Calibration, Validation, Quality Control Procedures and Error Estimates in HF Radar Current Observations

The Northern Adriatic Sea Test Case

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Outline

- Short description of past/present HFR projects @ OGS

- Focus on Codar-type HF radars:
  - calibration and validation -- approaches & examples
  - wind – related noise
  - qaqc approach @ OGS

- Error assessment & analysis: more general approach
  - Least-squares fitting approaches and modification
  - Importance of the (unknown) current field

- Some conclusions

Previous radar experiments in the Adriatic Sea

1995 – 1997 PRISMA –II project
ancona – italia centrale

2001 – 2006 CUMVELA – Venice Lagoon

2002 – 2004 DOLCEVITA project

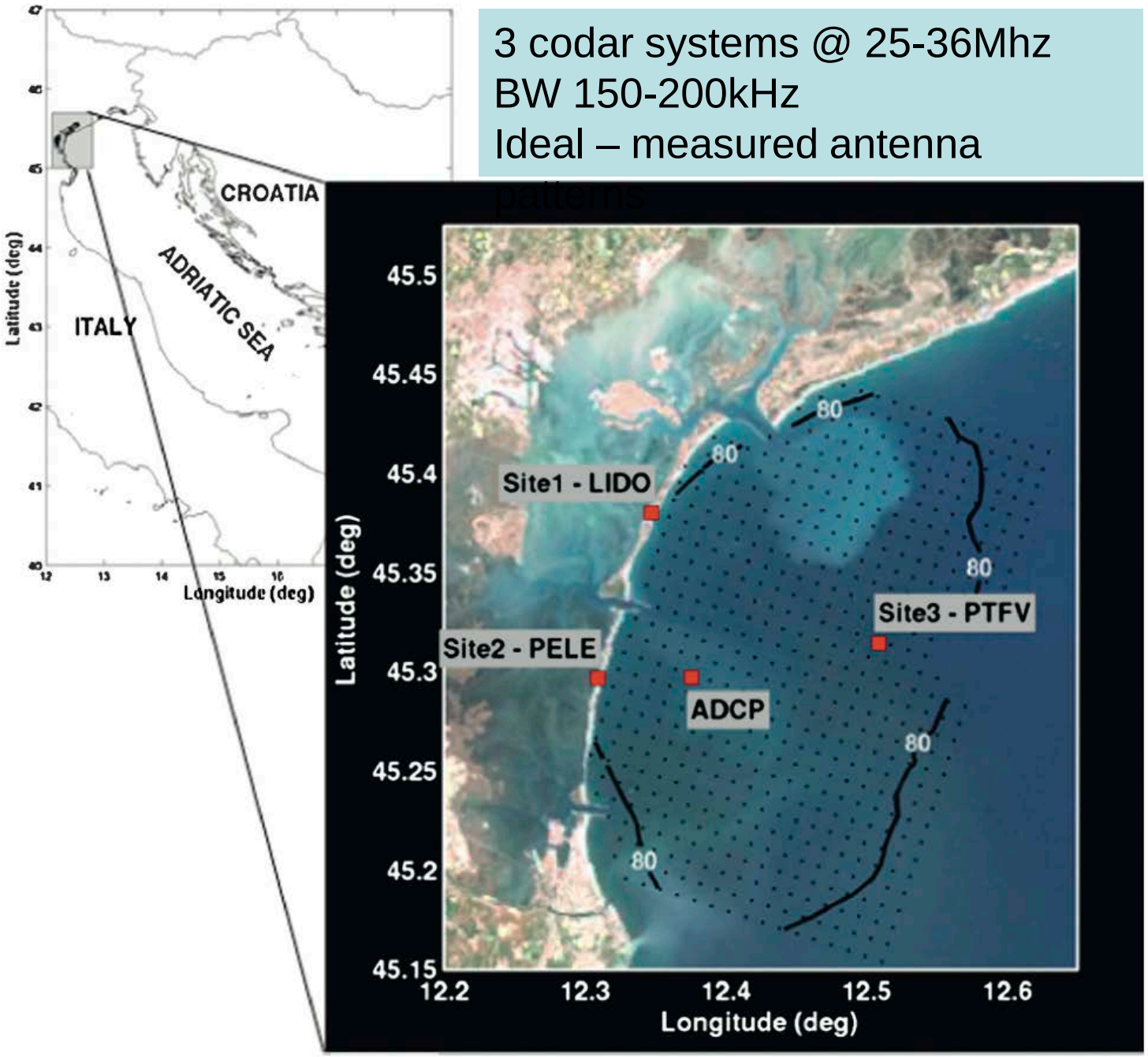
2007 – 2010 NASCUM project
1st effective identification and backtracking-forward oil-spill detection

2010 freshwater test (Garda Lake)

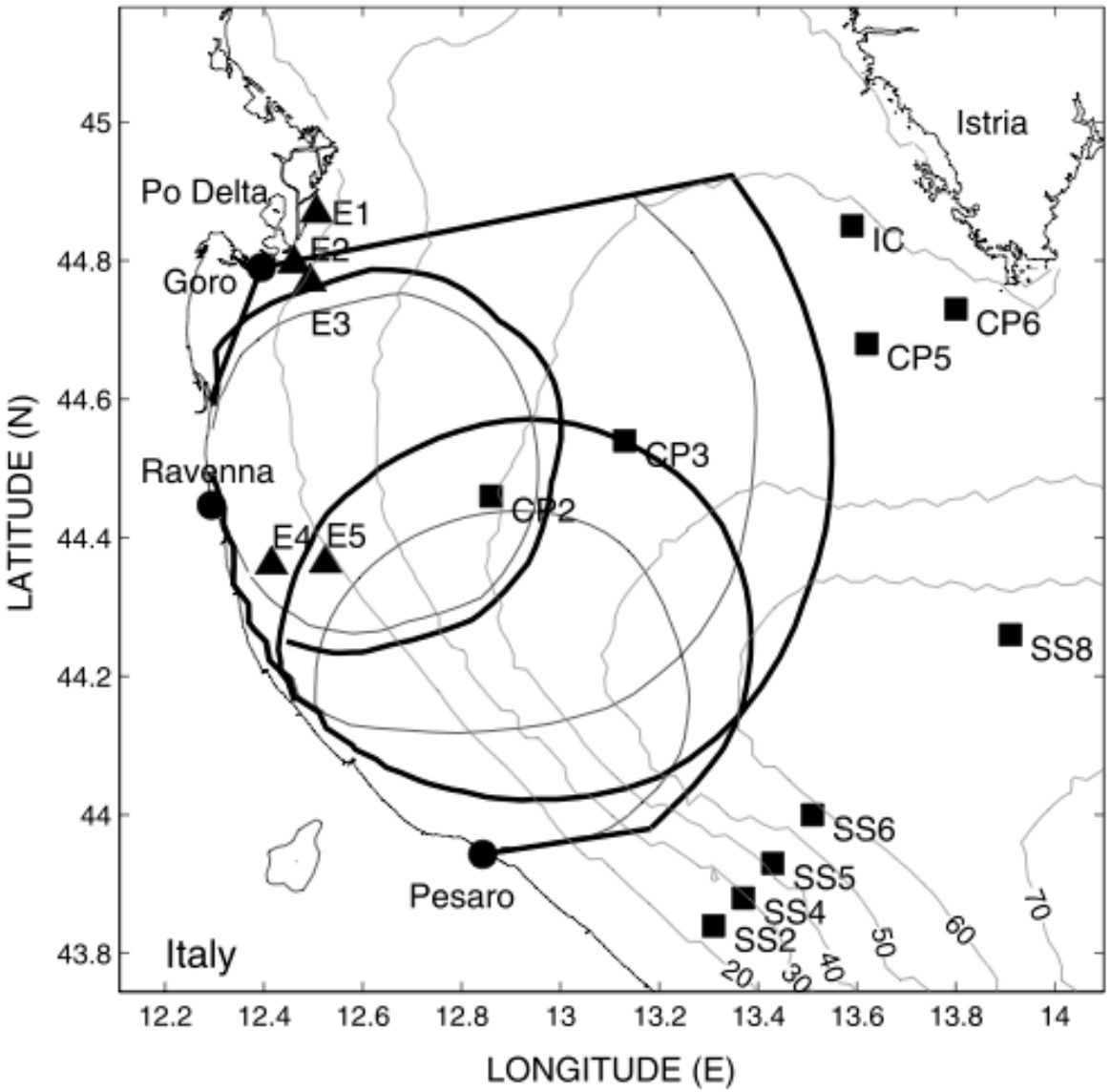
2011 – 2013 TOSCA project

- 2001 – 2006 CUMVELA – Venice Lagoon

3 codar systems @ 25-36Mhz
BW 150-200kHz
Ideal – measured antenna patterns



- 2002 – 2004 DOLCEVITA



Dynamics **o**f **L**ocalized **C**urrents and **E**ddy **V**ariability **i**n **t**he **A**driatic

3 WERA systems @ 16MHz

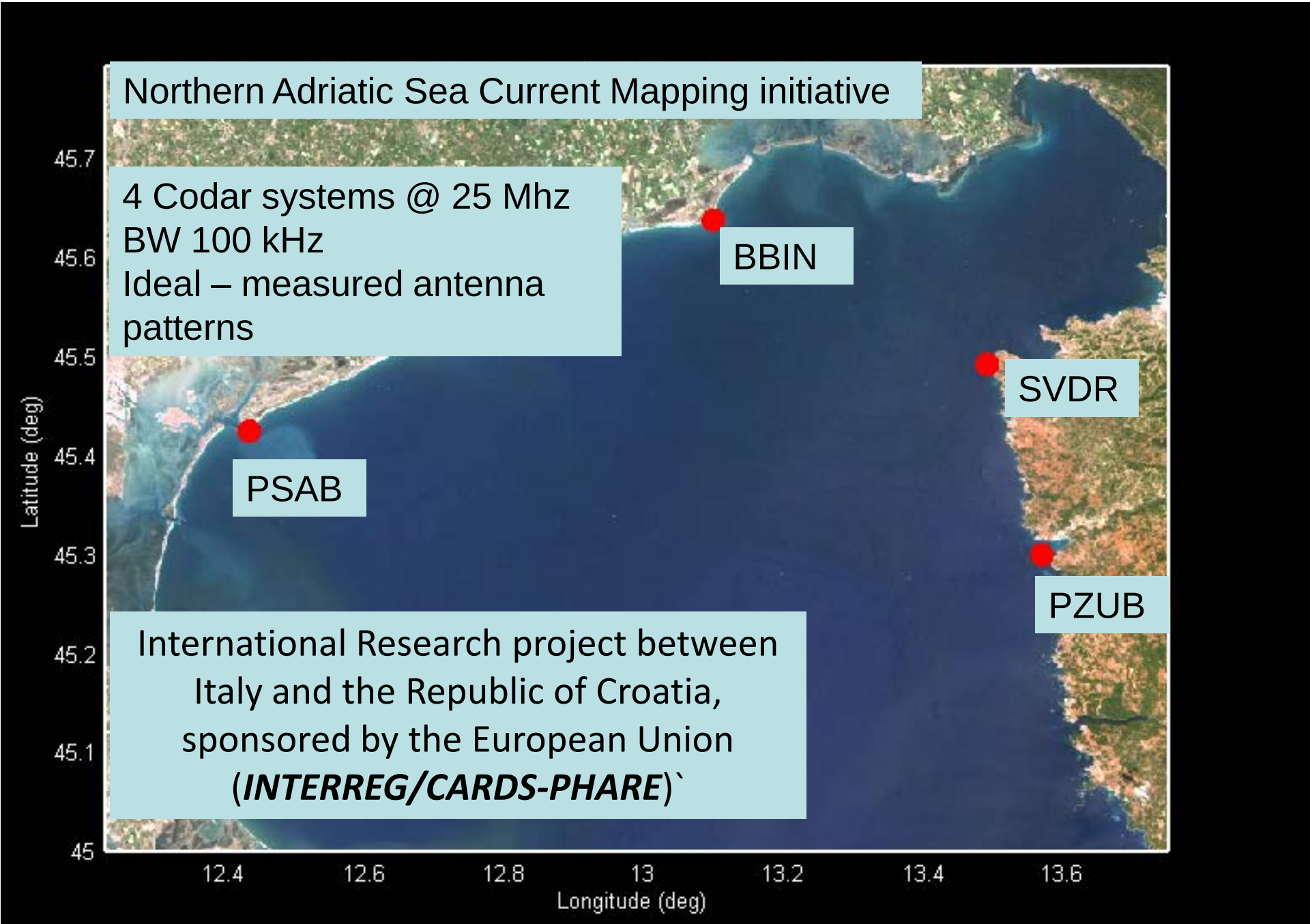
BW 100kHz – various current meters, drifters, …

- 2007 – 2010 NASCUM project

International Research project between Italy and the Republic of Croatia, sponsored by the European Union (***INTERREG/CARDS-PHARE***)

	CNR-ISTITUTO DI SCIENZE MARINE - ISMAR (Venice, Italy)
	ISTITUTO NAZIONALE DI OCEANOGRAFIA E DI GEOFISICA SPERIMENTALE - OGS (Trieste, Italy)
	INSTITUT ZA OCEANOGRAFIJU I RIBARSTVO - IZOR (Split, Croatia)
	"Ruđer Bošković" INSTITUT - CENTAR ZA ISTRAZIVANJE MORA CMR (Rovinj, Croatia)
	Lead Partner: **CORILA** (Consorzio per la Gestione del Centro di Coordinamento delle attivita' di Ricerca inerenti il Sistema Lagunare di Venezia)

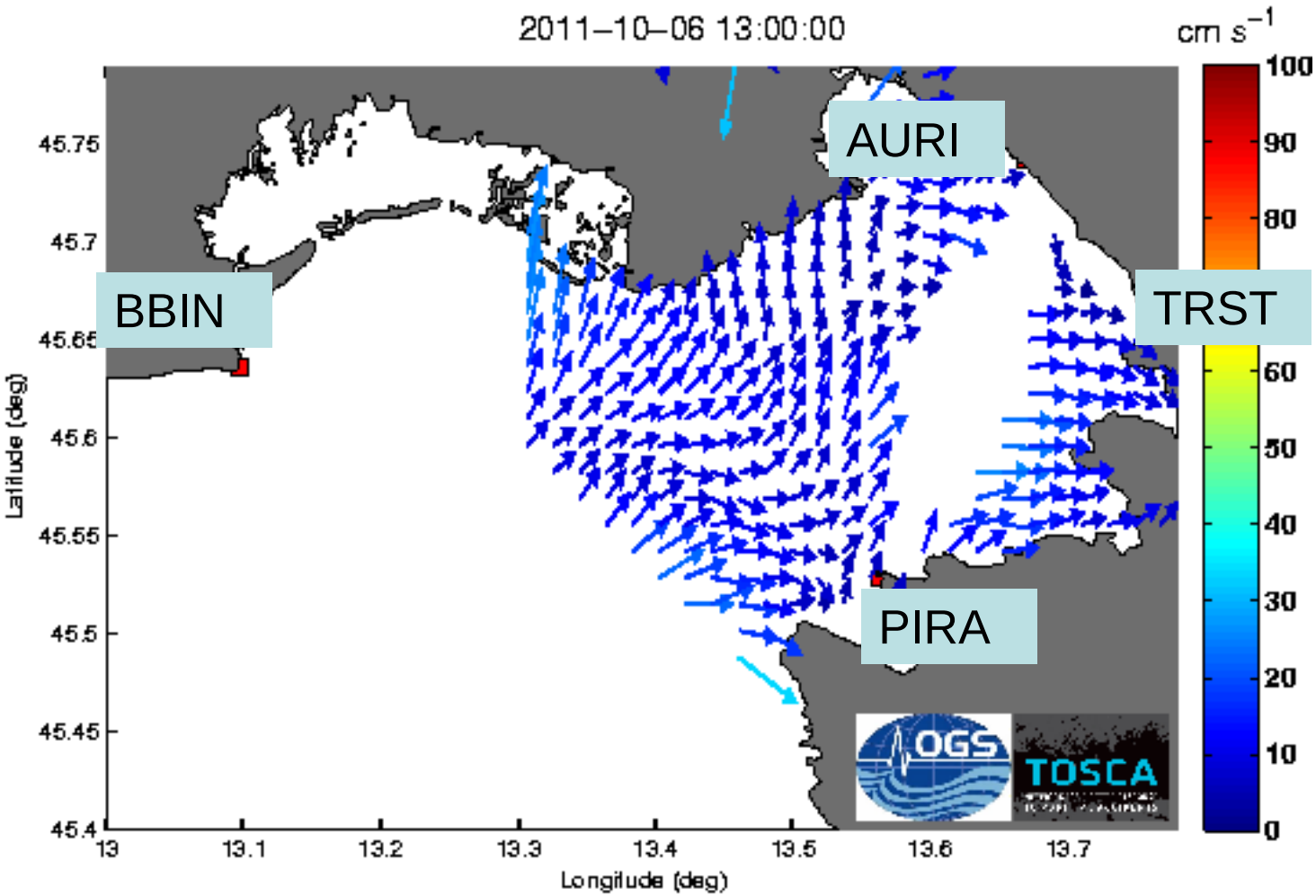
- 2007 – 2010 NASCUM project



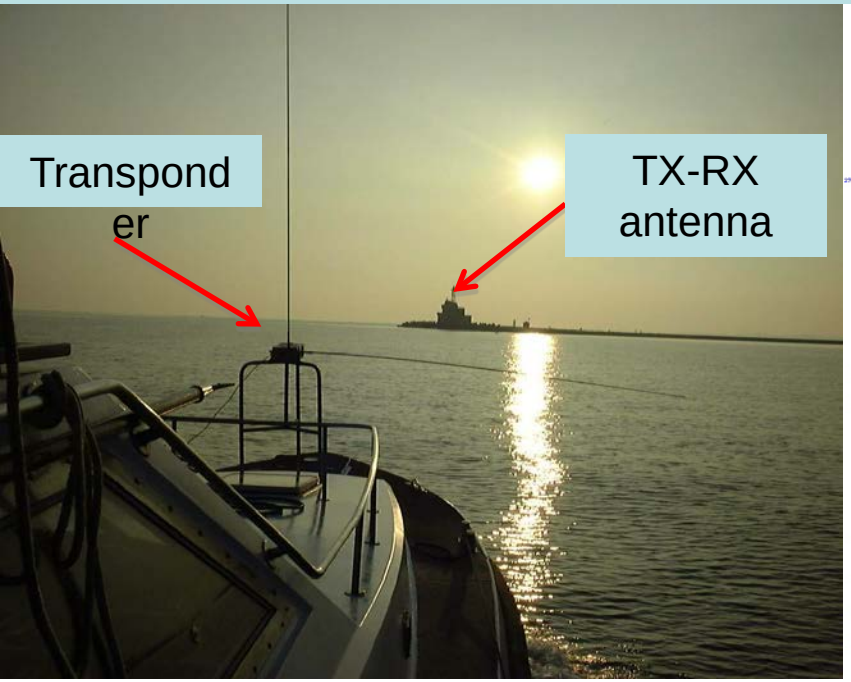
- 2011 – TOSCA project

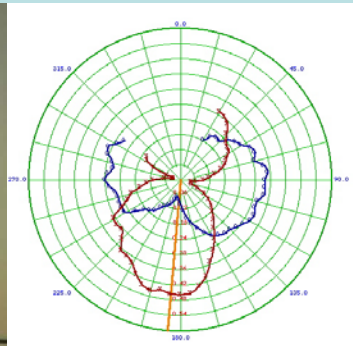
Tracking Oil Spills and Coastal Awareness Network

4 Codar systems @ 25 Mhz, 150-200 kHz BW
Ideal – measured antenna patterns

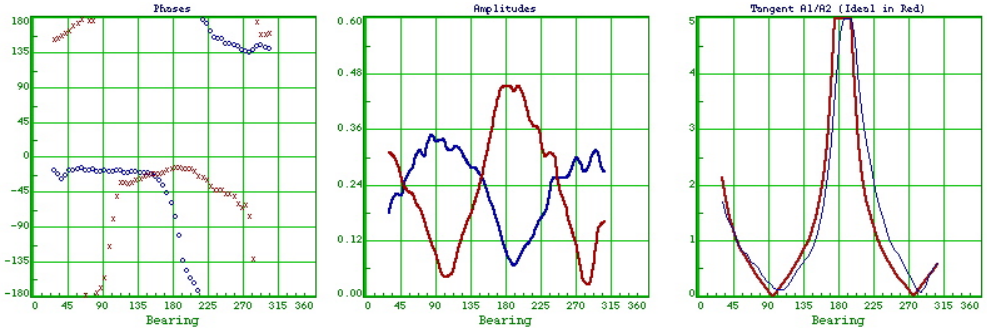


System calibration – data validation

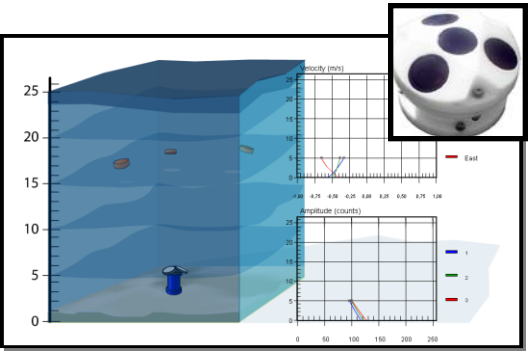


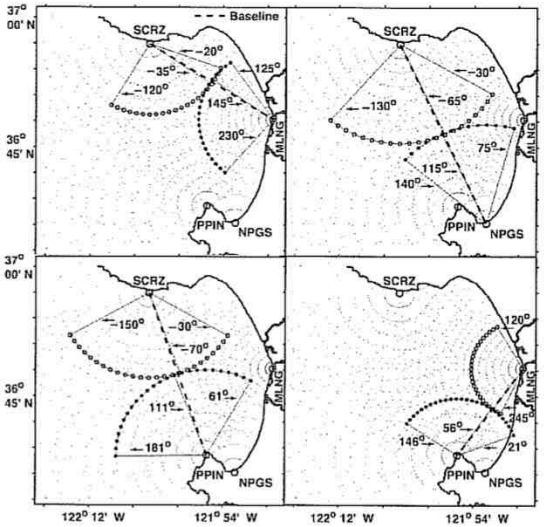


System **calibration** to measure the response patterns of the receive antenna elements and account for local environment

