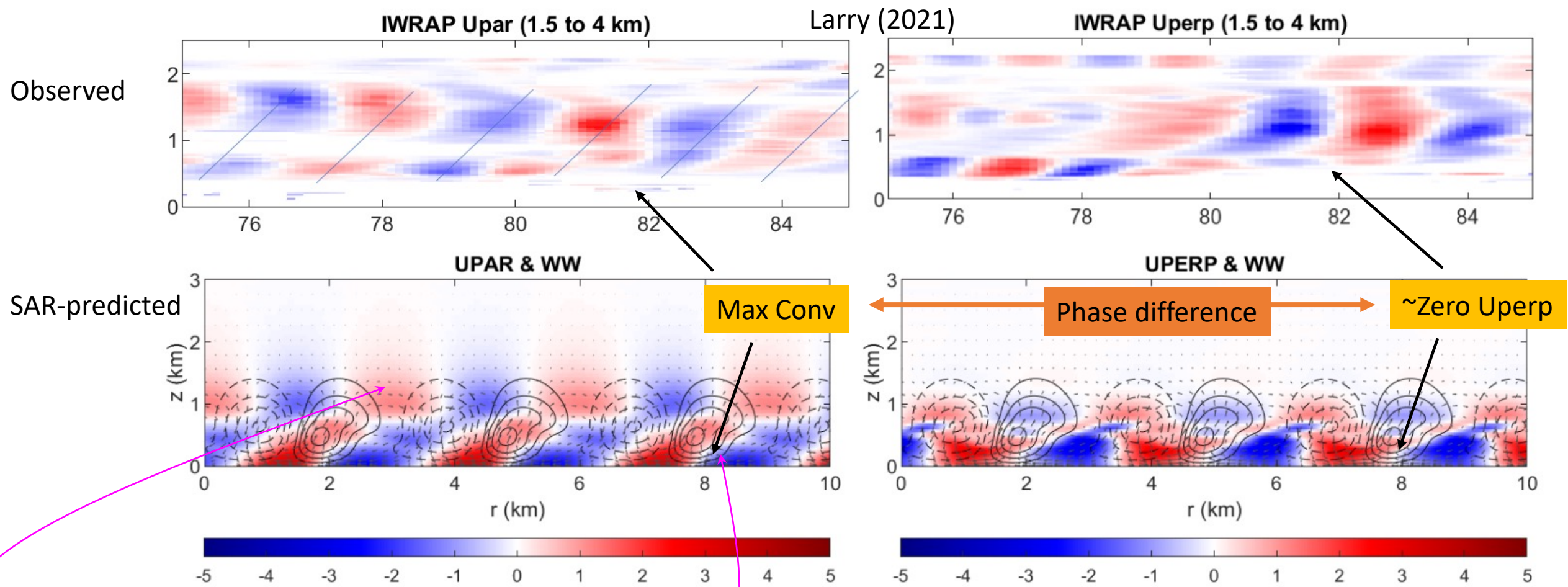


Figure 4: TCBL roll signature extracted from IWRAP winds. (a) Upar; (b) Uperp. Calculated TCBL rolls using mean wind and eddy viscosity profiles derived from IWRAP and SAR. (c) Upar; (d) Uperp. Calculated vertical velocity included on c & d with  $0.5 \text{ m s}^{-1}$  contours. Vectors show calculated overturning roll circulation (Upar, W).

Contours are SAR-predicted vertical velocity ( $0.5 \text{ m s}^{-1}$  contours)