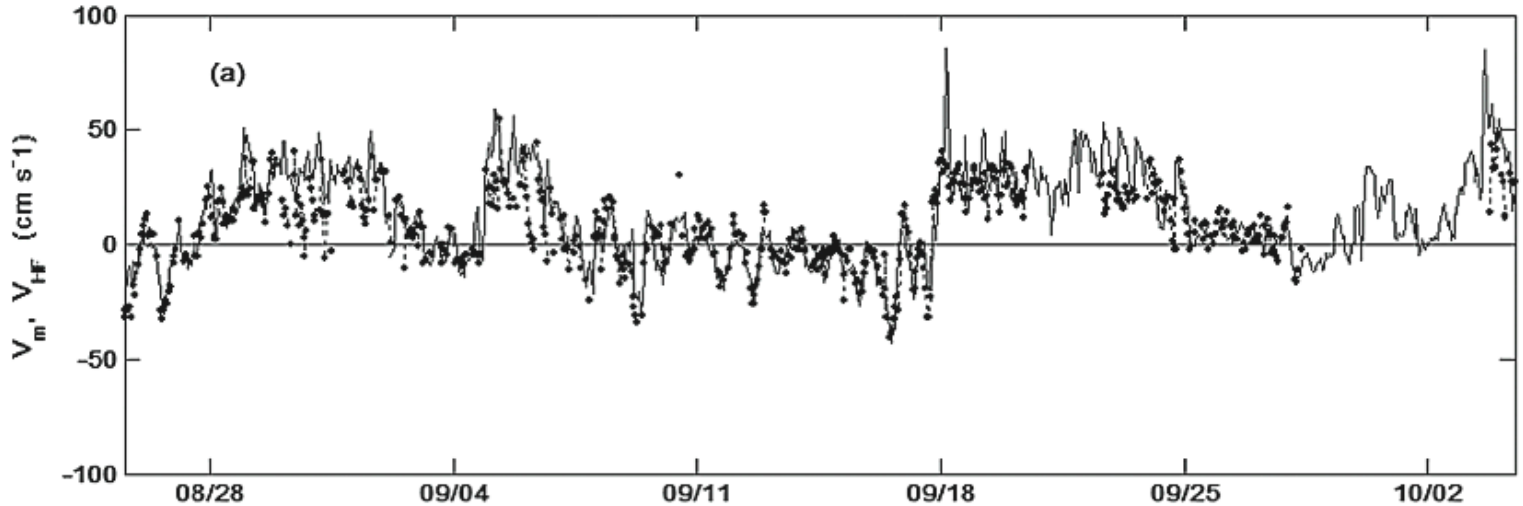


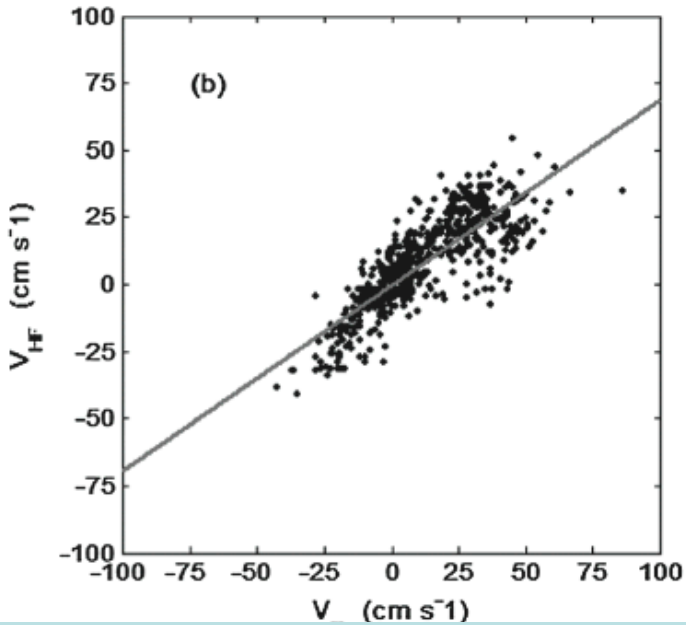
Data validation with current meters, drifters, site-to-site baselines to "bound" accuracy of current estimates





Data validation

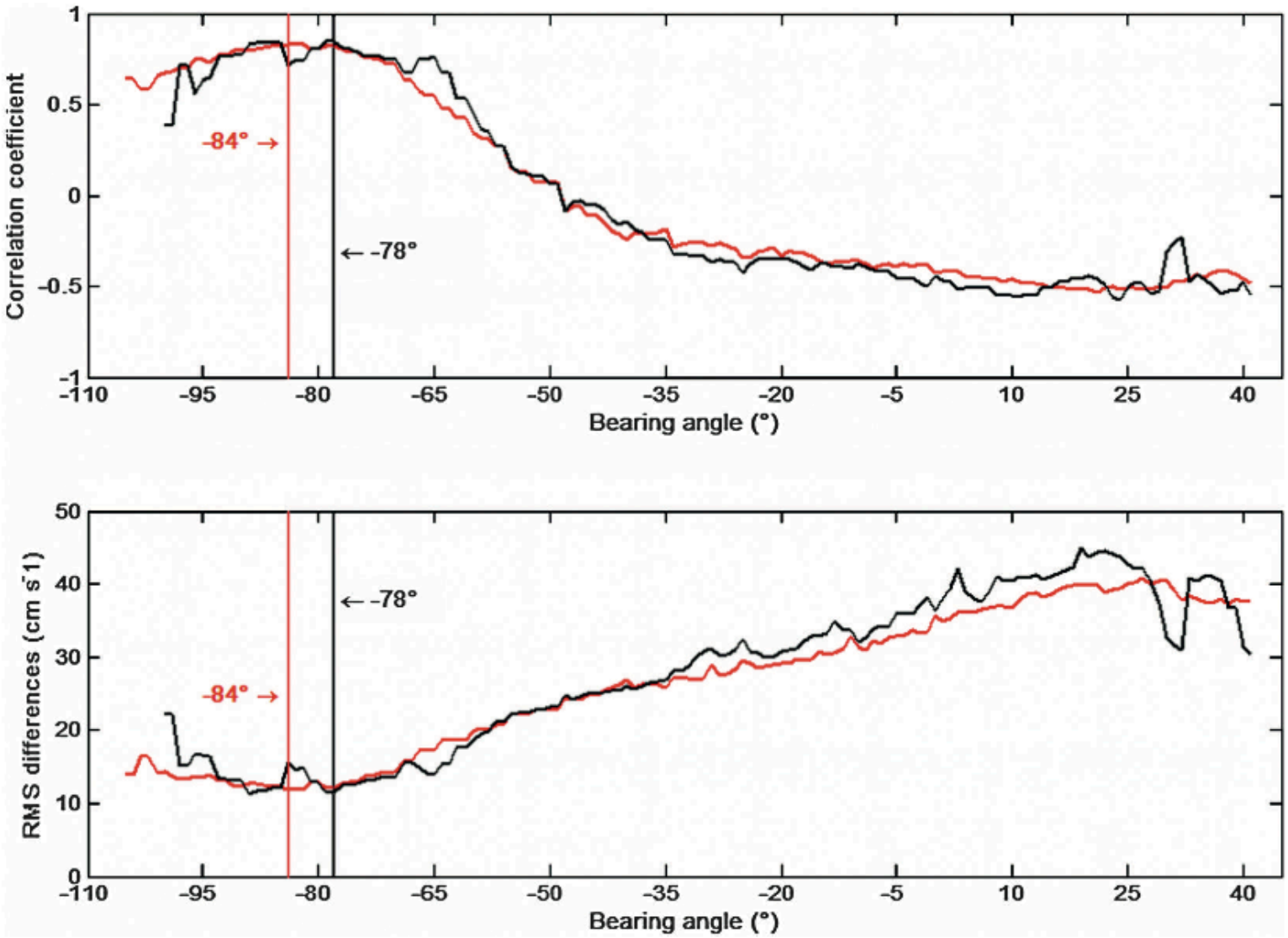




r = 0.82
rms diff. = 12 cm / s
slope = 0.69
intercept = -0.24
bias = 3.8 cm / s

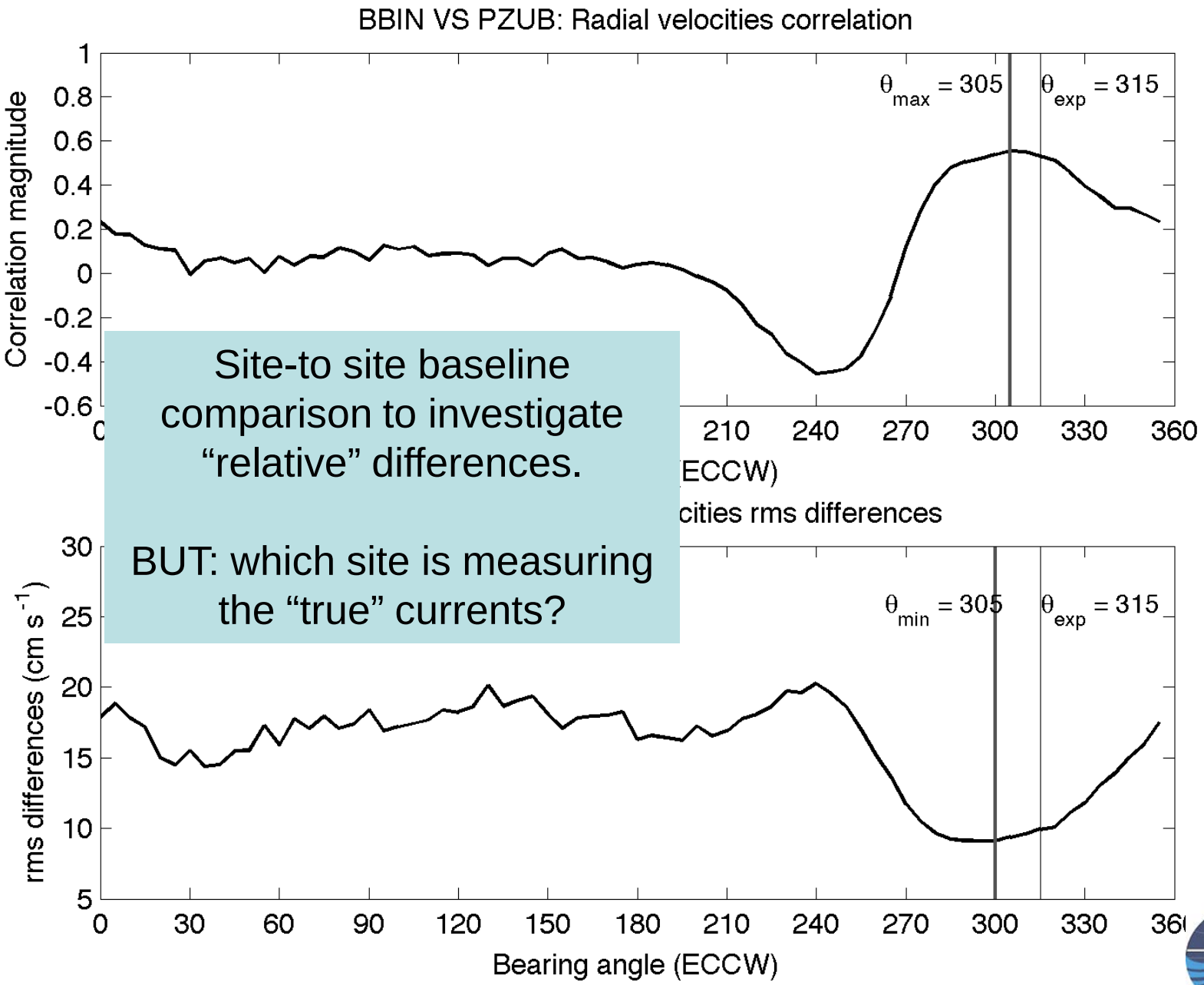
Comparisons with current meters provide “upper bounds” to current accuracy
Error sources not investigated at this level
Comparisons should be “adjusted” to account for the intrinsic sampling scales and

Data validation



Bearing offset not statistically significant for both the ideal and measured antenna pattern

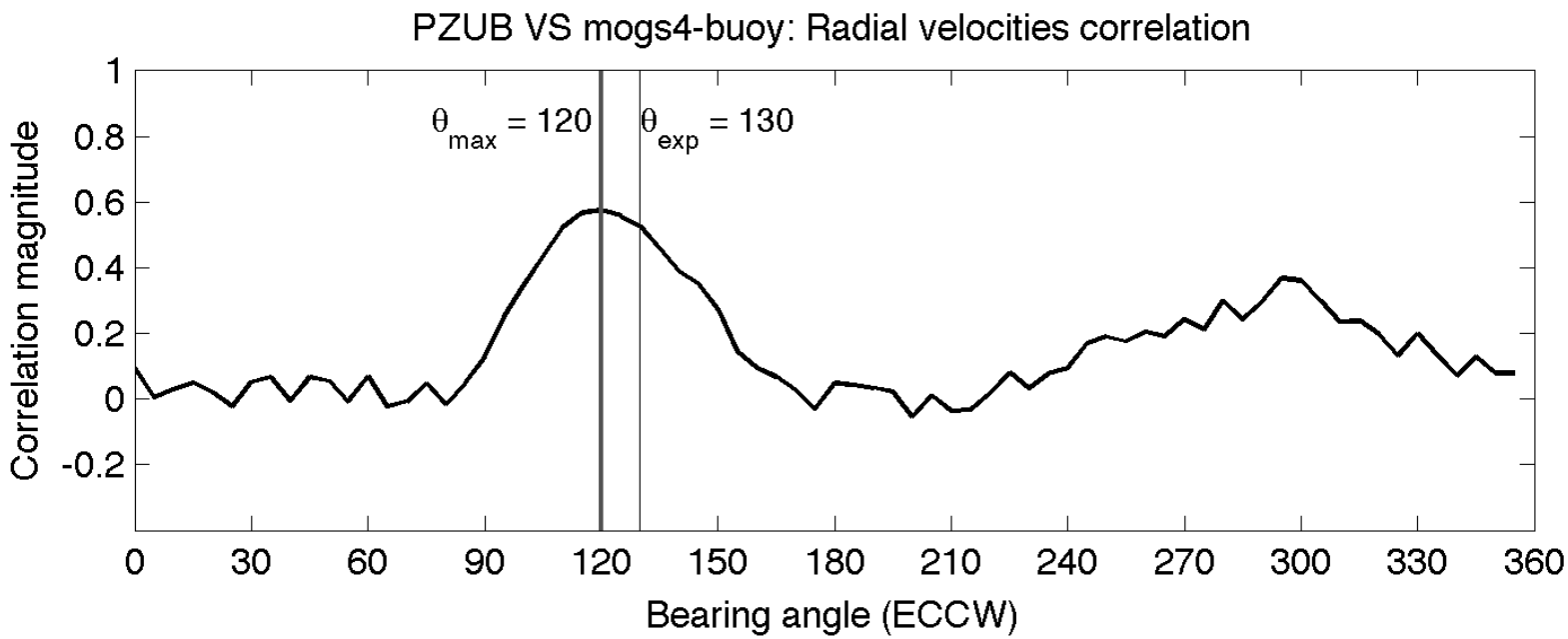
Data validation

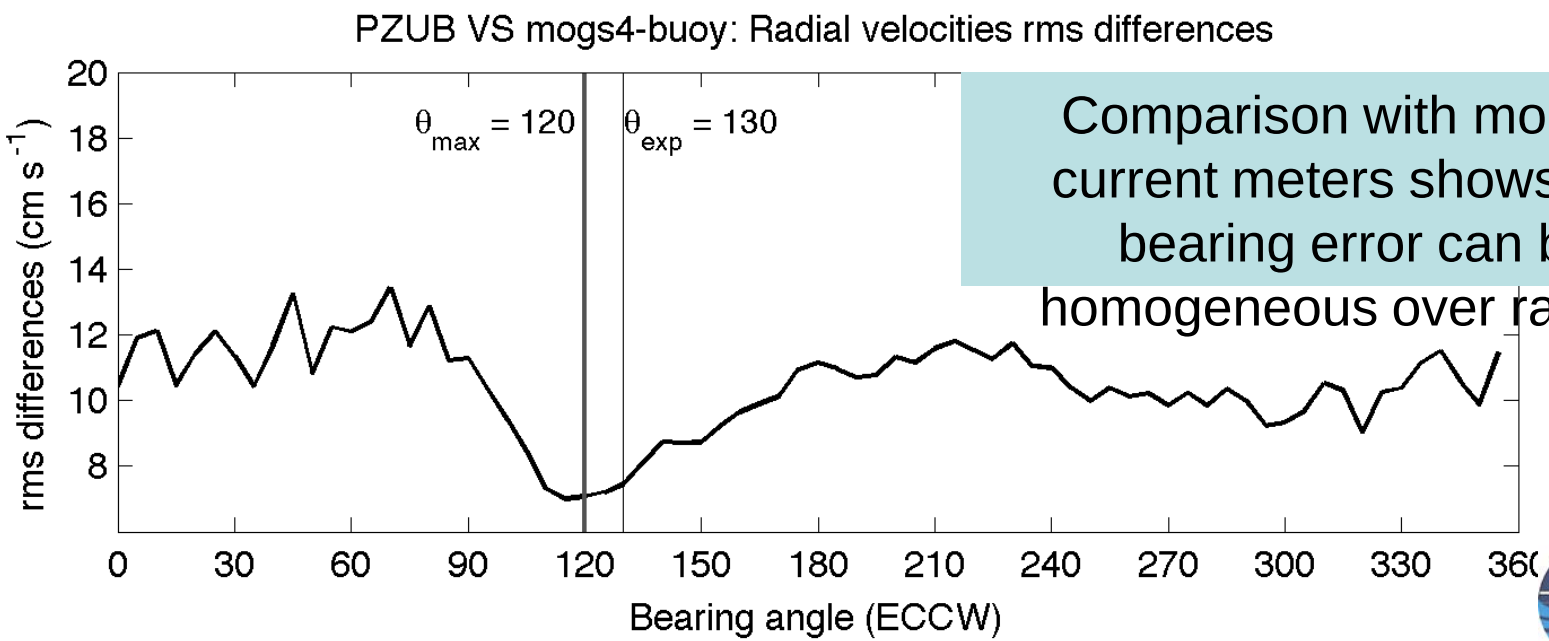


Site-to site baseline comparison to investigate "relative" differences.

BUT: which site is measuring the "true" currents?

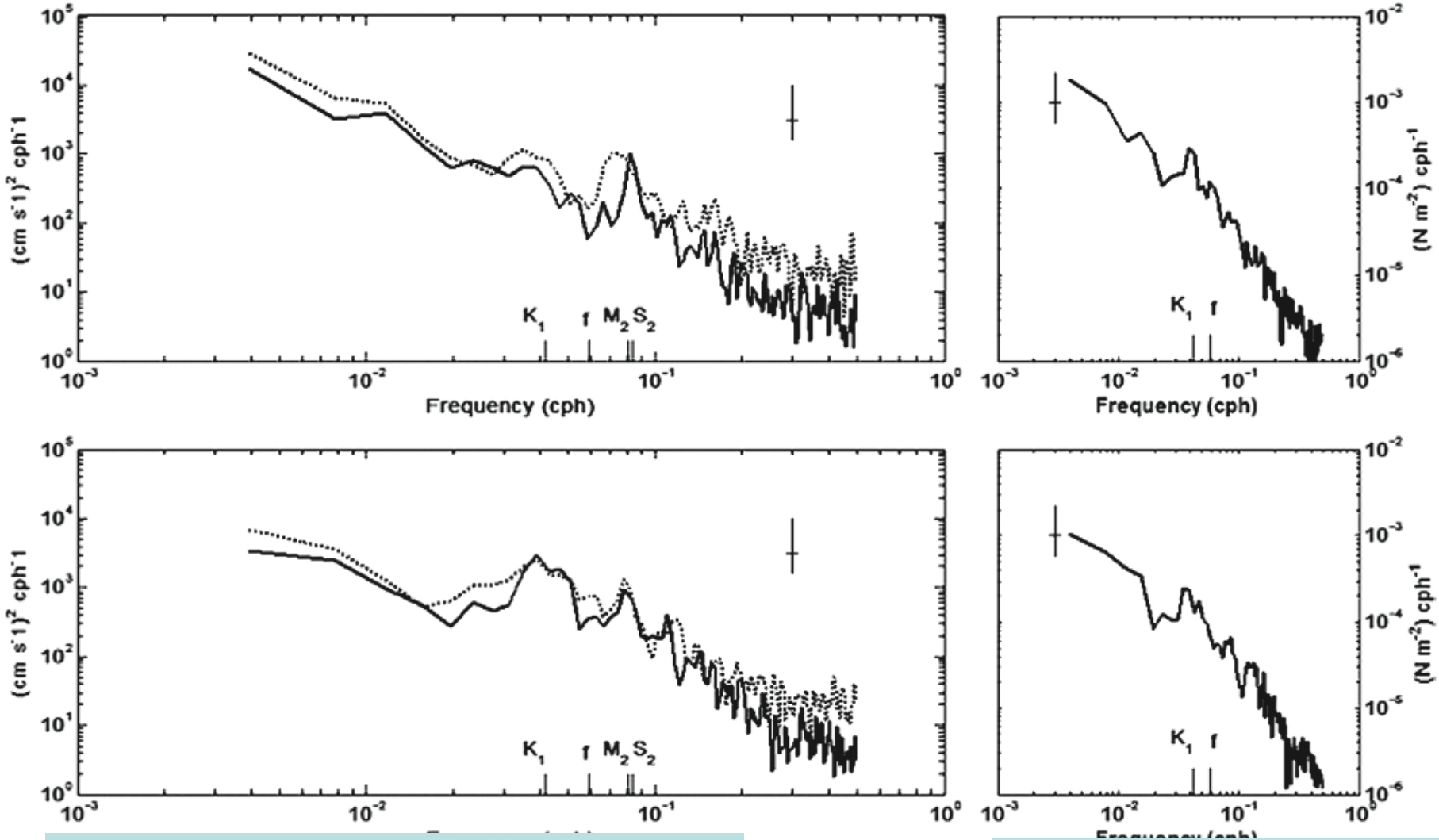
Data validation





Comparison with moored current meters shows that bearing error can be homogeneous over range !

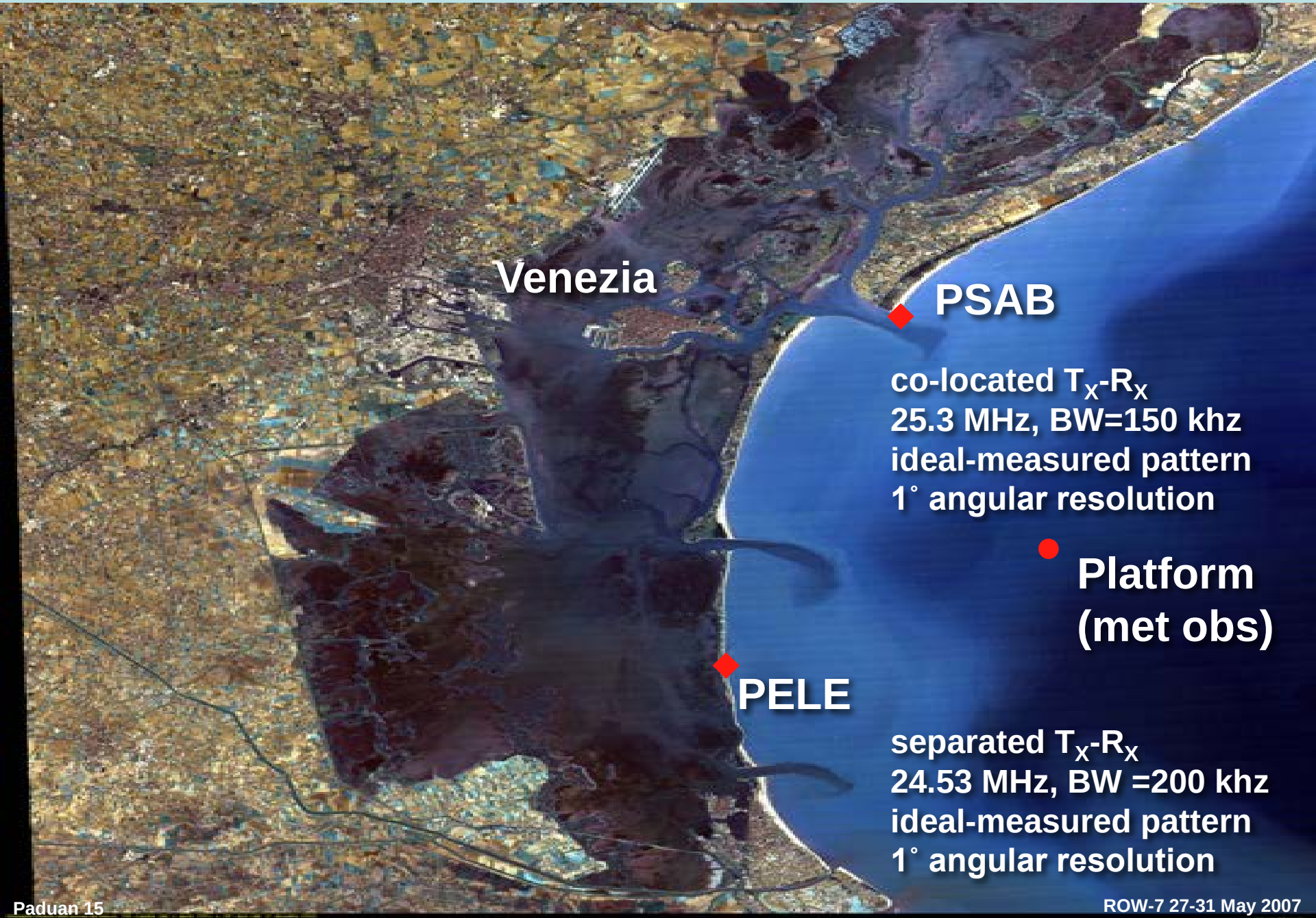
Data validation

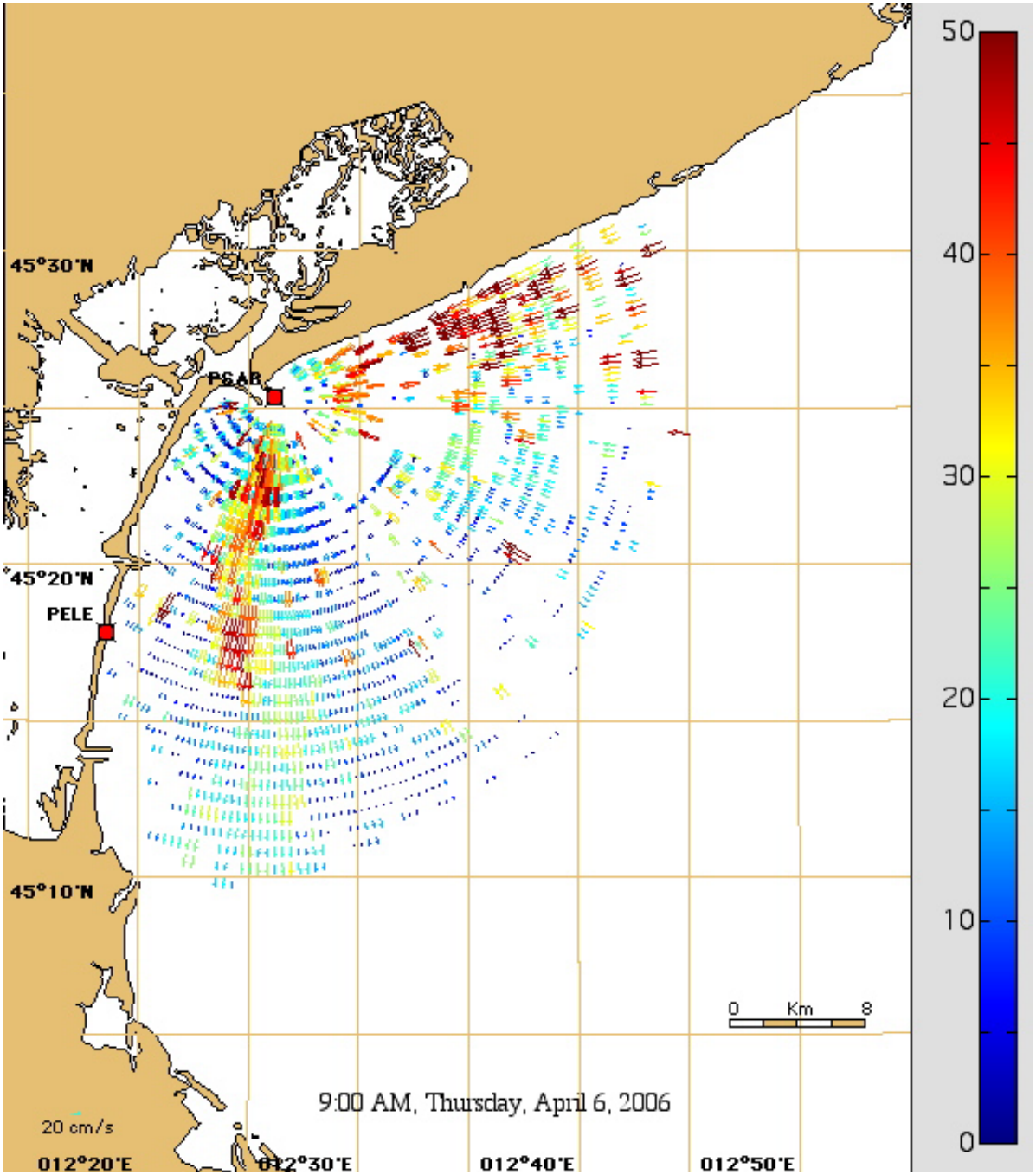


Frequency-domain analyses to compare dominant time scales: HF radars do their job in resolving current variability and dominant

Comparison with local winds to interpret sources of differences (“geophysical noise”)

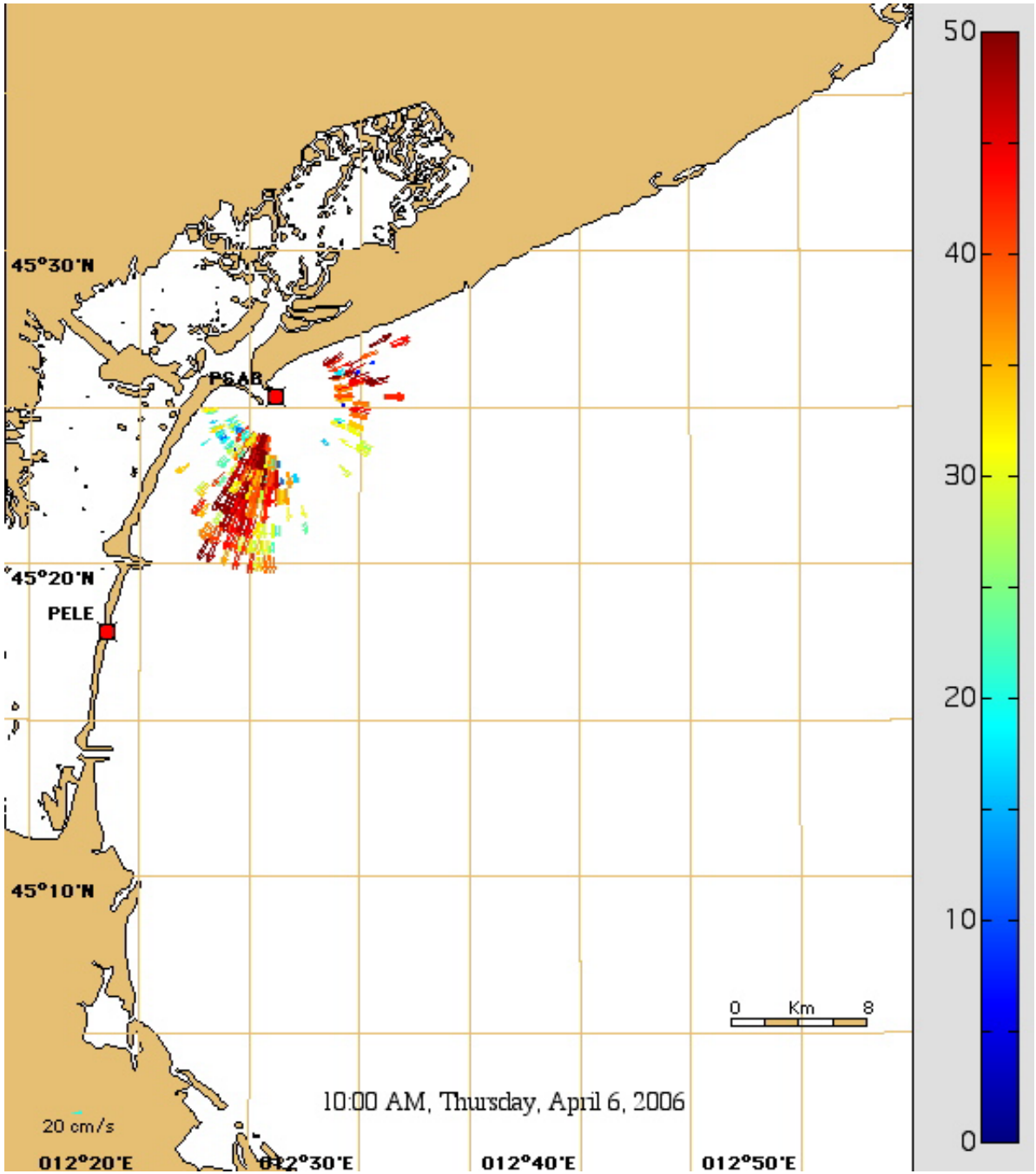
HF Noise Case Study-Venice: measurement error? Instrument limitation? Or what?





06-Apr-06 0900
Wind Speed 5 m/s

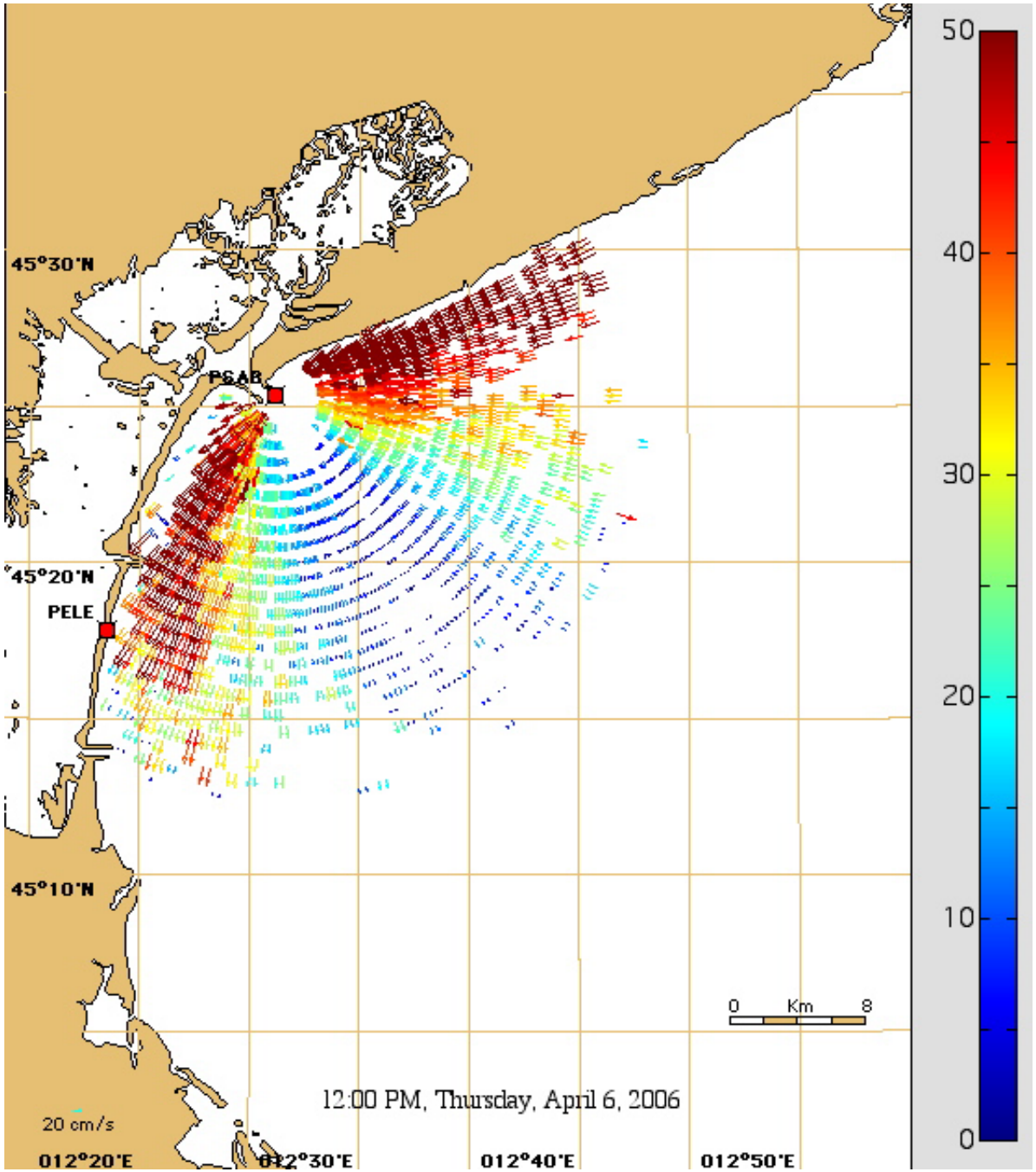
Initial coverage is very good under low wind conditions