Vectors are SAR-predicted overturning circulation

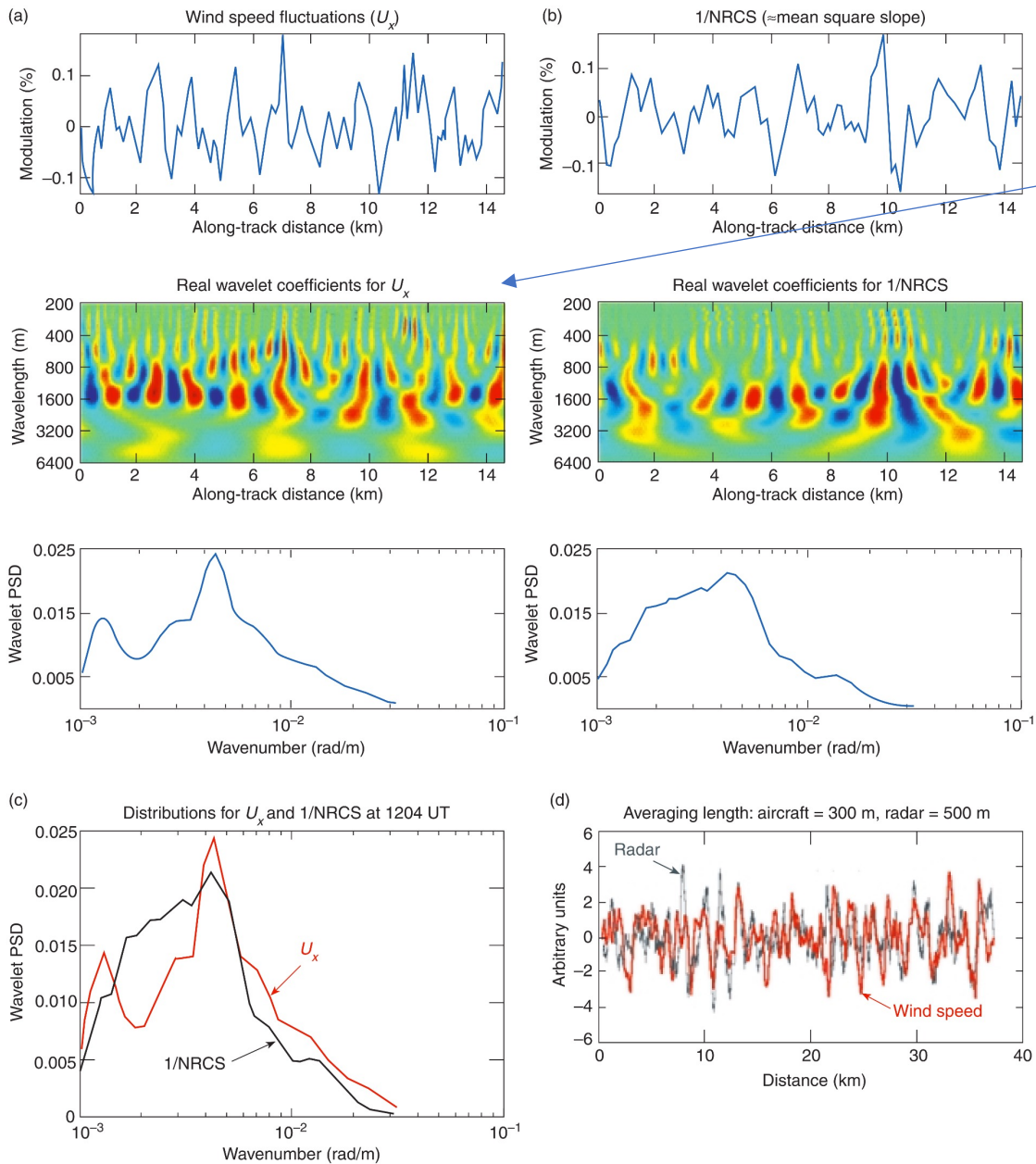
Upar: horizontal component of overturning flow (nearly radial)  
 Uperp: horizontal along-roll flow (in/out of page; nearly azimuthal)