06-Apr-06 1000
Wind Speed 20 m/s

Initial coverage is very good under low wind conditions

Wind front passage raises noise level and lowers coverage

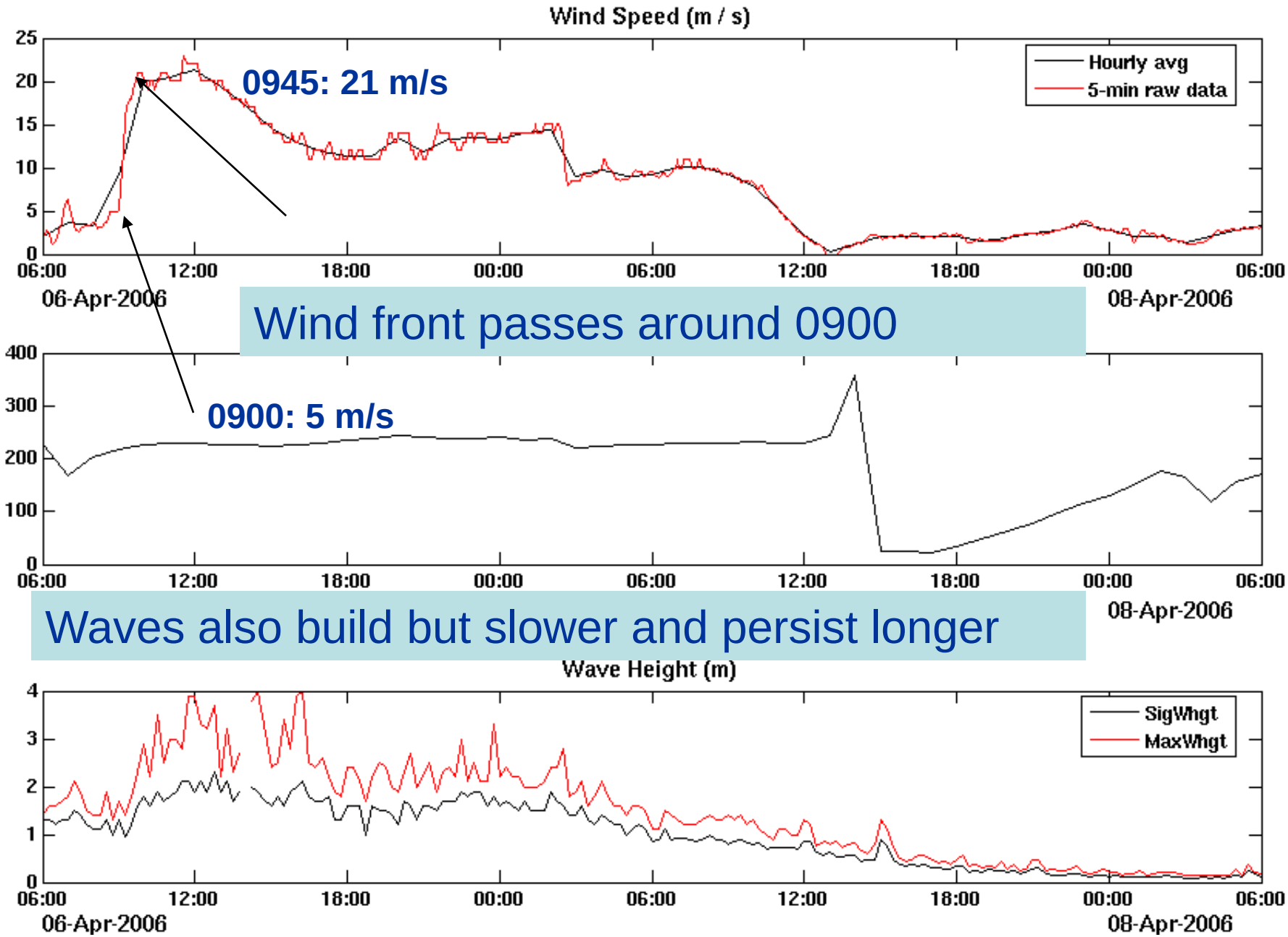


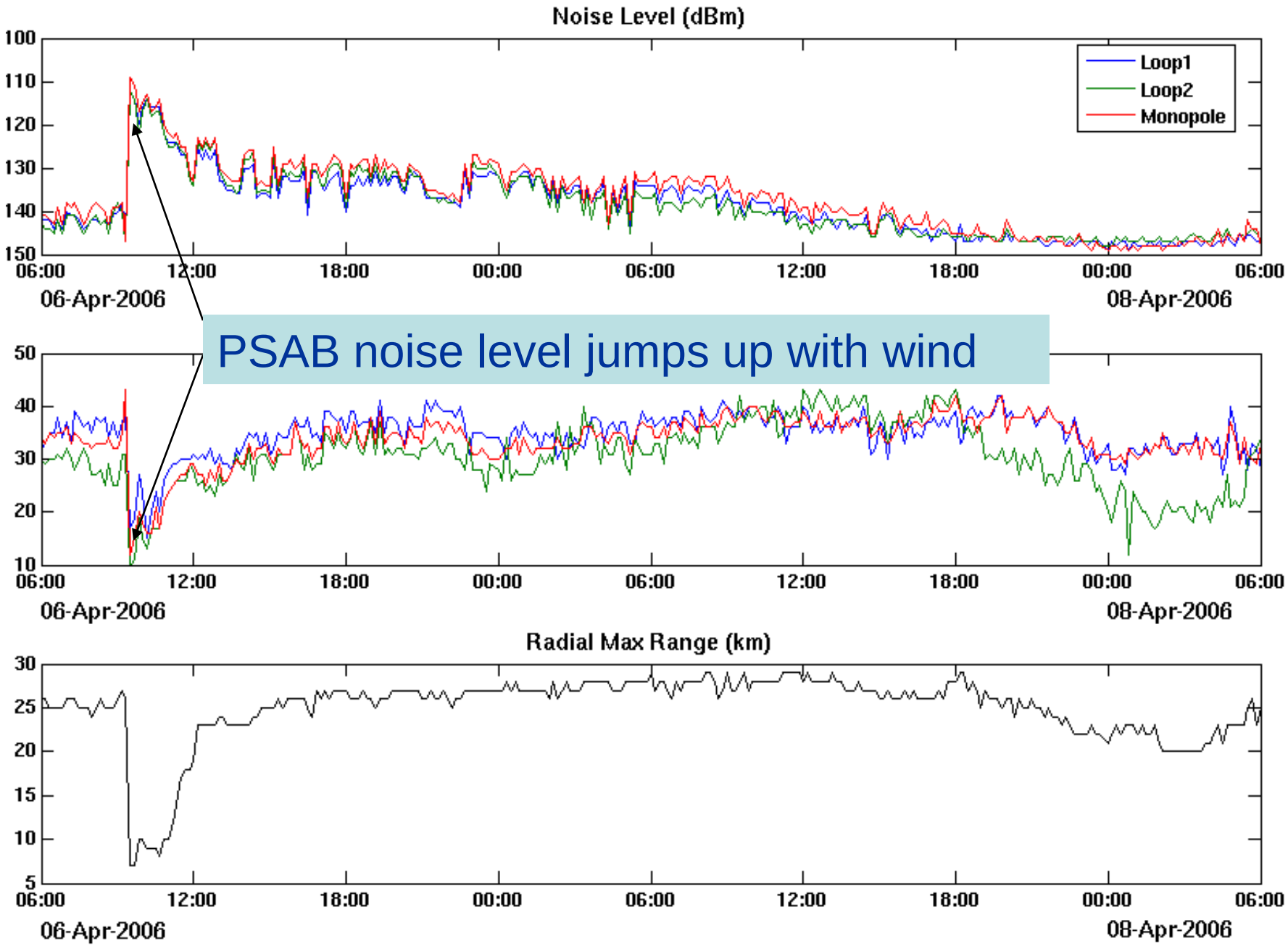
06-Apr-06 1200
Wind Speed 21 m/s

Initial coverage is very good under low wind conditions

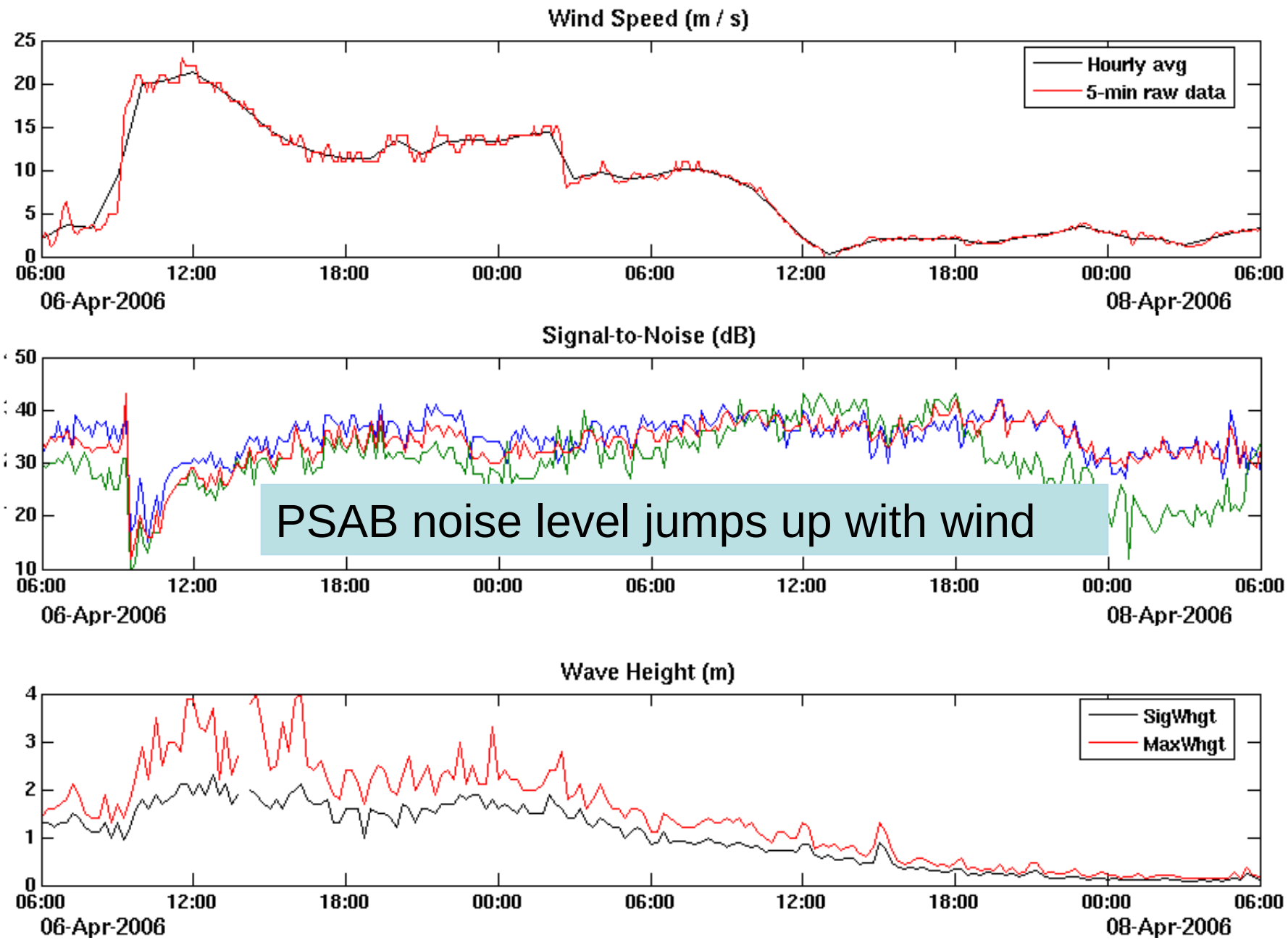
Wind front passage raises noise level and lowers coverage

Coverage returns <u>before</u> wind dies


Wind Speed (m / s)
Hourly avg
5-min raw data
0945: 21 m/s
0900: 5 m/s
06:00
12:00
18:00
00:00
06:00
06-Apr-2006
08-Apr-2006
Wind front passes around 0900
Waves also build but slower and persist longer
Wave Height (m)
SigWhgt
MaxWhgt



PSAB noise level jumps up with wind



PSAB noise level jumps up with wind

Known and Unknown Sources of Errors, Spikes and Bias

- Hardware:
  - Cables, connectors, amplifiers, power supply, ….
  - Interferences: navigation radars, CB or radioamateur broadcasters (Venice; Istria; Slovenia); ionospheric noise

- Software:
  - *First-Order Settings* (user selectable) – may introduce spurious signals
  - Failure in ship *detection-and-removal* algorithm

- Geophysical "noise":
  - Sampling strategies (space - time)
  - Unresolved physical processes occurring at sub-grid spacing scale

- Total vector computation: *LS* method itself introduces a bias, proportional to the current field[1,2]

[1] *S. Cosoli, Bolzon G., 2008. The NASCUM Project: A Near-Real Time Surface Currents Monitoring Network in the Northern Adriatic Sea,* EGU Assembly

[2] *S. Cosoli, Bolzon G., 2011* **Simulation-based error estimates in LS-fit surface currents from High-Frequency (HF) radars, in preparation**

Data Despiking Approaches and Techniques

- Quality control Recommendations[1]:

  - Radial vector level (Level-1 QAQC):
    - SNR, 1st order peak and Bragg Region, single VS dual angle solution (DF), eigenvalue (DF)

  - Total vector level (Level-2 QAQC)
    - Misfit Error; GDOP; radial contribution from individual sites

[1] *Quality Assurance of Real-Time Oceanographic Data (QARTOD)* - http://www.qartod.org

- Usually performed at Total Vector level:

  - Statistical properties of the time series of currents (&/OR their 1st – 2nd derivatives) for each grid point define spike thresholding criteria

  - Anomalous data removed if some thresholding criteria is not satisfied
    e.g. $U_i = (u_i, v_i)$ Spike if MAD < 3σ

  - Interpolation of despiked data set

Level-1 Quality control procedures @ OGS: snrqaqc

- Signal-to-noise ratio qaqc[1] approach on radial maps (Level-1 qaqc)

  Key assumption: snr controls DOA accuracy and sets errors on radial velocities (magnitude and bearing)

  - Inverse approach: determination of snr values for the doppler lines that define the hourly radial velocity at each (R,θ) pair – *NOT trivial but not impossible*
  - Discrimination of true "signal" vs "spike" based on statistical properties of the background noise level
  - Radial Velocities weighted by their spectral strength and spectral quality

[1]*Cosoli S. and Bolzon G., Real-time and offline signal-to-noise ratio quality control for SeaSonde® HF radars, submitted*

  - Coverage improved without interpolation over bearing, range, or both
  - Despiking at total vector level is minimized
  - High quality radial maps for real-time / offline data assimilation
  - Output fully compatible with proprietary software

Level-1 Quality control procedures @ OGS: snrqaqc

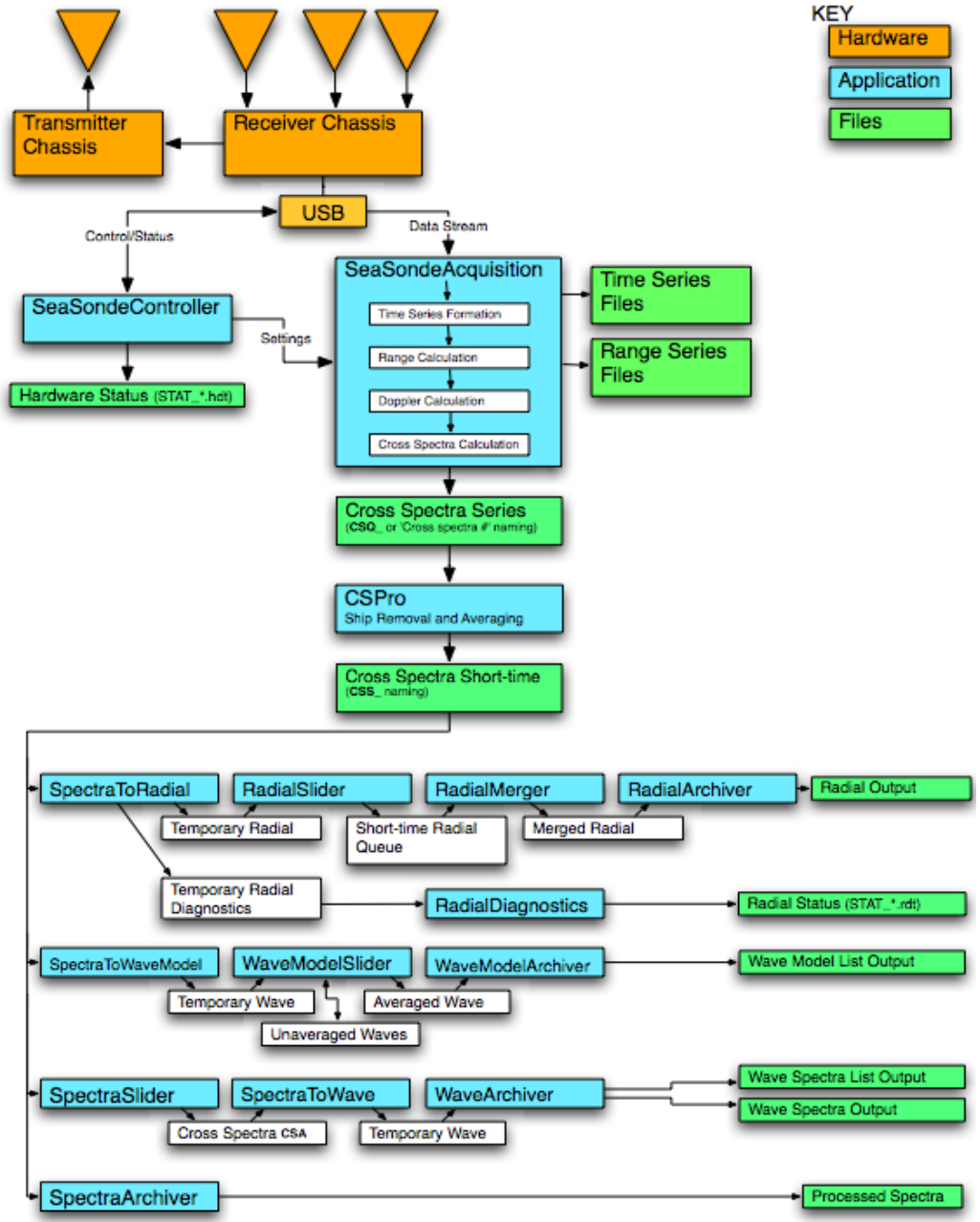
snrQAQC definition of (hourly) radial velocity:

v_1	snr_1
v_2	snr_2
…	…
v_n	snr_n

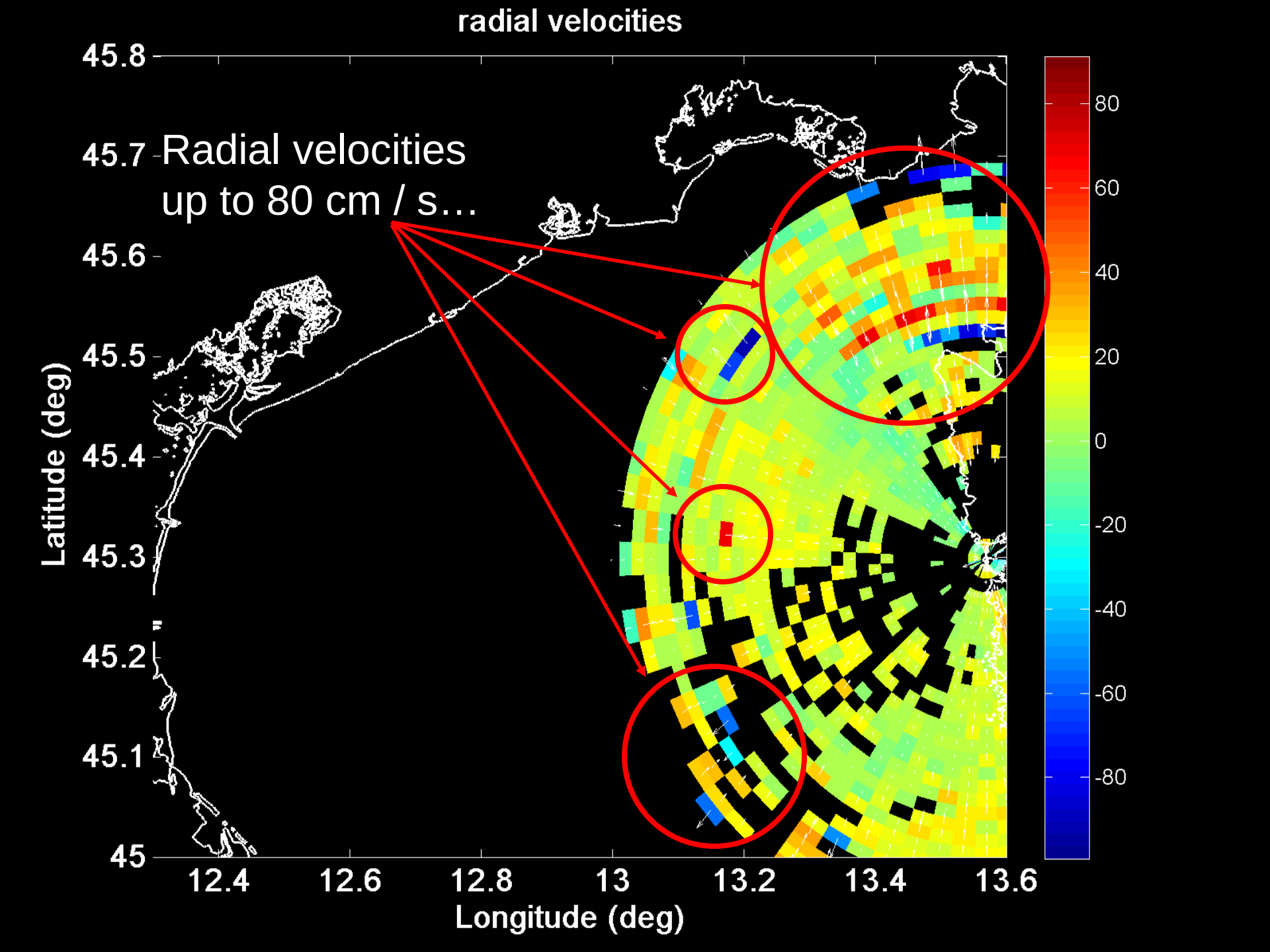
$$v_i(R,\theta) = \frac{\sum_i v_i \cdot snr_i}{\sum_i snr_i}$$

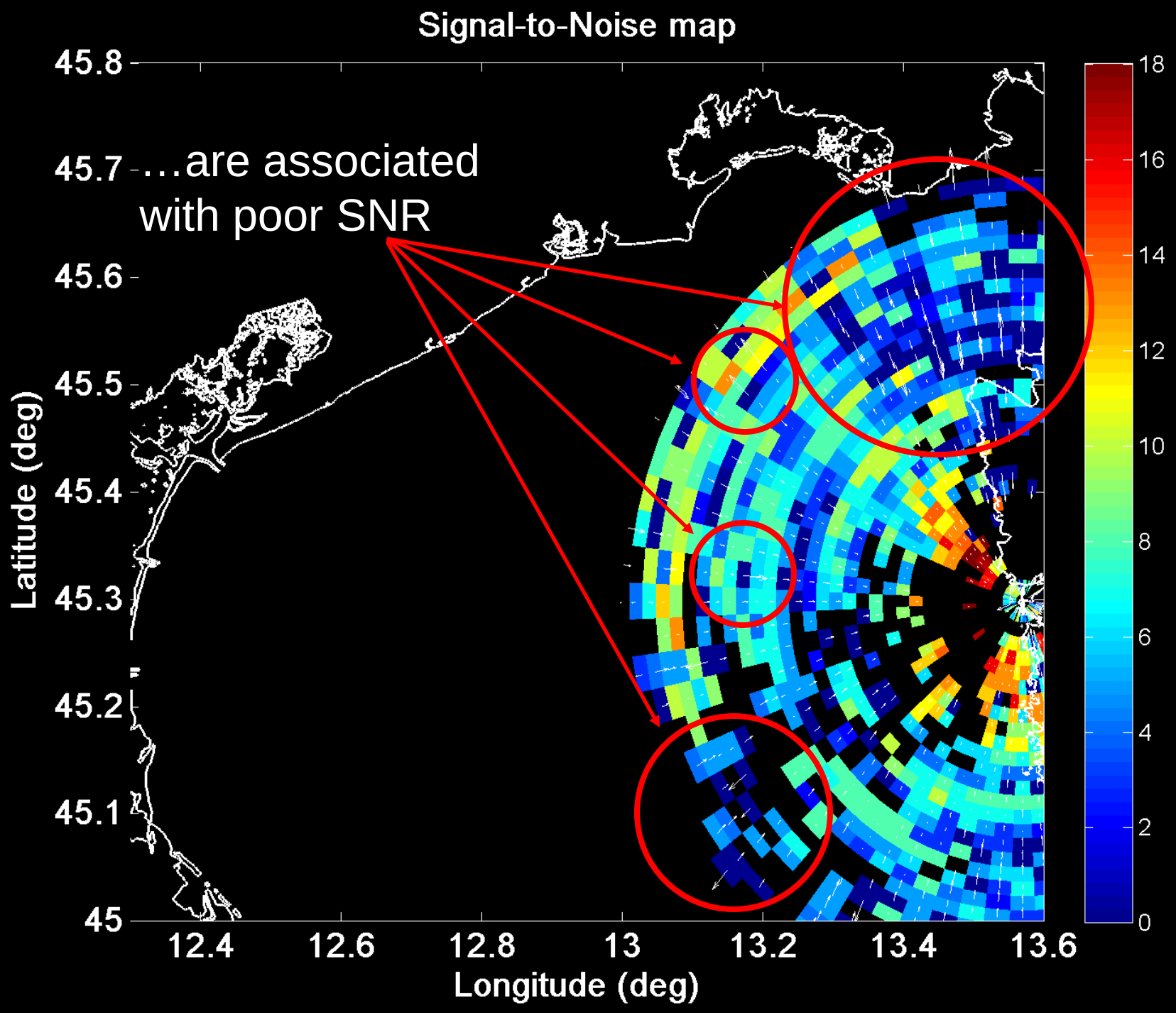
Hourly velocities at each (R,t) are obtained as ***average*** of Doppler velocities ***weighted*** with their *snr*' s

Data Acquisition and Processing scheme for SeaSonde systems

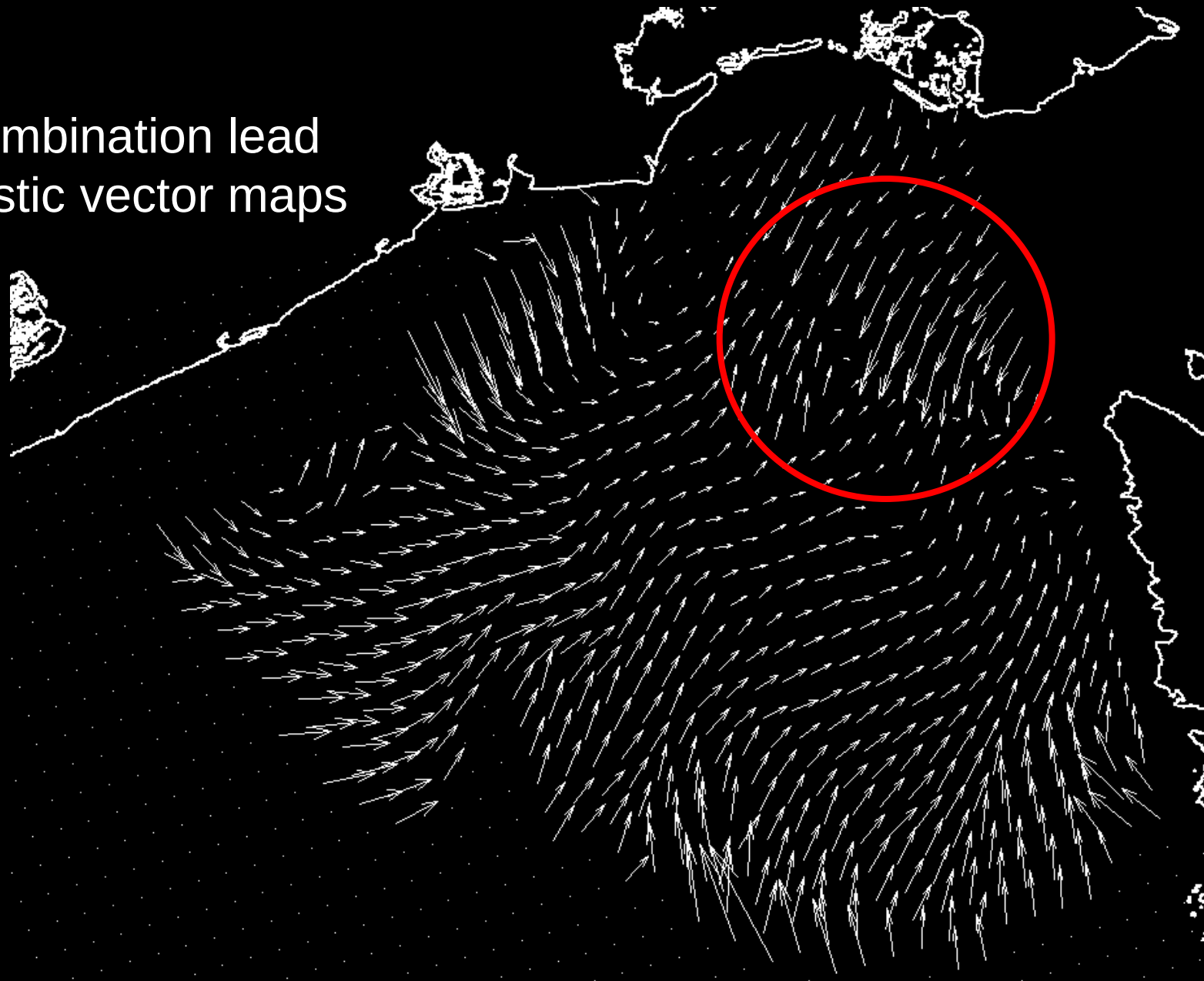


- Voltage t.s. collected every 256s
- 1st *fft* processing gives *Range* -- 2nd *fft* gives *speed*
- Creation of *short-term voltage cross-spectra*
- Every 10 minutes:
  - *short-term radial* maps through *MUSIC;*
  - *System diagnostics*
- Every hour:
  - *merging* of short-term radials
  - creation of *hourly* radial maps
  - archiving of sensible data


radial velocities
Radial velocities
up to 80 cm / s…
45.8
45.7
45.6
45.5
45.4
45.3
45.2
45.1
45
Latitude (deg)
12.4
12.6
12.8
13
13.2
13.4
13.6
Longitude (deg)
80
60
40
20
0
-20
-40
-60
-80


Signal-to-Noise map
…are associated
with poor SNR
Latitude (deg)
Longitude (deg)
45.8
45.7
45.6
45.5
45.4
45.3
45.2
45.1
45
12.4
12.6
12.8
13
13.2
13.4
13.6
18
16
14
12
10
8
6
4
2
0

…their combination lead
to unrealistic vector maps
….



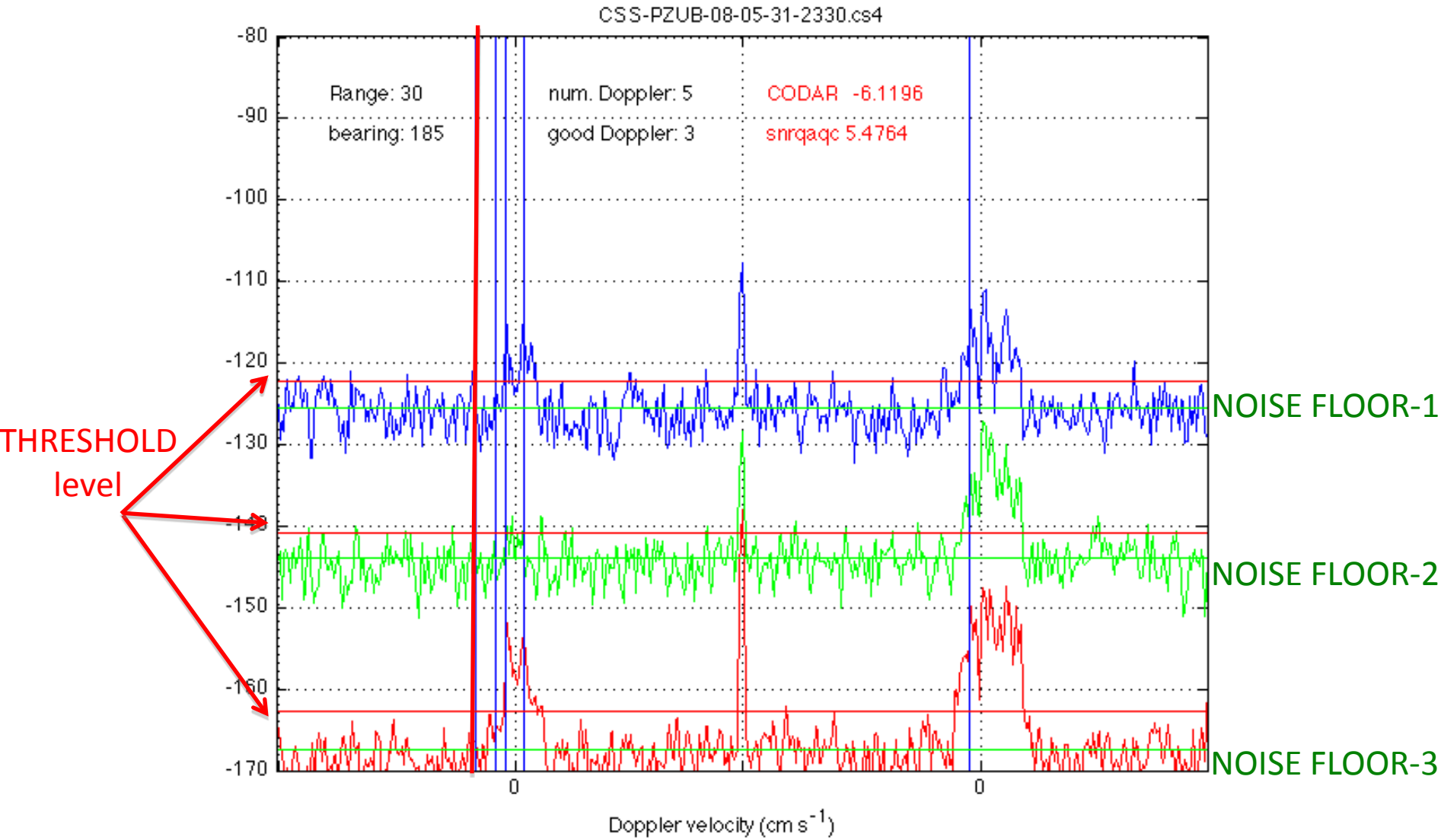
unweighted least-squares total vector map

SNR weighted least-squares total vector map

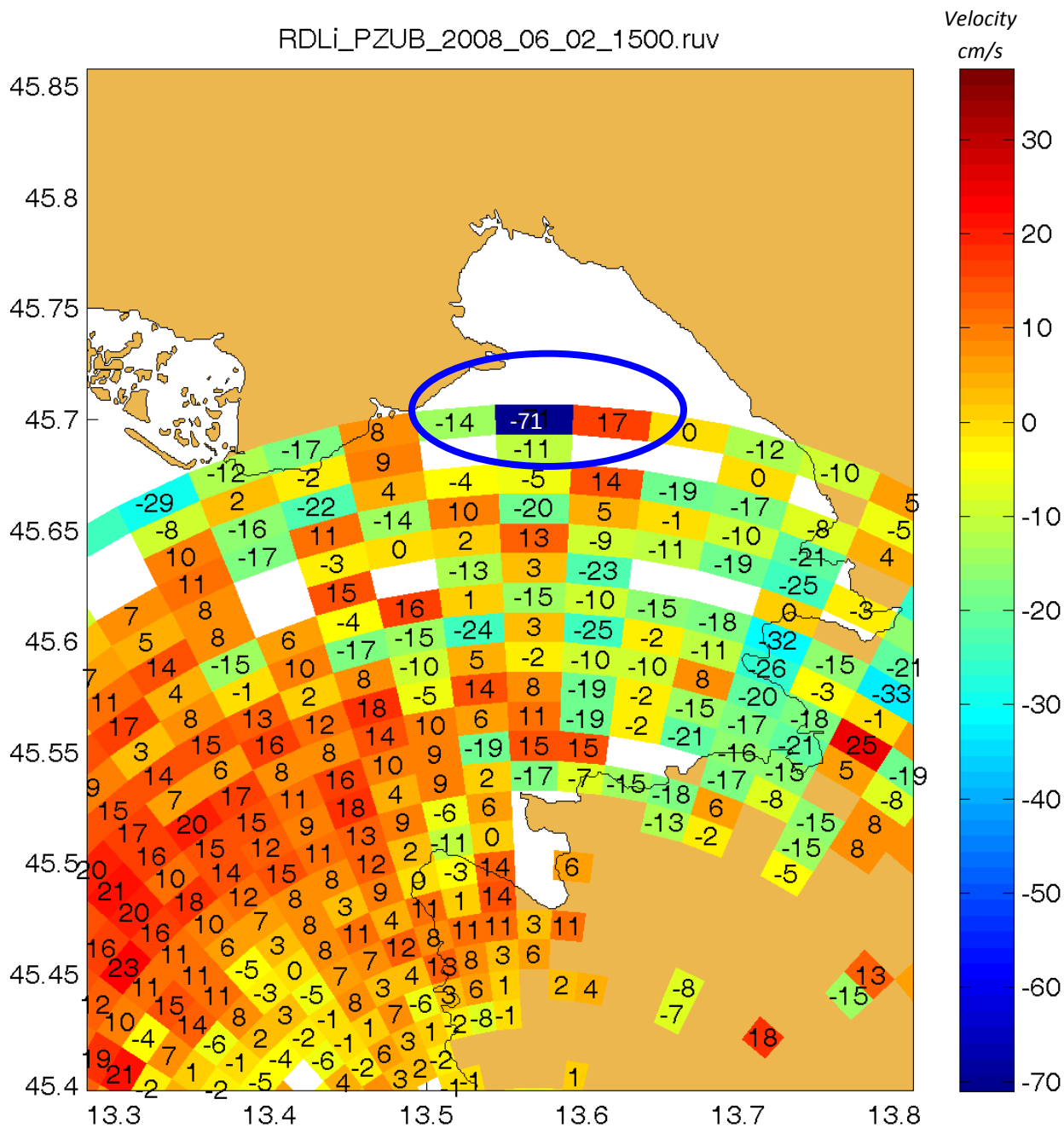
Level-1 Quality control procedures @ OGS: snrqaqc

- Some Doppler velocities have snr values < 6dB or *negative*!

snr-1 = -1.12dB snr-2 = 0.04dB snr-3 = 1.38dB Doppler line is rejected!



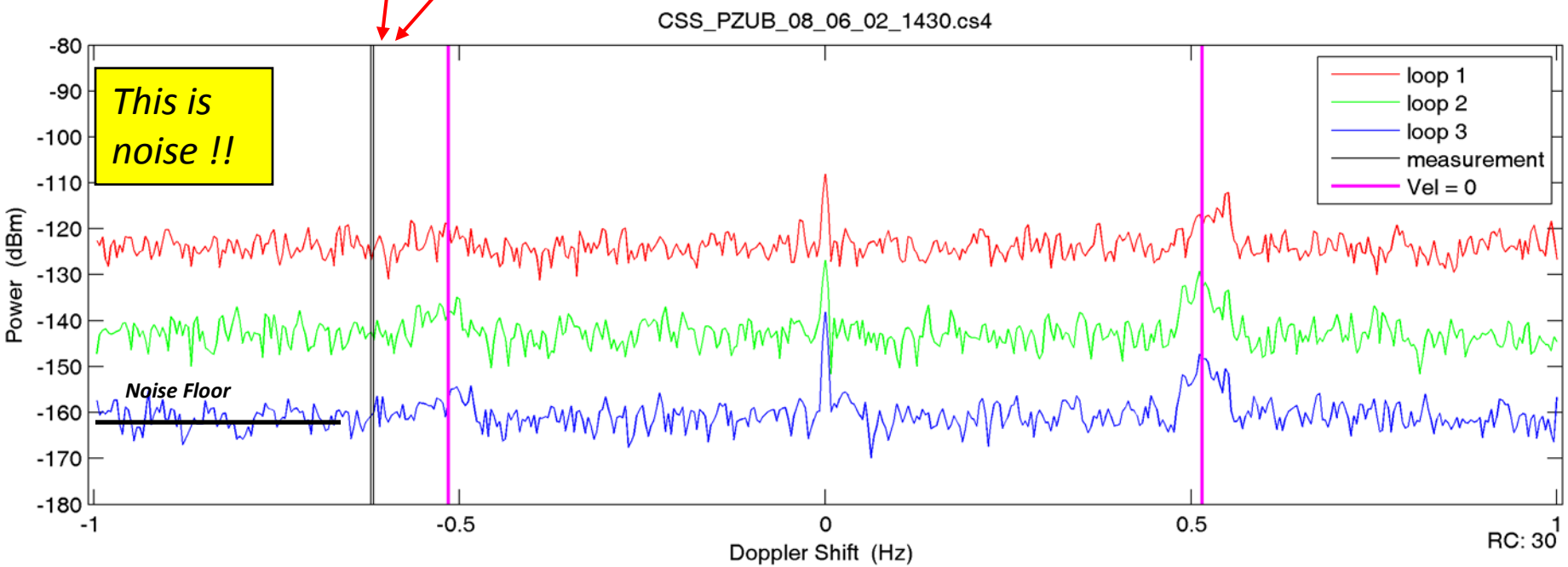
snrqaqc at work: spike removal



Cell=30
Bear=0

Who is responsible for that?

	02/06/2008 1430		02/06/2008 1440
	- 60.11 cm/s		- 81.93 cm/s
	2 Doppler lines		1 Doppler line
	- 61.225 cm/s	- 58.958 cm/s	- 81.930 cm/s
Doppler BIN	- 27	- 26	- 36
SNR	0.14	1.04	



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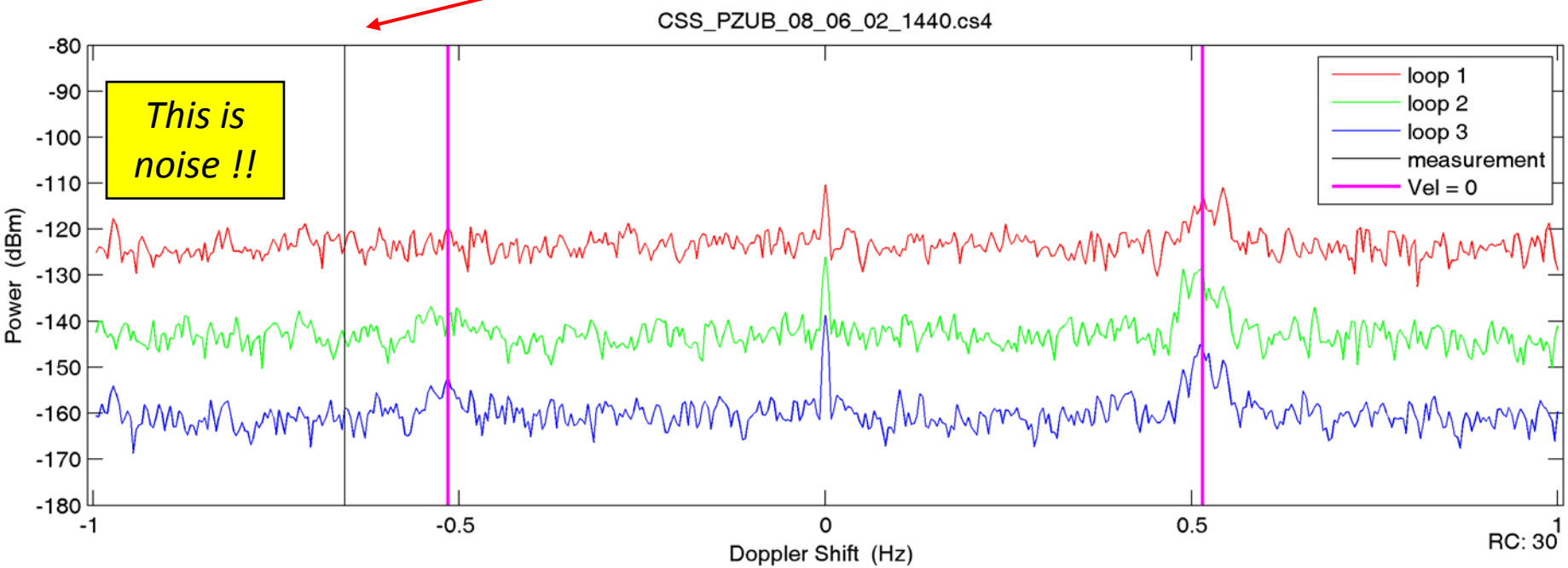
Doppler BIN	- 27	- 26	- 36
SNR	0.14	1.04	2.03



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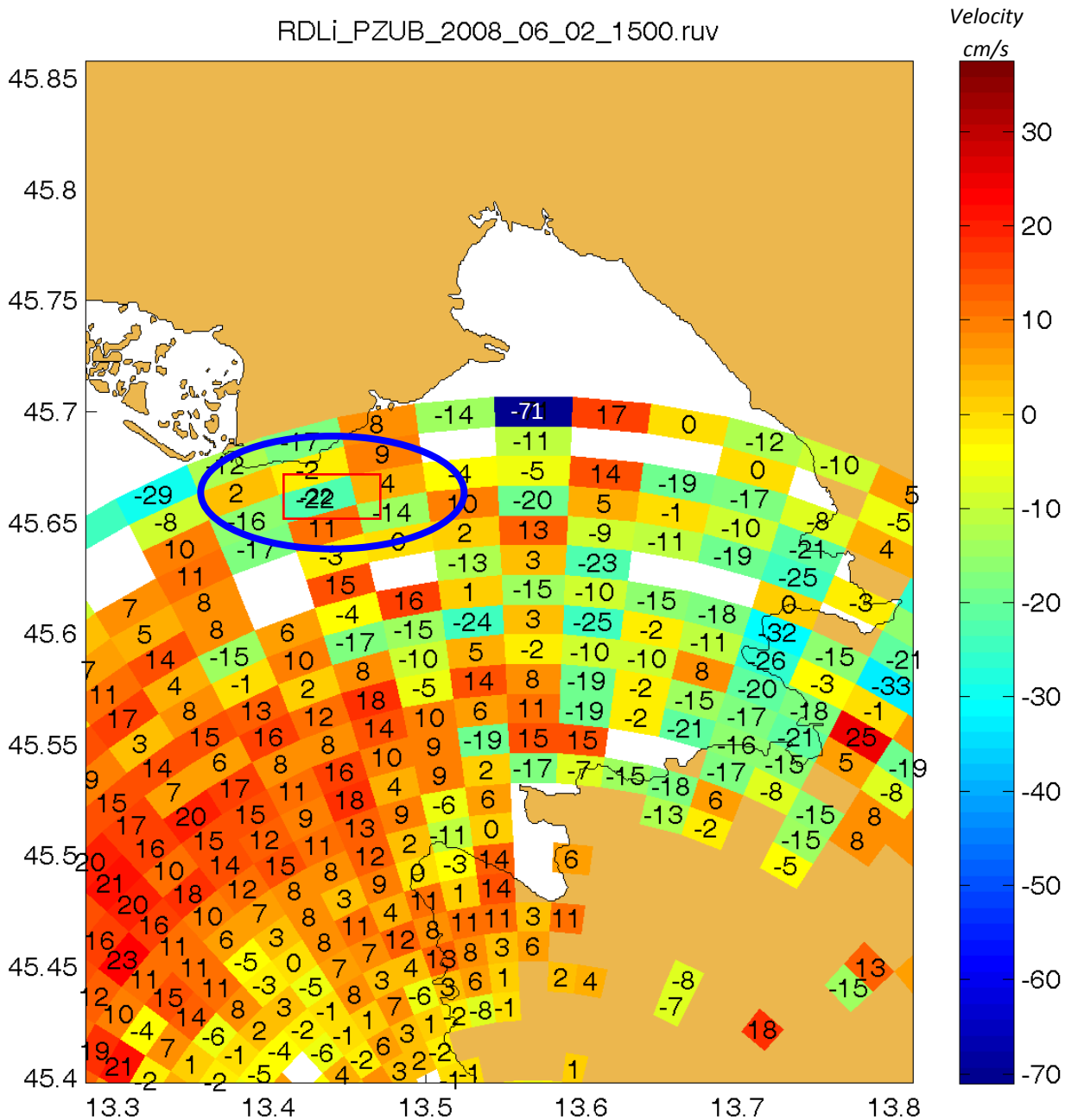
Doppler BIN	- 27	- 26	- 36
SNR	0.14	1.04	2.03

snrQAQC method :

SNR below Signal-to-Noise threshold

v=-71 cm/s is rejected

snrQaQc at work: the “hidden” spike



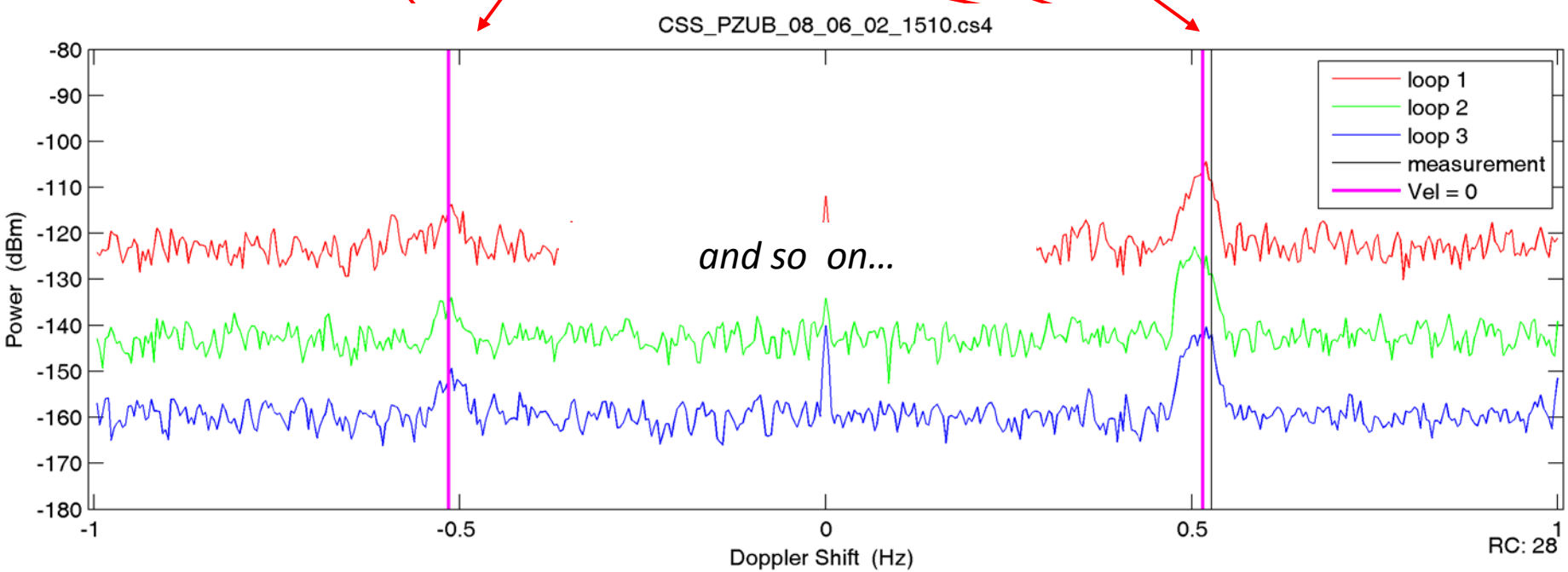
Cell=28

Bear=345

Who is responsible for that?