Note that the primary instability (Upar, w)  
 leans into the mean shear

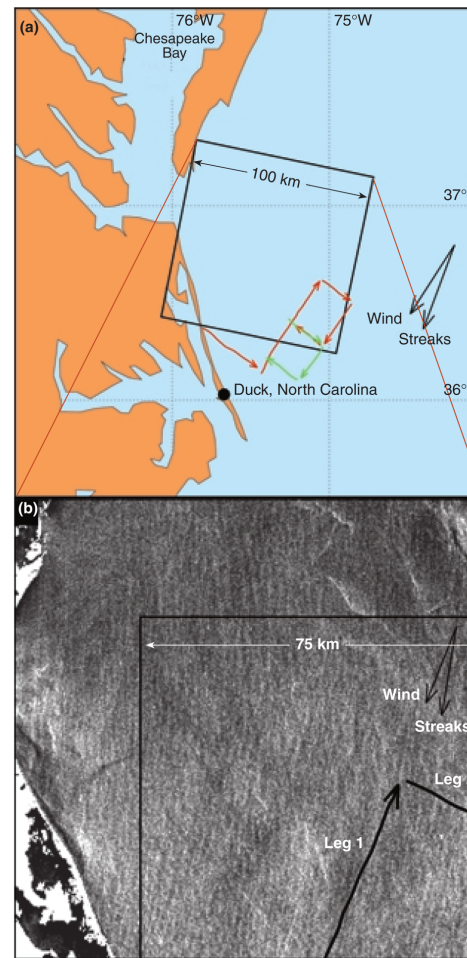
**These are NOT convective rolls!**

# LongEZ near-surface turbulence data coincident with SAR overpass

Roll-signal in SAR is primarily associated with Roll-induced surface wind modulation.



**Figure 4.** Results of an analysis of the fluctuations in wind ( $U_x$ ) and the inverse of the radar altimeter measurement (1/NRCS) for the LongEZ flight leg at 1204 UT. See text for details. (NRCS = normalized radar cross section, PSD = power spectral density.)

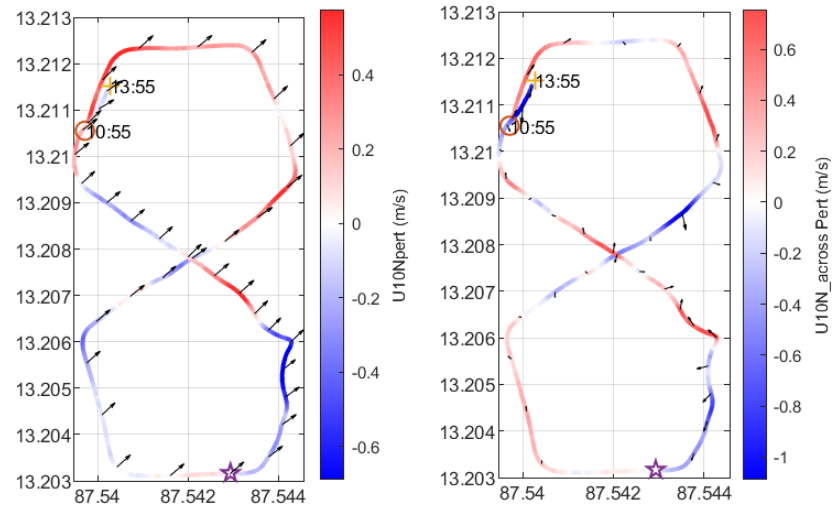


**Figure 1.** ONR Shoaling Waves Pilot Study experimental geometry (a) and associated Radarsat SAR image (b). The LongEZ flight path at 15 to 20 m above the water (orange arrows) and at 300 m (green arrows) are also shown. The 75-km square was used for the autocorrelation map in Fig. 2b.

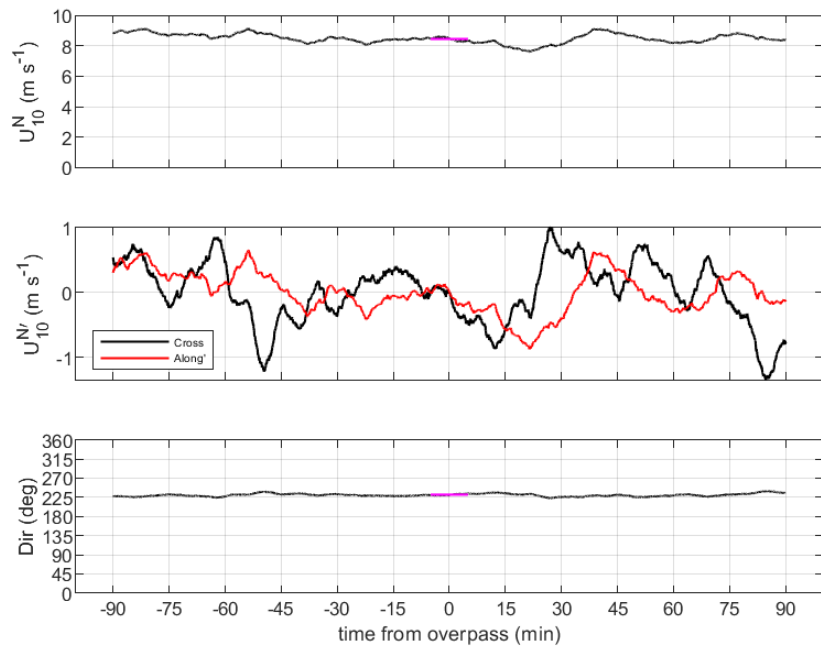
# Work in Progress

- Many SAR matchups left to process
- Interpreting  $S_3$
- Compare SAR & WG integral length scales (along/across)