02/06/2008 1430		02/06/2008 1500		02/06/2008 1510	02/06/2008 1520	02/06/2008 1530
- 31.01 cm/s		- 16.08 cm/s		6.12 cm/s	-22.20 cm/s	- 24.50 cm/s
2 measurements		2 measurements		1 measurement	1 measurement	1 measurement
- 60.497	- 1.527	- 42.12	+ 9.95	+ 6.12	-22.20	-24.50
Doppler BIN						
-26	- 1	- 18	4	3	-10	-11

02/06/2008 1430		02/06/2008 1500		02/06/2008 1510	02/06/2008 1520	02/06/2008 1530
- 31.01 cm/s		- 16.08 cm/s		6.12 cm/s	-22.20 cm/s	- 24.50 cm/s
2 measurements		2 measurements		1 measurement	1 measurement	1 measurement
- 60.497	- 1.527	- 42.12	+ 9.95	+ 6.12	-22.20	-24.50
Doppler BIN						
-26	- 1	- 18	4	3	-10	-11
SNR						
-1.29	8.08	-1.82	9.02	17.44	1.30	-1.39



02/06/2008 1430		02/06/2008 1500		02/06/2008 1510	02/06/2008 1520	02/06/2008 1530
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Doppler BIN						
-26	- 1	- 18	4	3	-10	-11
SNR						
-1.29	8.08	-1.82	9.02	17.44	1.30	-1.39

Standard merging method: the median of averages

Result :-22.20 cm/s

02/06/2008 1430		02/06/2008 1500		02/06/2008 1510	02/06/2008 1520	02/06/2008 1530
- 31.01 cm/s		- 16.08 cm/s		6.12 cm/s	-22.20 cm/s	- 24.50 cm/s
2 measurements		2 measurements		1 measurement	1 measurement	1 measurement
- 60.497	- 1.527	- 42.12	+ 9.95	+ 6.12	-22.20	-24.50
Doppler BIN						
-26	- 1	- 18	4	3	-10	-11
SNR						
0	0	0	9.02	17.44	0	0

snrQAQC method : weigthed average

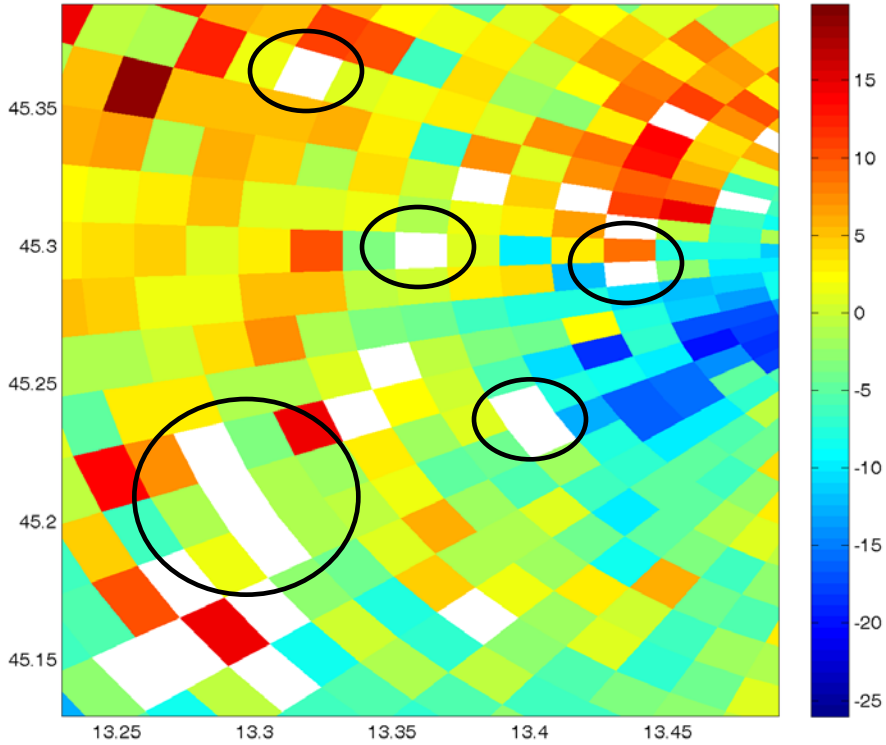
In this case… +7 cm/s

Instead of *-22 cm/s!!*

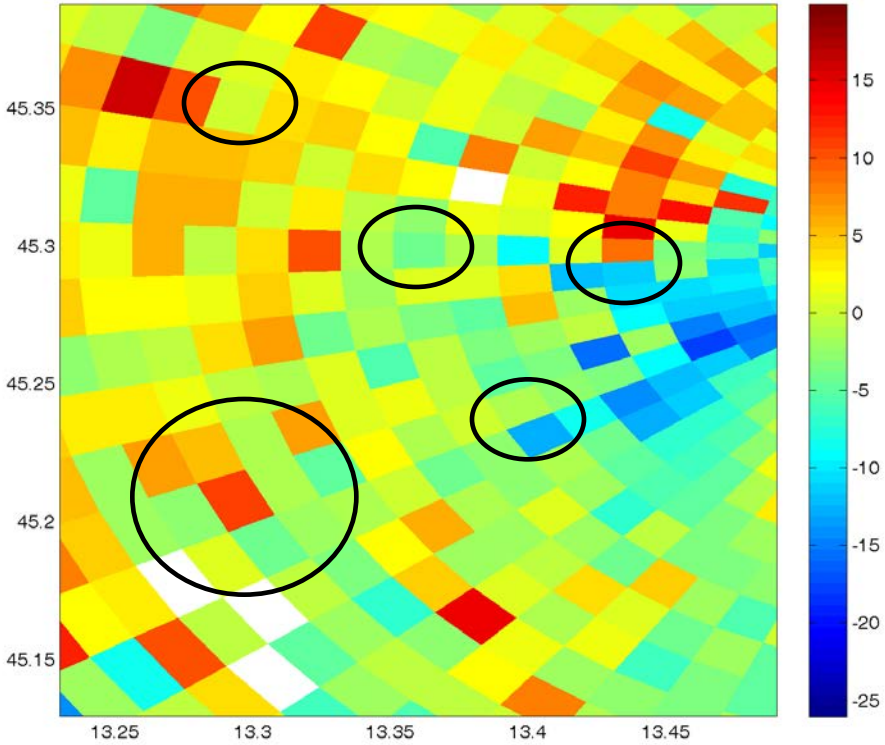
Even if statistically robust, the median approach can fail

snrQAQC at work: radial coverage improved

Proprietary software



snrQAQC approach



Increase in Radial Coverage NOT obtained through interpolation

All individual Doppler velocities are used when their SNR meet snrQAQC requirements

Level-2 Error Analysis: error on Total current vectors

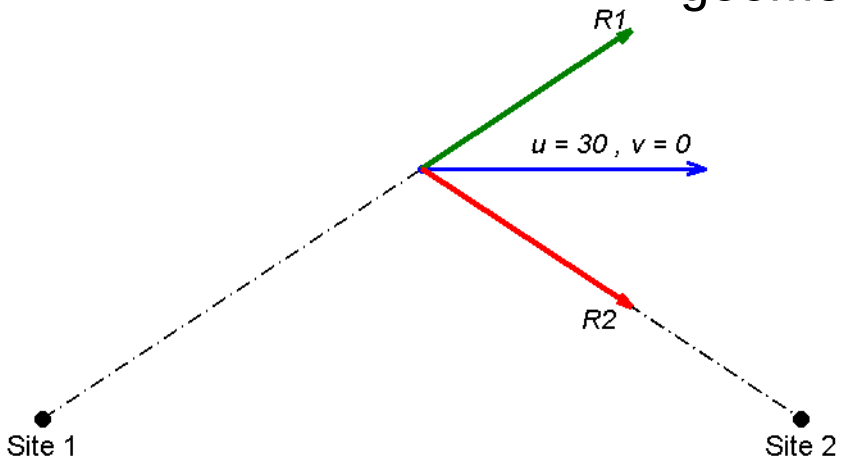
- Accuracy on surface current maps depend:
  - on radar network geometry (GDOP - GDOSA)
  - on the Least-Squares (LS) fit algorithm: introduces bias and numerical correlation
  - <u>and</u> on the (unknown) current field

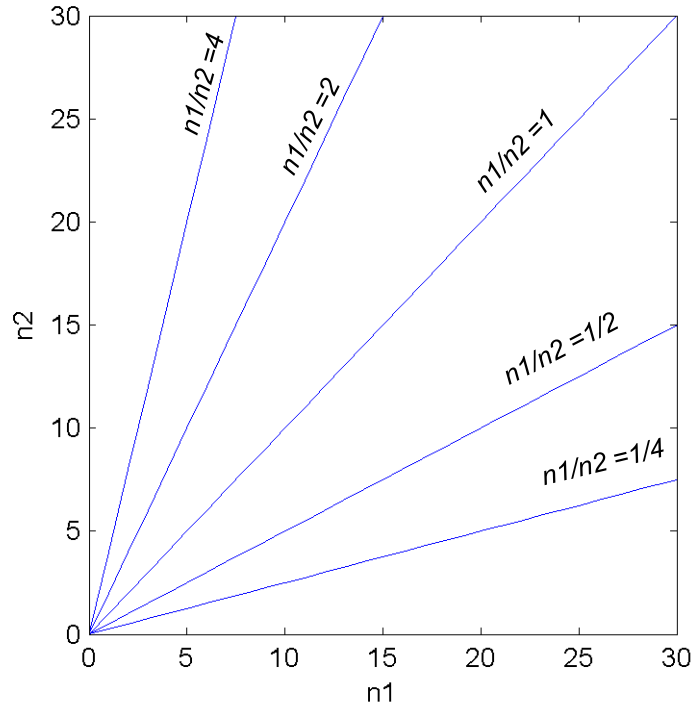
- Error analysis approach: simulation
  - Mathematical definition of the flow field
  - Decomposition into radial velocities
  - Inversion to current field (w. / w.o. perturbation)
  - Error mapping

Level-2 Error Analysis: relation to number of radial velocities

Test case: single point in the domain; zonal flow; 2 sites

geometry



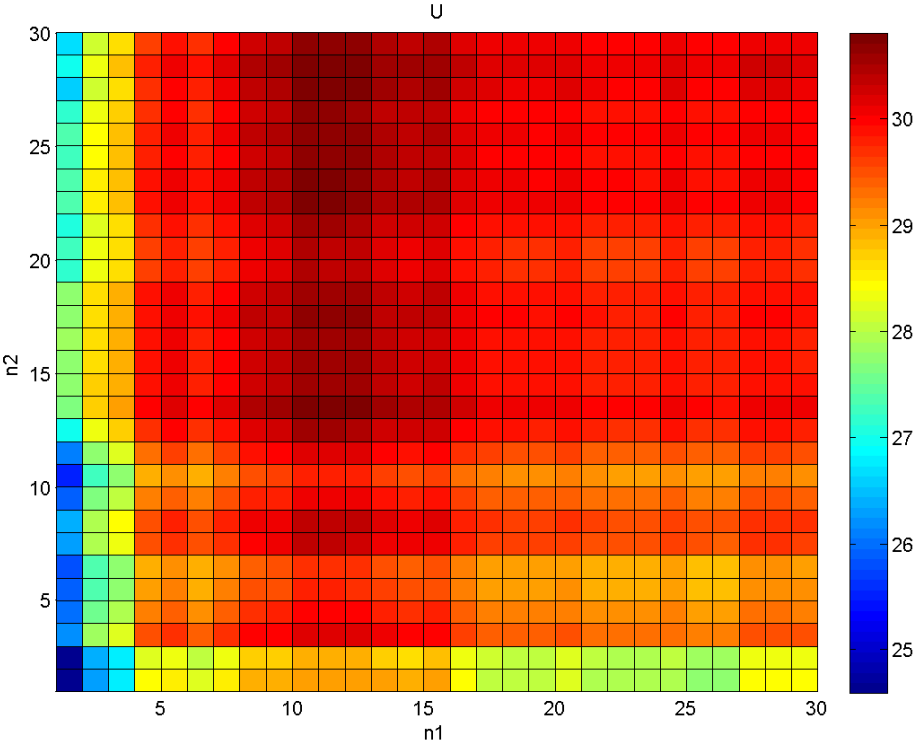


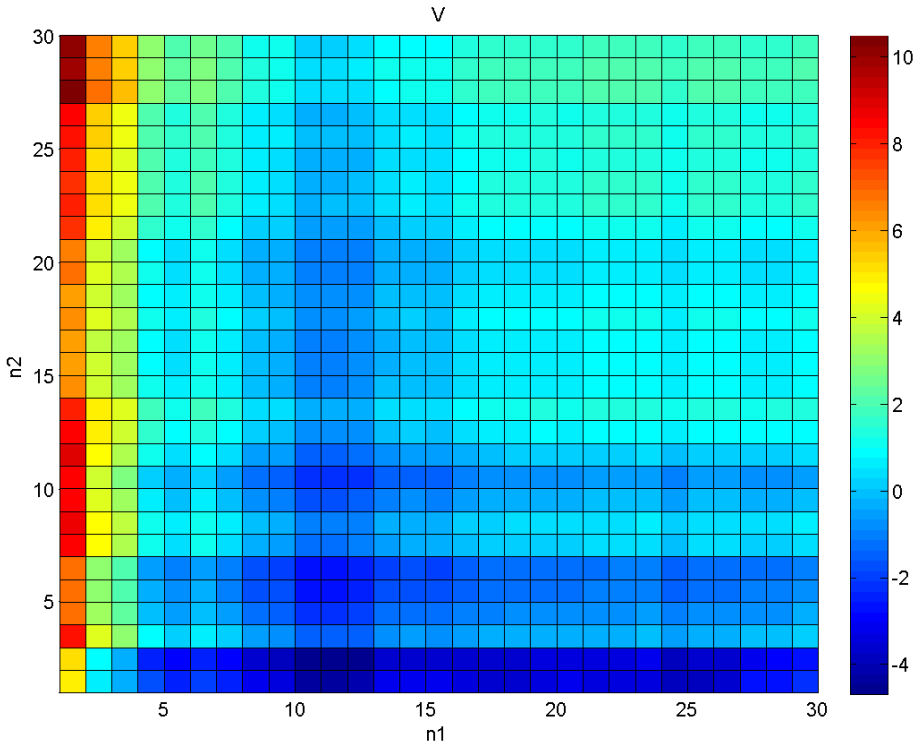
Radial current	R_1	R_1	R_1	R_1	R_1	…
			+			
Random Noise	r_1	r_2	r_3	r_4	r_5	…

Vector reconstruction

- n_1 radials from site 1, $n_1 = 1 \ldots 30$
- n_2 radials from site 2, $n_2 = 1 \ldots 30$

Level-2 Error Analysis: relation to number of radial velocities





Error is NOT $f\left(\frac{n_1}{n_2}\right)$!!

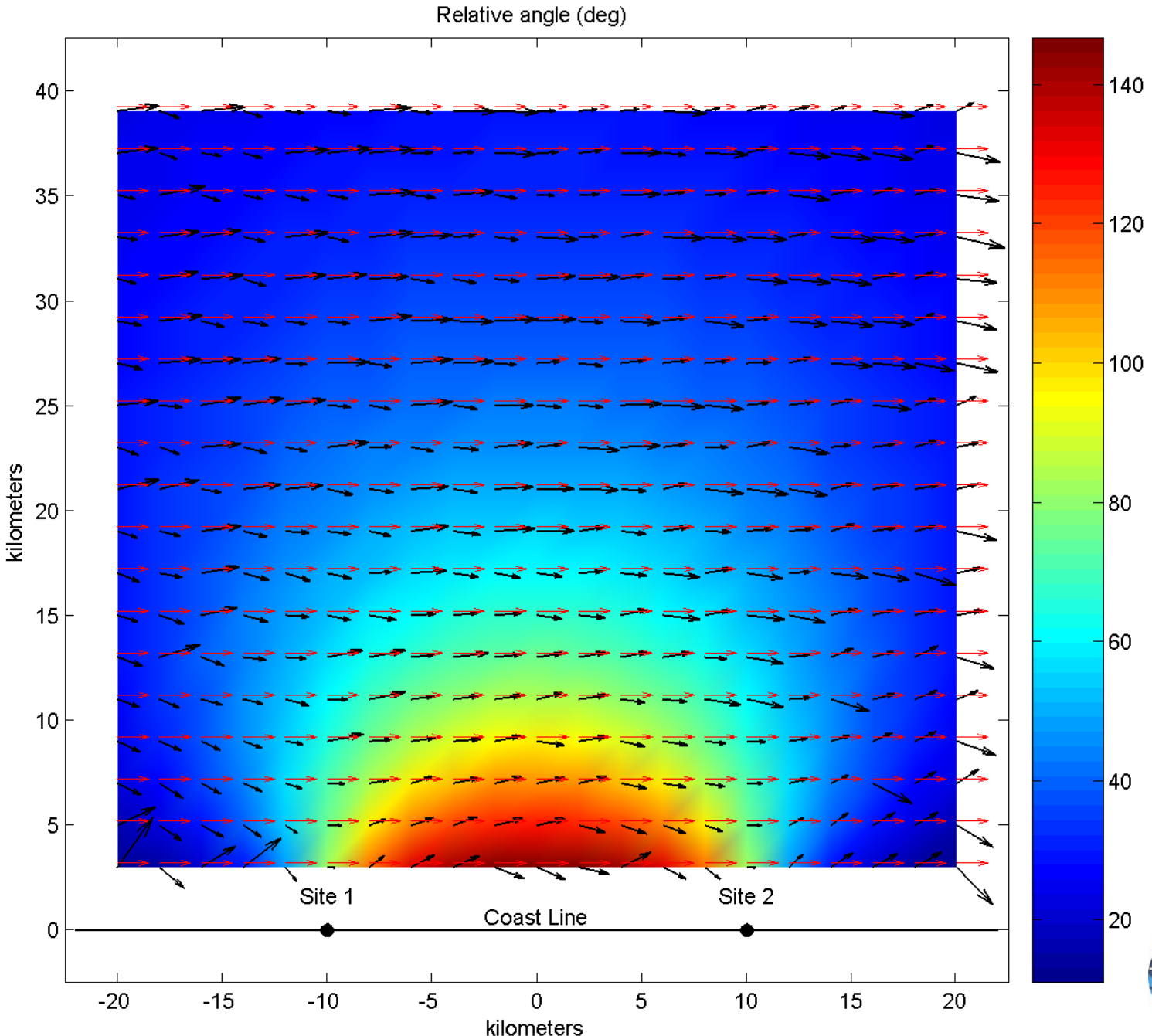
Problem when n_i (i=1,2) is low!