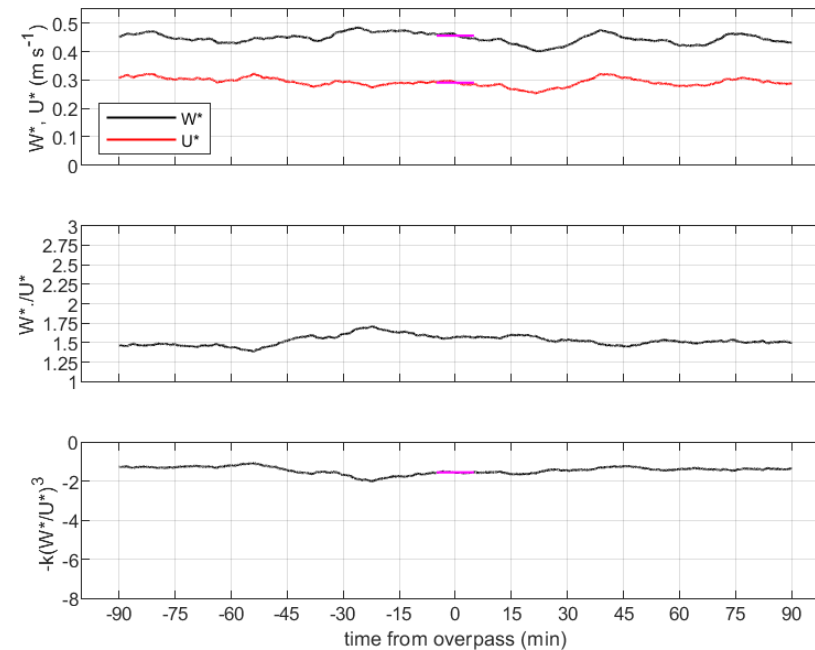
### Kelvin\_20250602T122507



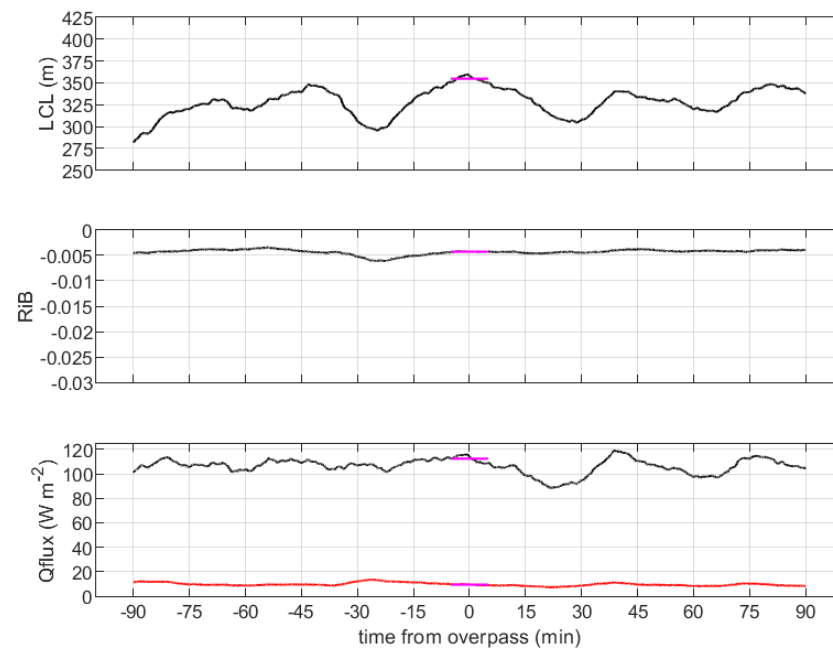
### Kelvin\_20250602T122507



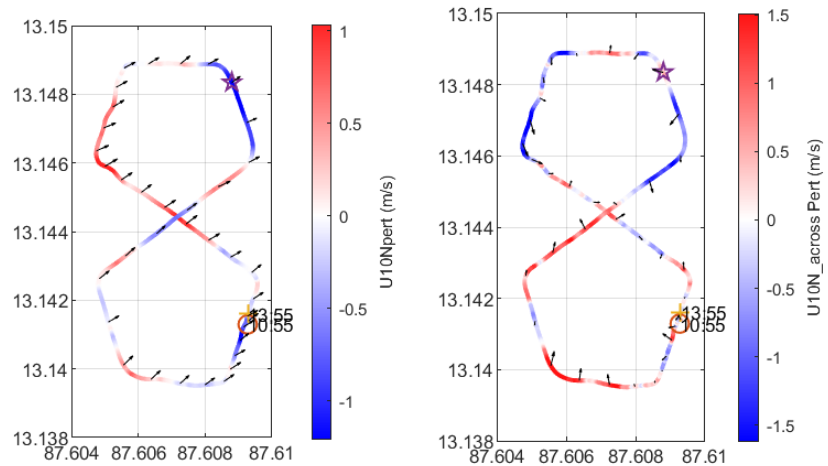
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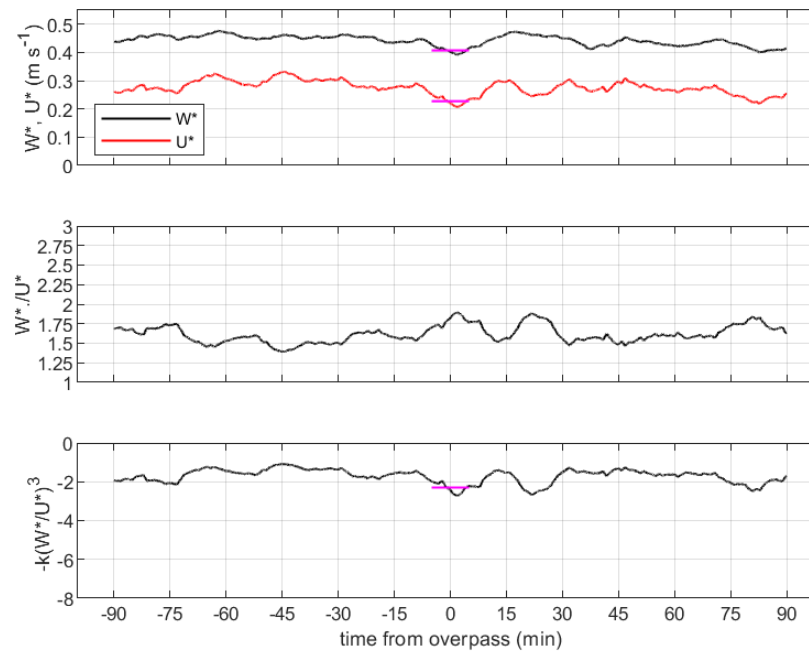
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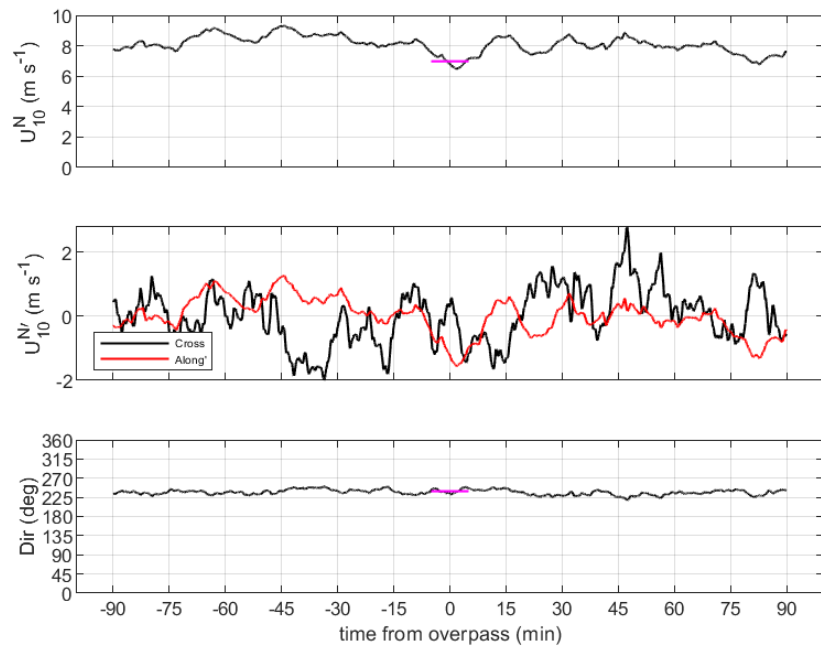
# WHOI43\_20250602T122507