$n_1=1,\ n_2 >> n_1$

$n_2=1,\ n_1 >> n_2$

→ ERROR

Level-2 Error Analysis: relation to number of radial velocities



Level-2 Error Analysis: modifications to the LS fit

1) Weighted Least Squares

$$\cos\alpha_1\, u + \sin\alpha_1\, v = r_1 \qquad * W_1$$

$$\cos\alpha_2\, u + \sin\alpha_2\, v = r_2 \qquad * W_2$$

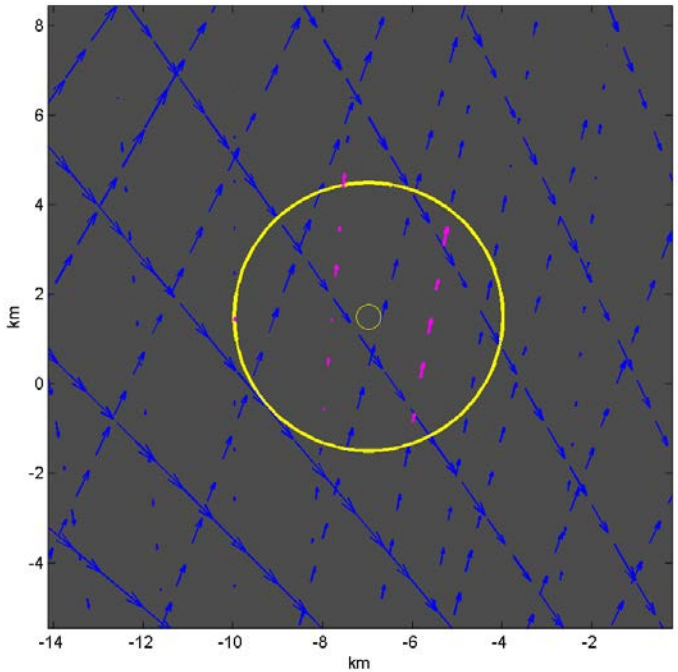
$$\cos\alpha_n\, u + \sin\alpha_n\, v = r_n \qquad * W_n$$

$$W = \frac{1}{\sigma}$$

$$W = f(d) = e^{-kd^2}$$

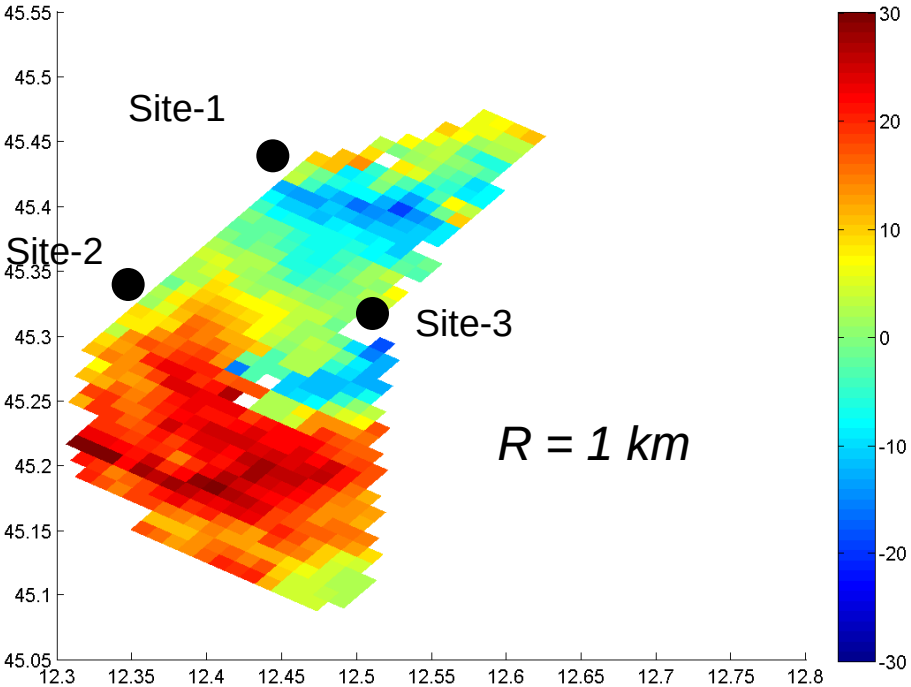
Statistical independence

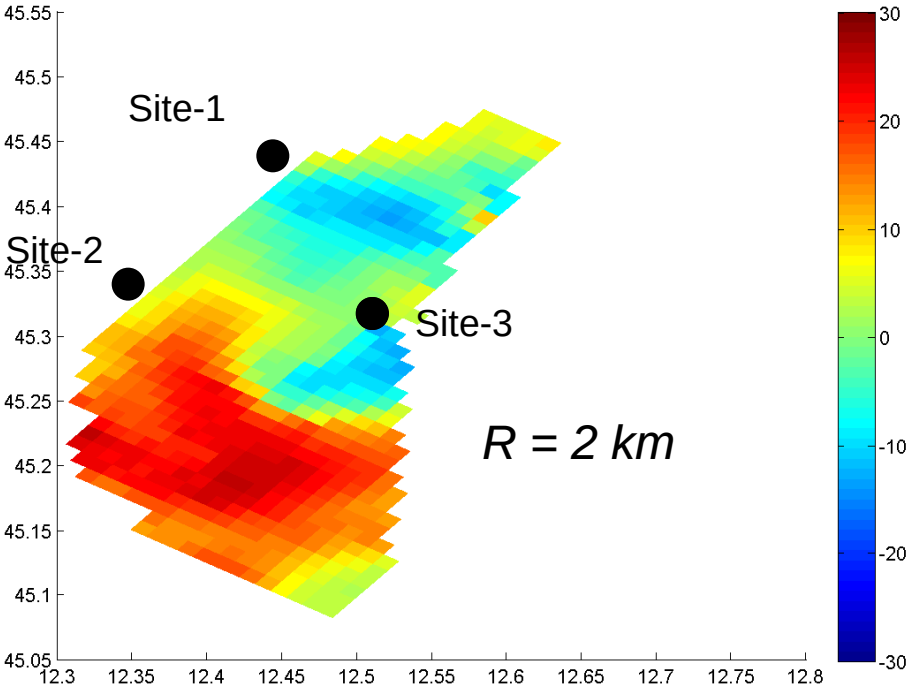
2) Mean Radial



"Exact" solution – not an overdetermined problem

Level-2 Error Analysis: modifications to the LS fit



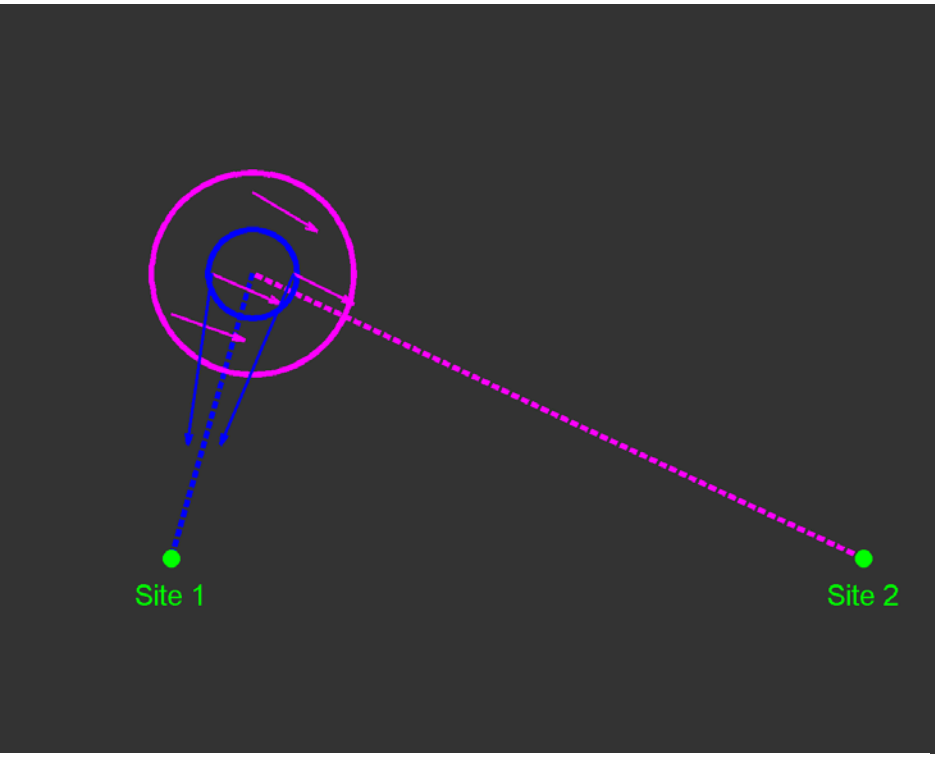


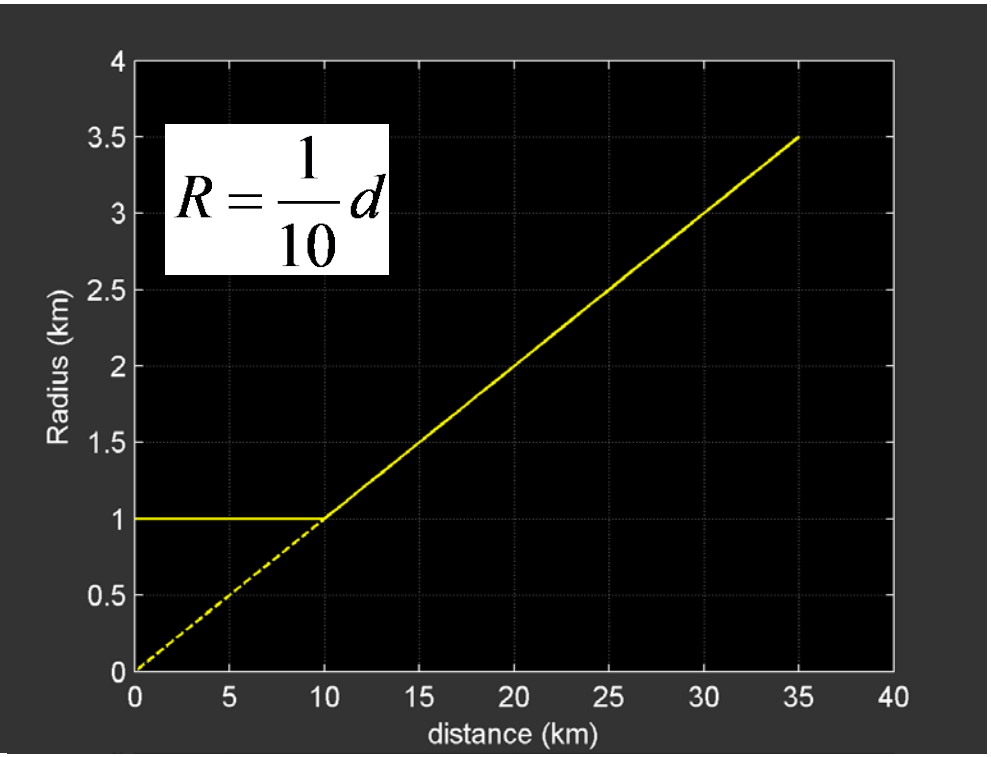
Statistical-numerical Indipendence ⟵ - ***R*** + ⟶ Smoothness

$$W = e^{-kd^2}$$

Level-2 Error Analysis: modifications to the LS fit

Modification to the LS fit: the variable search radius approach





AIM:

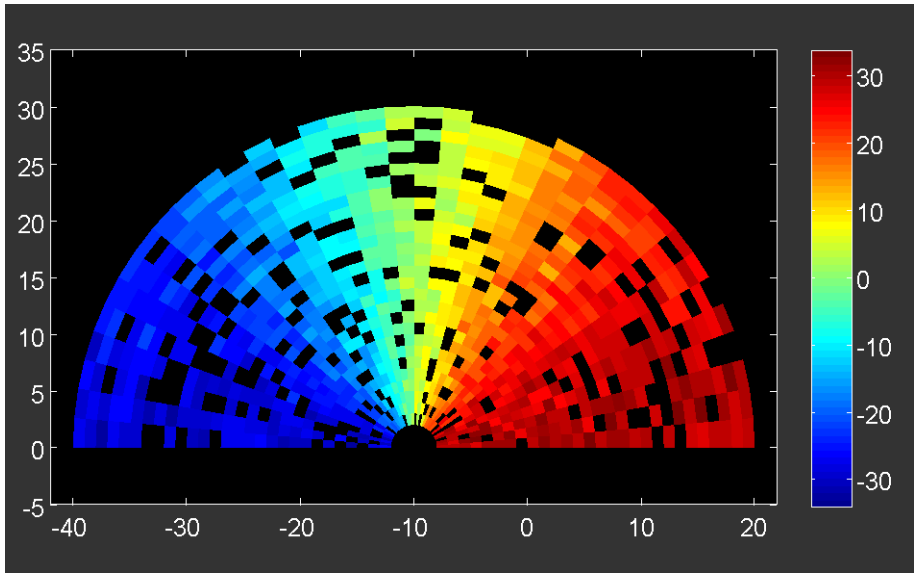
Obtain a more uniform response in the radar domain as for:

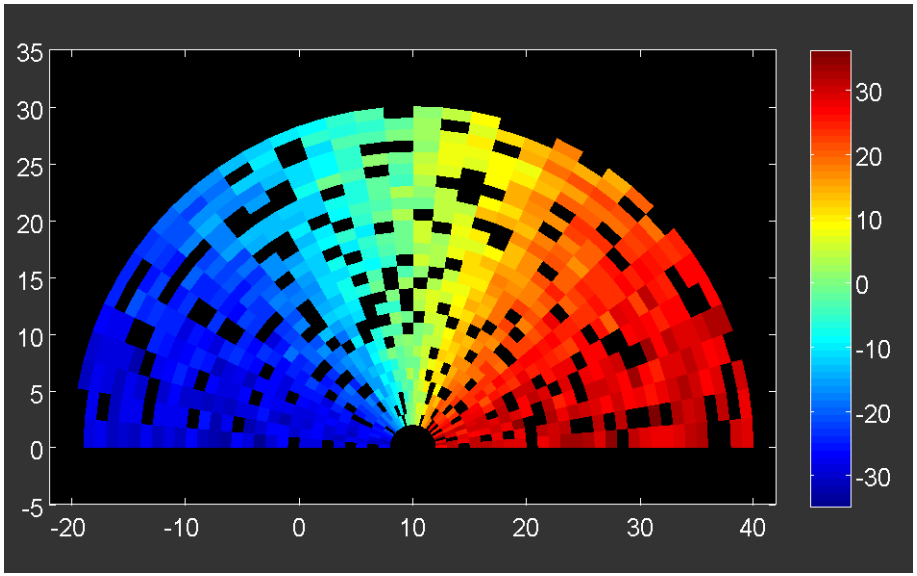
- amount of radials from each site
- angular spread

$\Longrightarrow R = f(d)$

Level-2 Error Analysis: Zonal flow

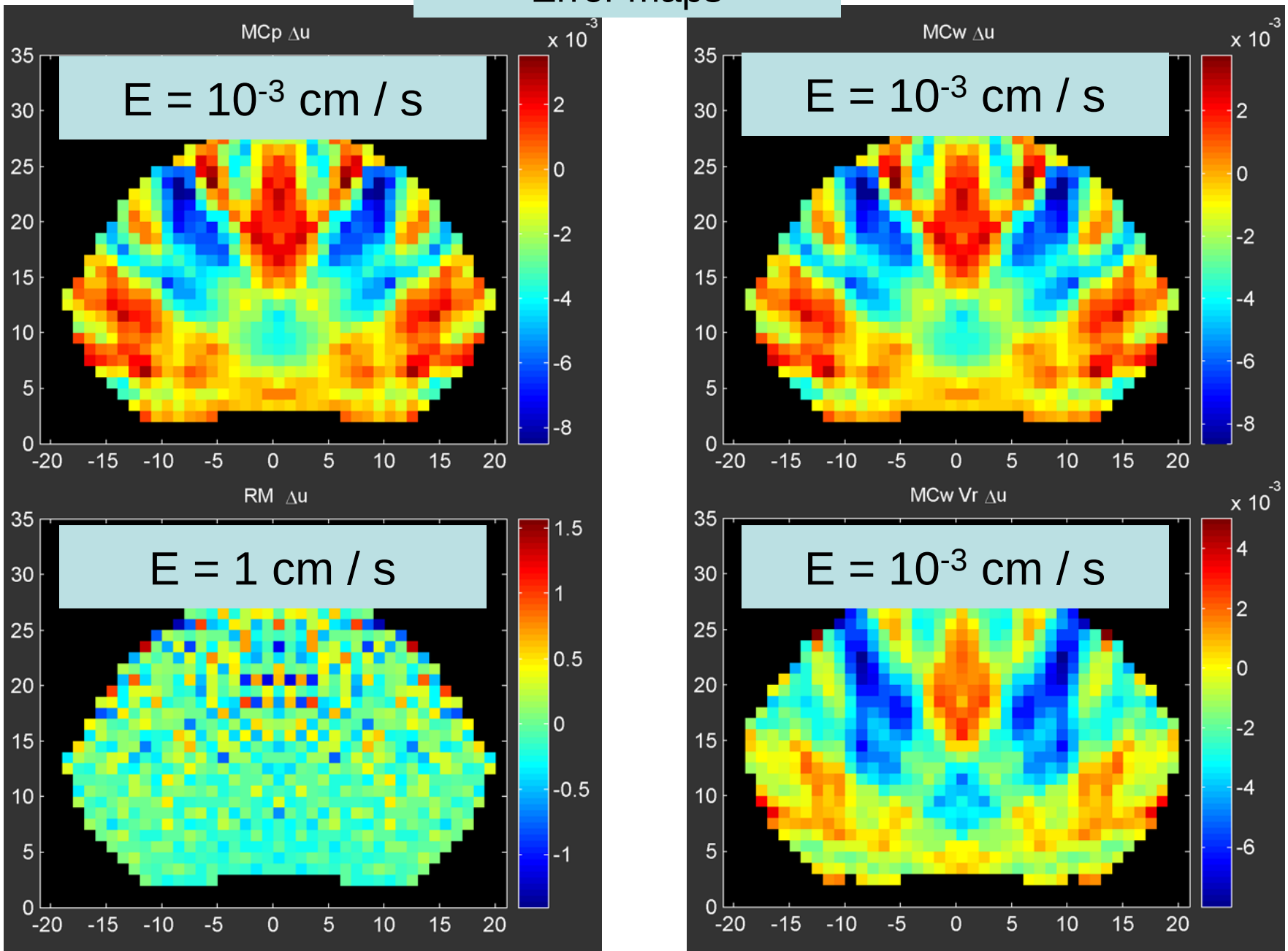
$$u = 30, v = 0$$





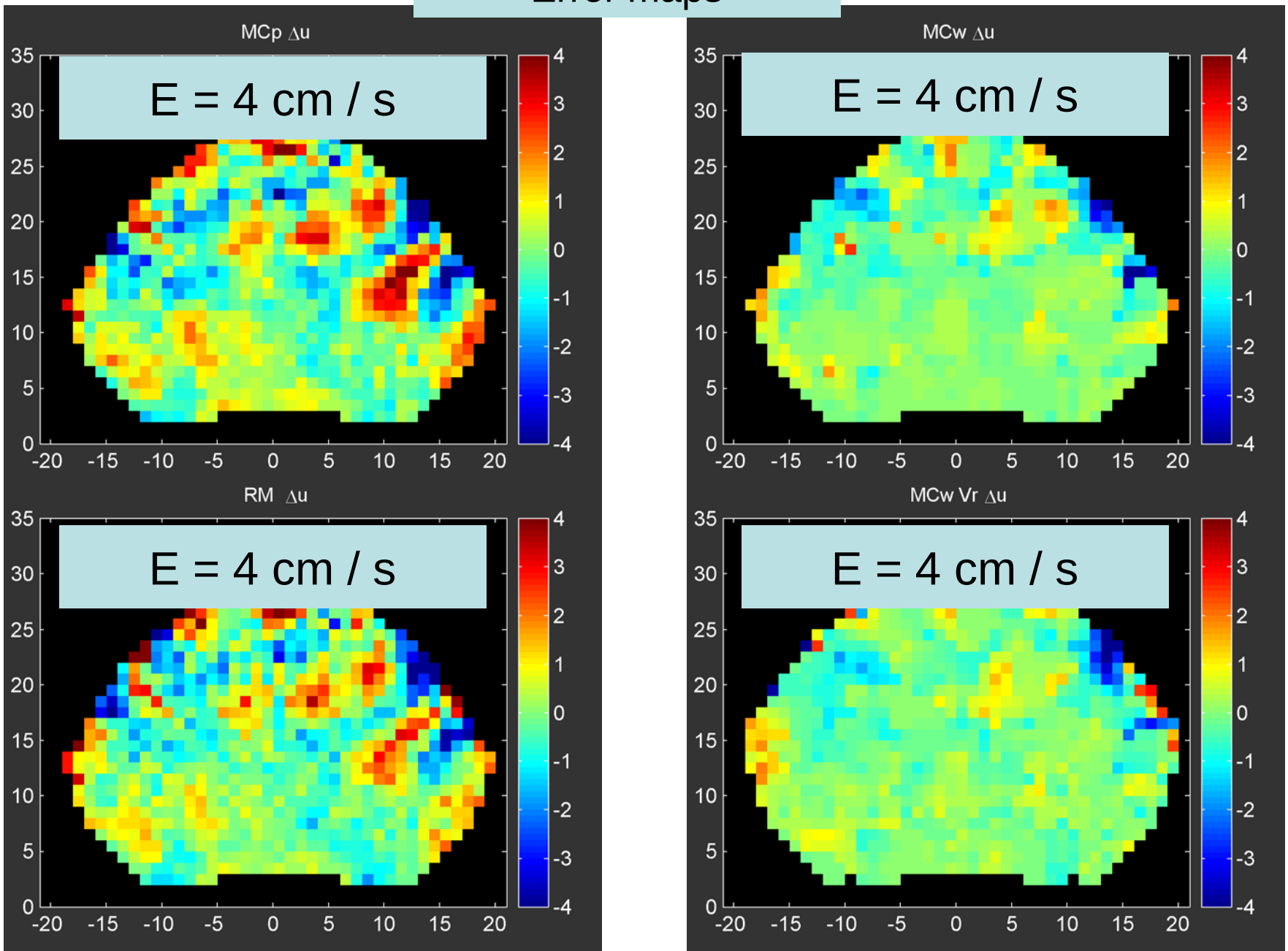
Level-2 Error Analysis: Zonal flow – no perturbation

Error maps



Level-2 Error Analysis: Zonal flow – perturbation (2 cm / s)