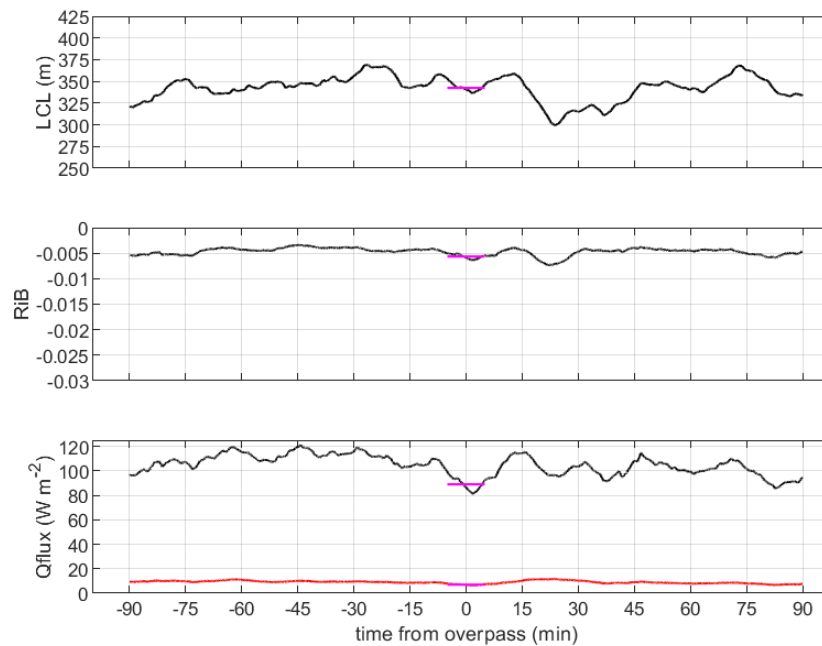
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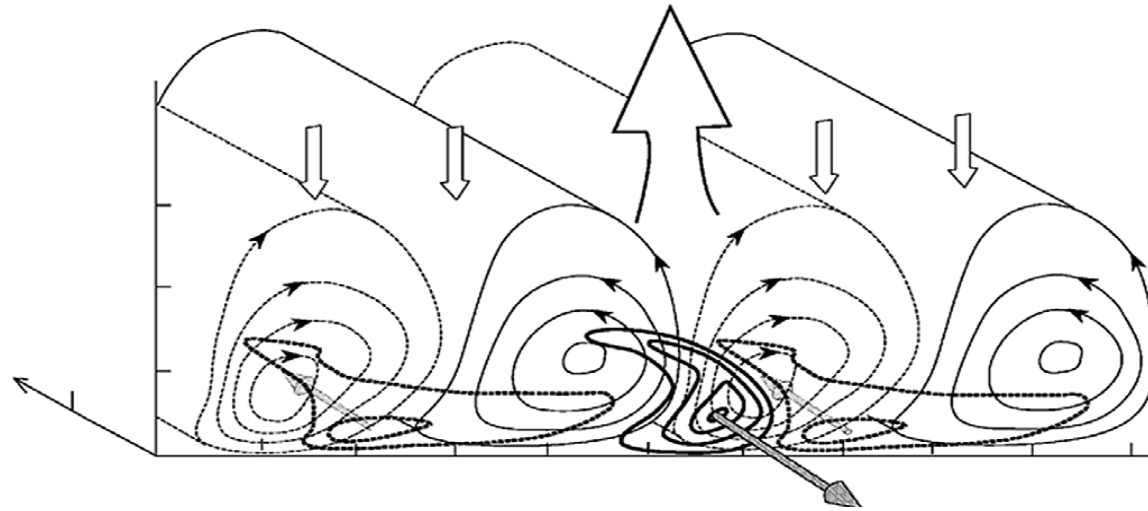
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# WHOI43\_20250602T122507



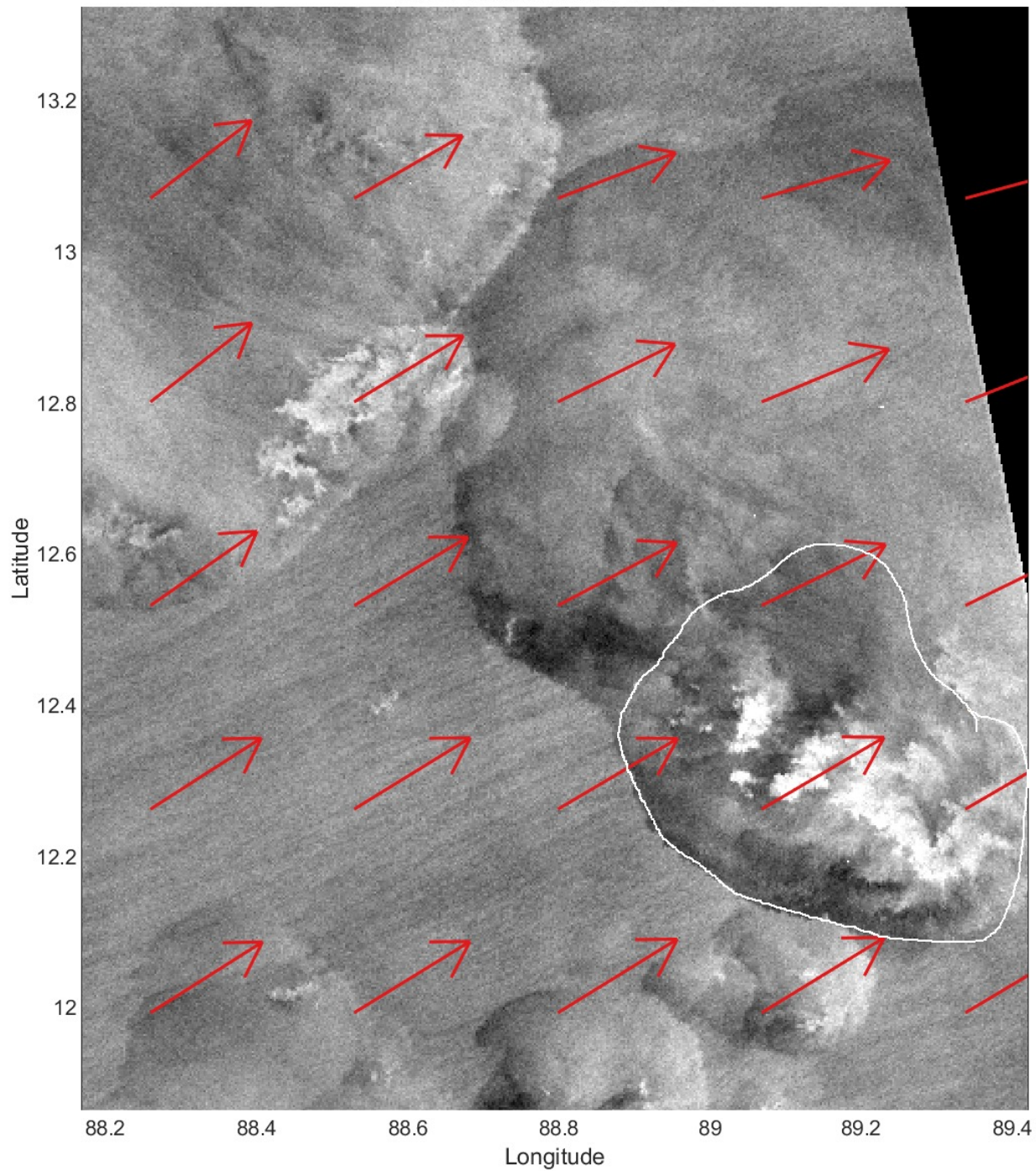
# Organized Large Eddies (PBL Rolls)



(Foster, *Oceanography*, 2013)

- Planetary Boundary Layer (PBL) rolls are spatially periodic, quasi-equilibrium embedded secondary circulations that span the depth of the boundary layer.
- Boundary layer depths vary from 0.5 to 2 km with roll wavelengths of 2.4 to 4 times the PBL.
- Unstable stratification strengthens the roll circulation.
- Spatially periodic near-surface convergence beneath the updrafts and a broader divergence beneath the downdrafts.
- 100–900 km Crest length.
- 2 – 12 km wavelengths.

RSAT2: 09-Jun-2025 12:21:14



CP09: IMERG