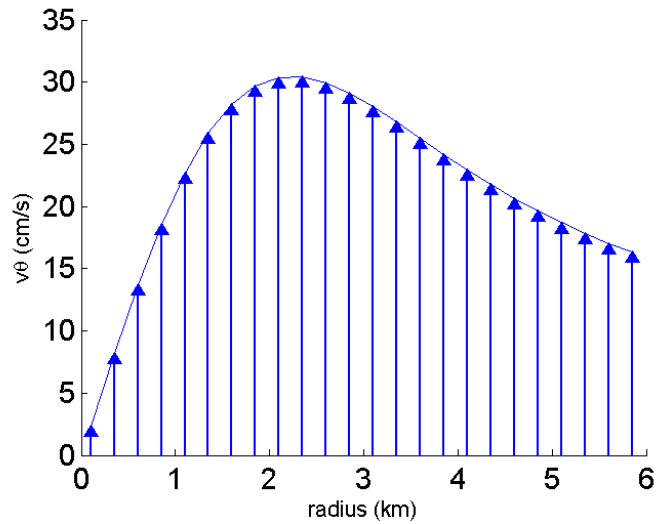
Error maps



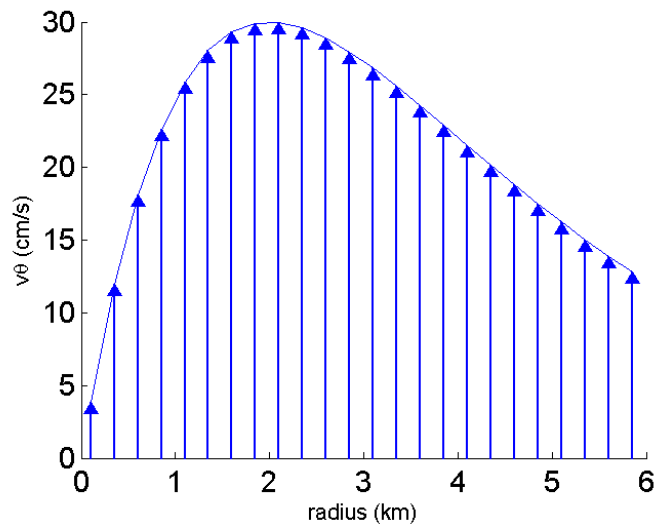
Level-2 Error Analysis: Vortex simulation

$$v_\vartheta = \frac{\Gamma}{2\pi r}$$

Ideal vortex

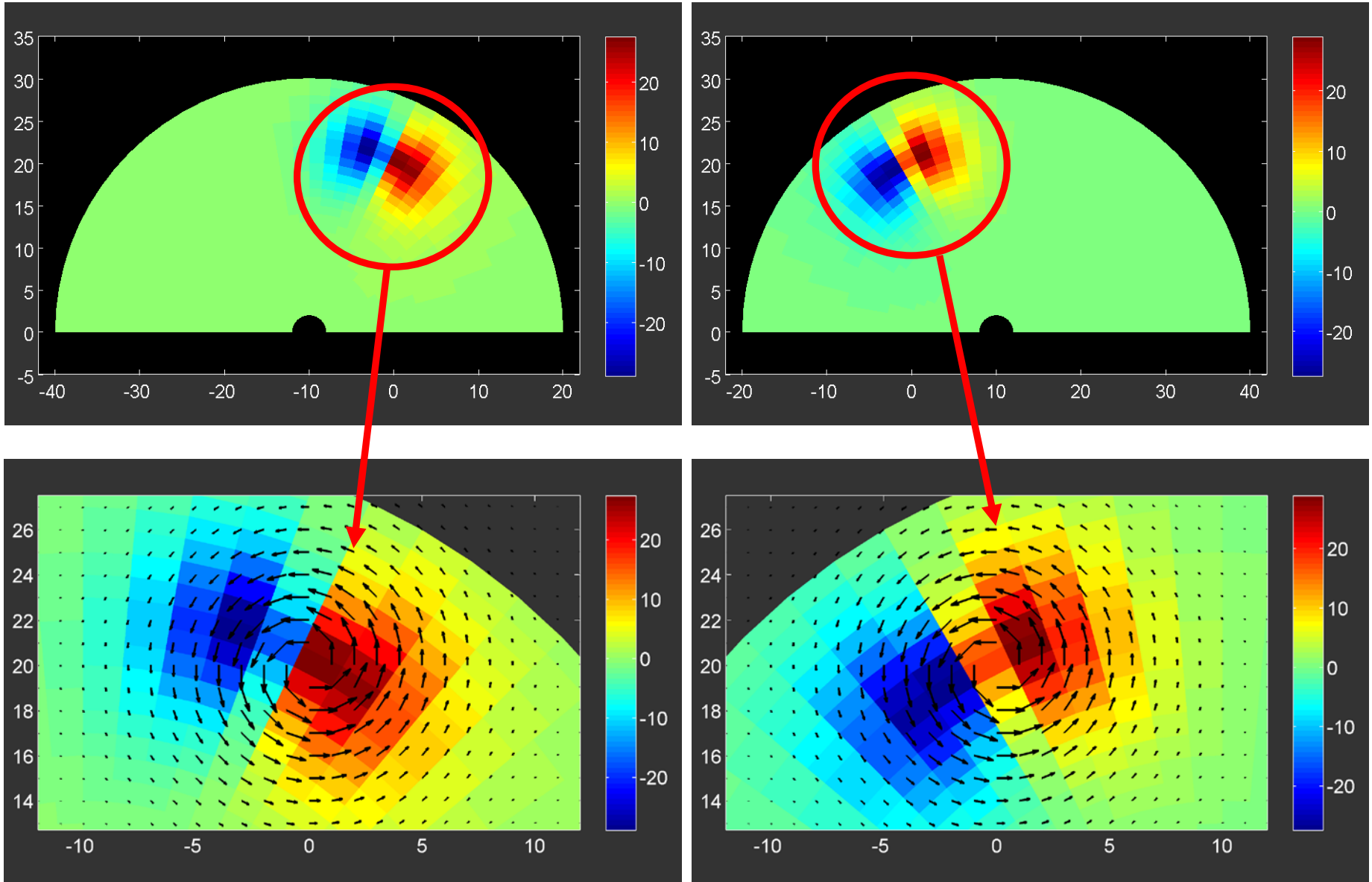


$$v_\vartheta = \frac{\Gamma}{2\pi r}\left(1 - e^{-\frac{r^2}{4}}\right)$$



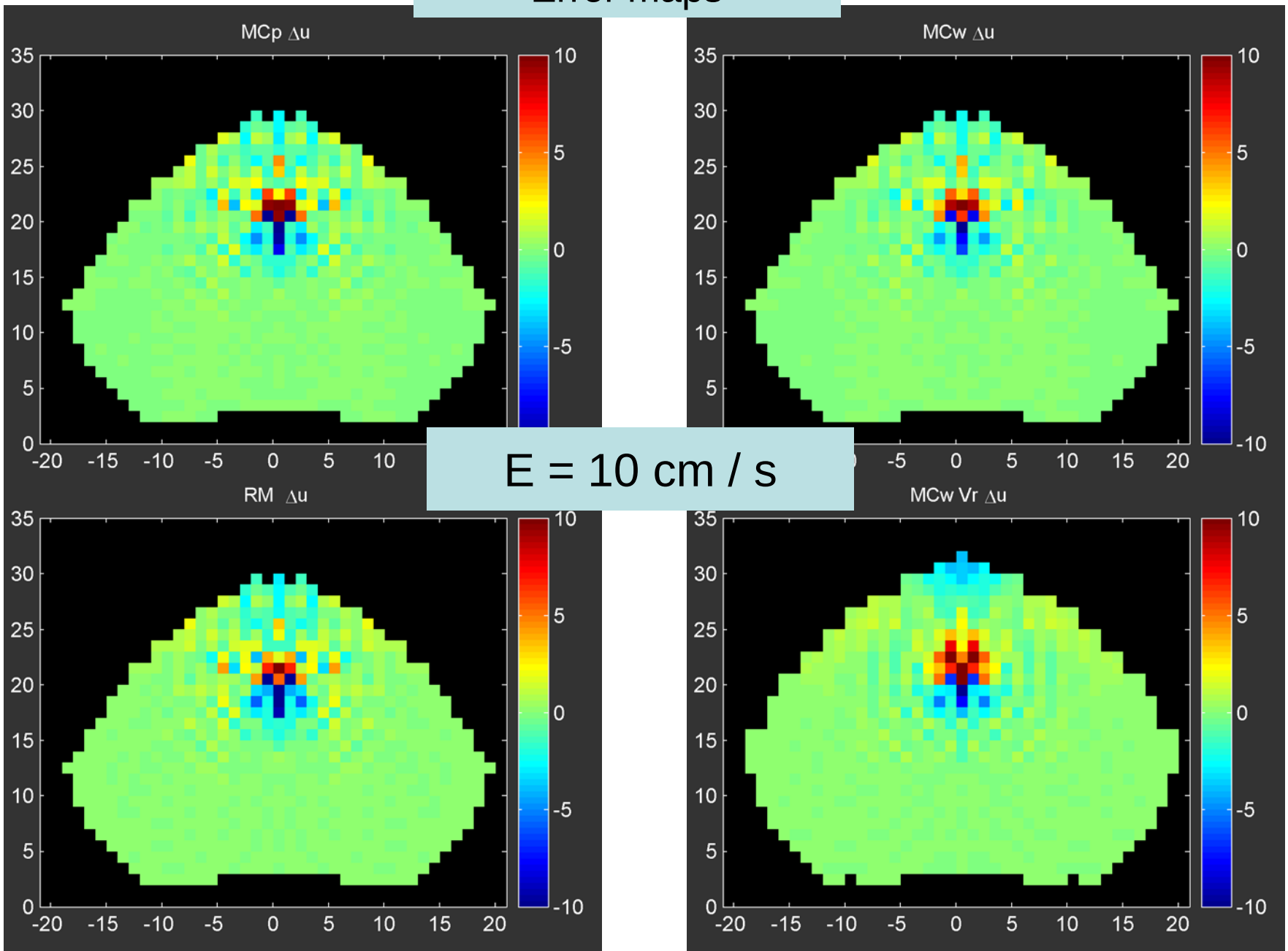
$$v_\vartheta = v_{\max}\frac{r}{r_{\max}}\left(1 - e^{\frac{r}{r_{\max}}}\right)$$

Level-2 Error Analysis: Vortex in (x=0, y=20)



Level-2 Error Analysis: Vortex - no perturbation

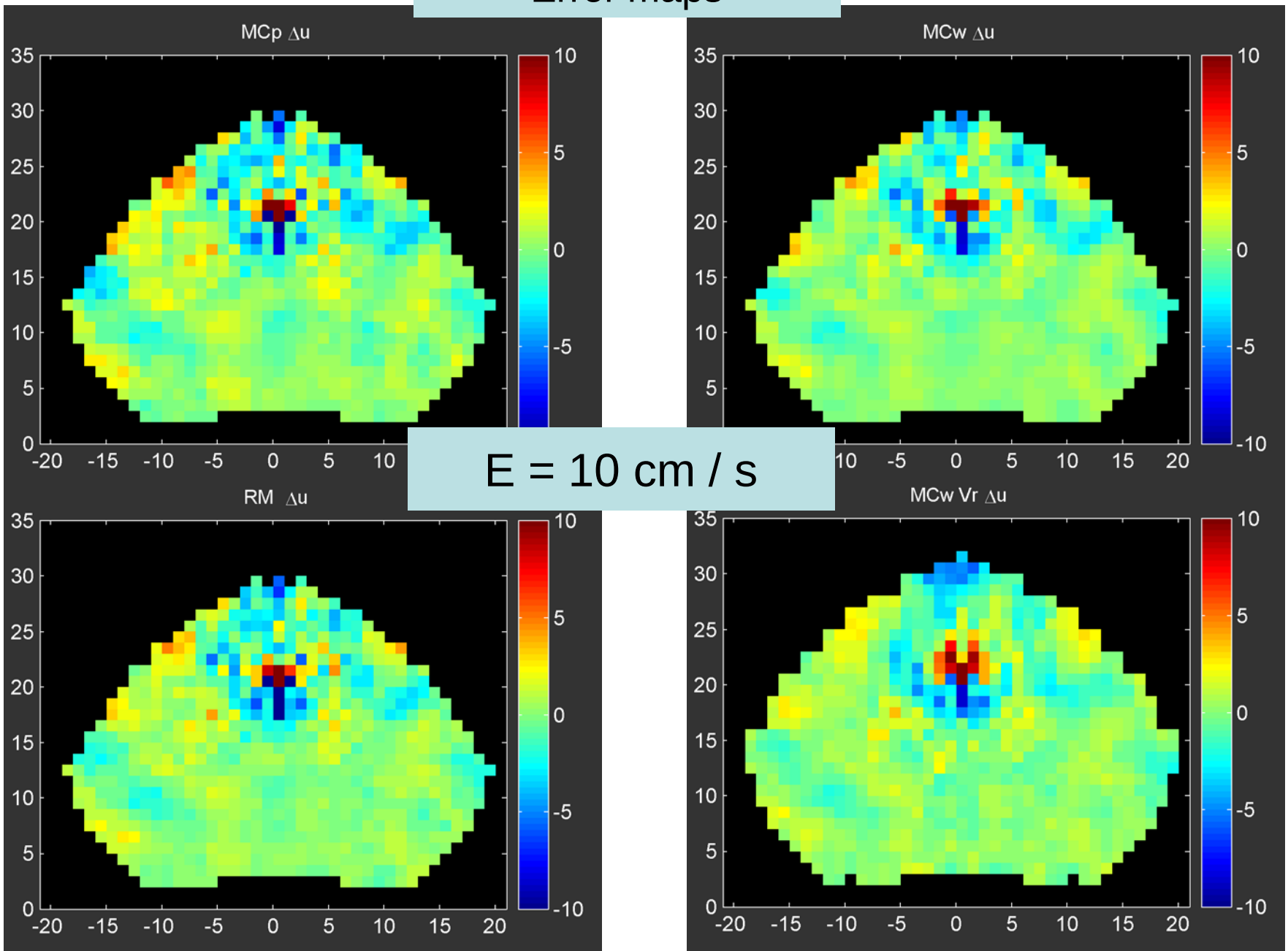
Error maps



E = 10 cm / s

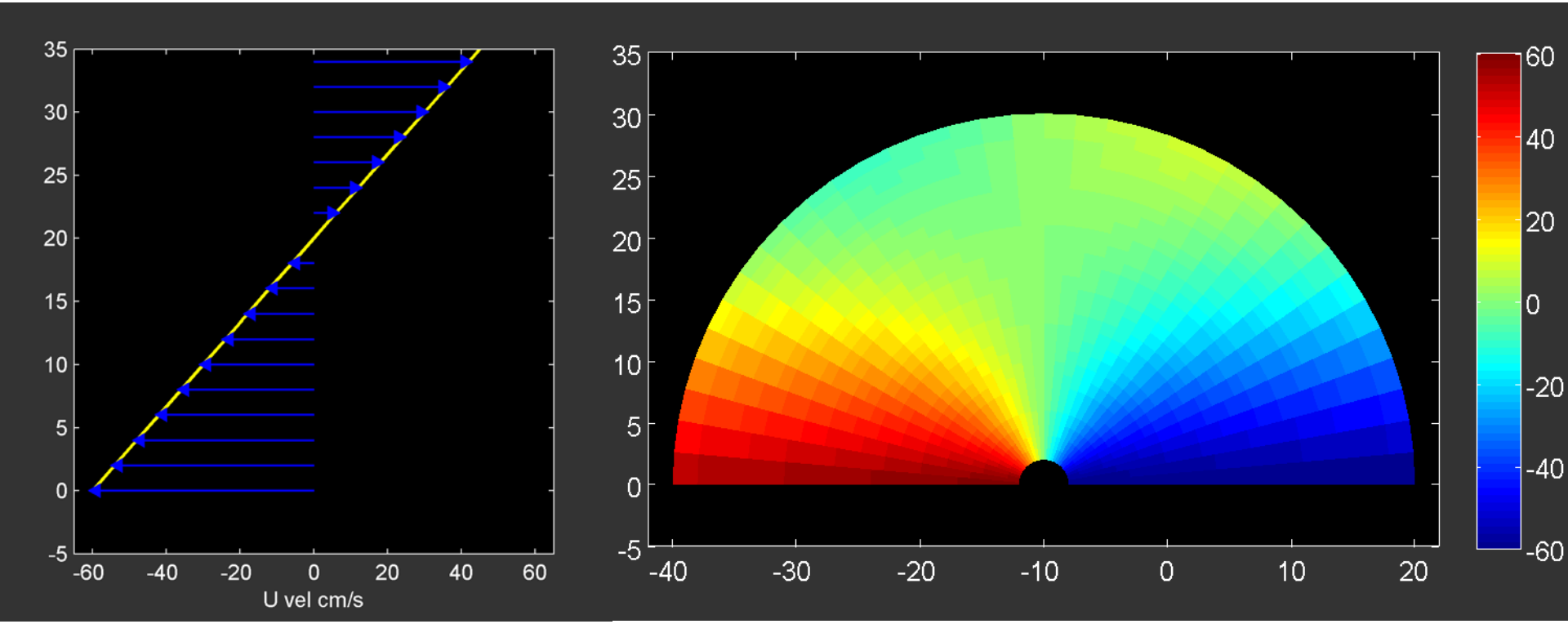
Level-2 Error Analysis: vortex – perturbation (2 cm / s)

Error maps



E = 10 cm / s

Level-2 Error Analysis: Shear Flow

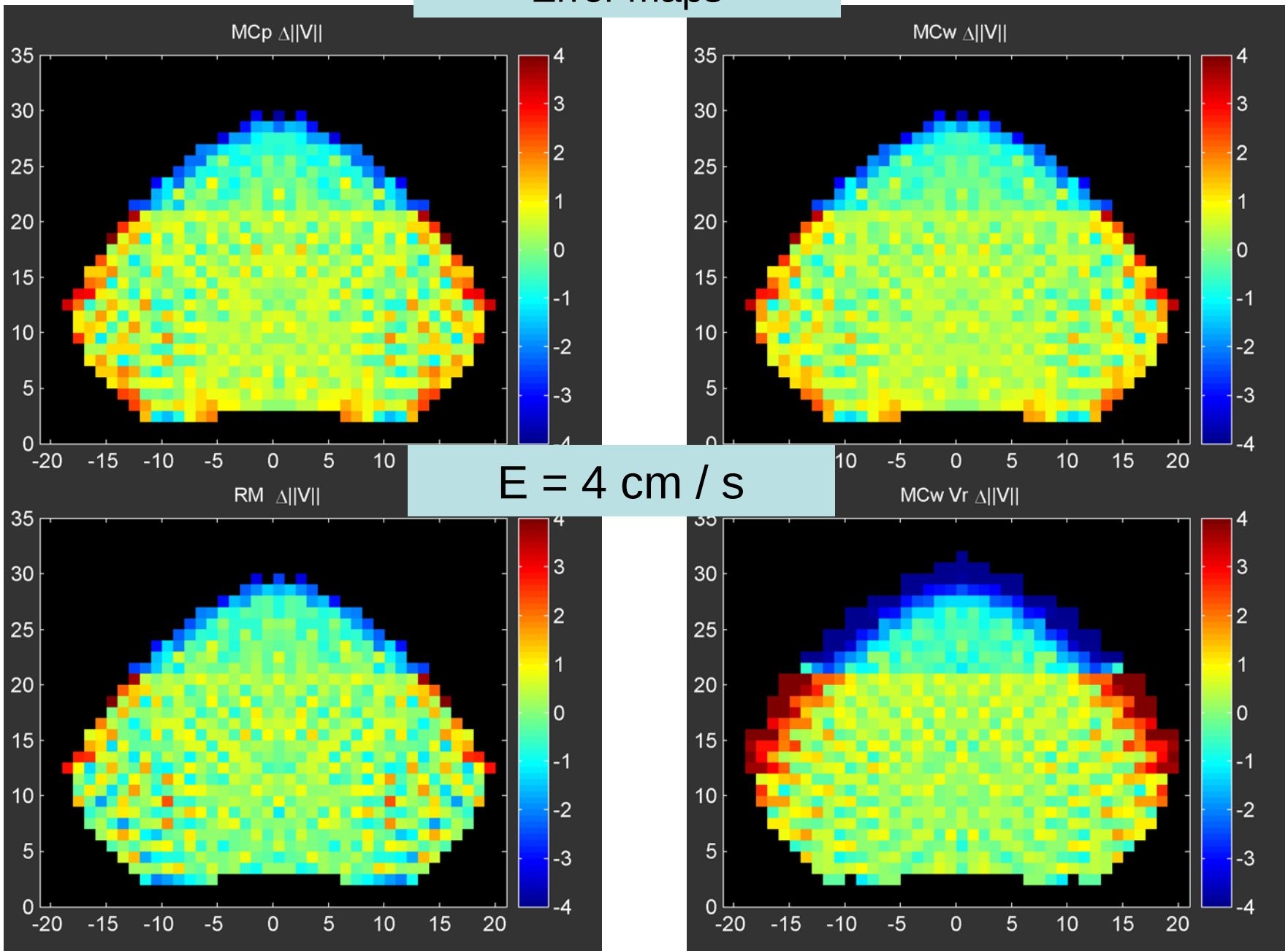


$$u = c(y - y_0)$$

$$v = 0$$

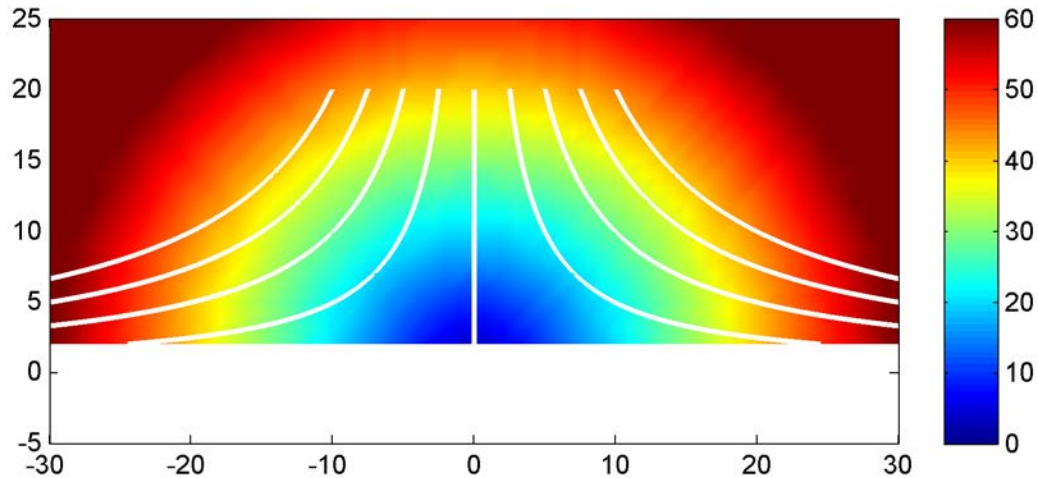
Level-2 Error Analysis: Shear Flow – no perturbation

Error maps



E = 4 cm / s

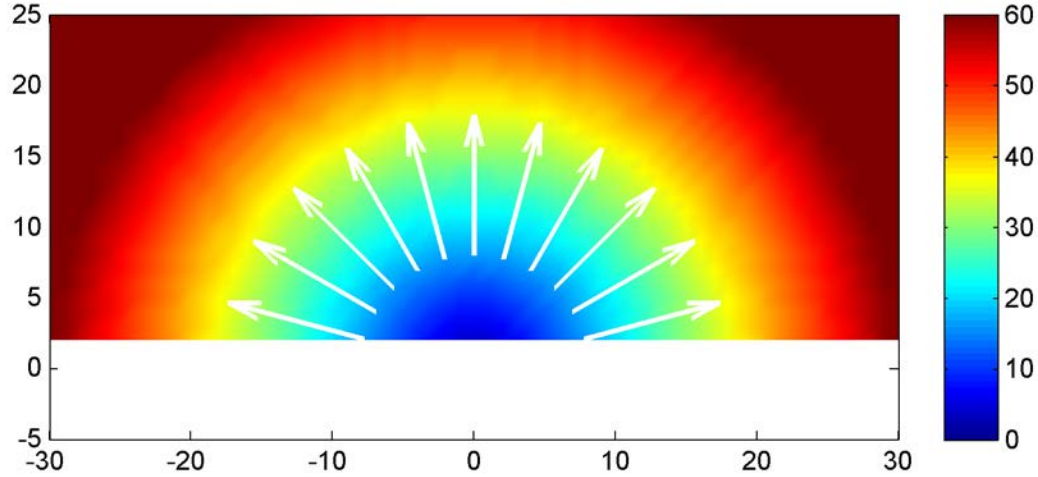
Level-2 Error Analysis: further examples



Stagnation Point

$$u = cx$$

$$v = -cy$$



Source Point

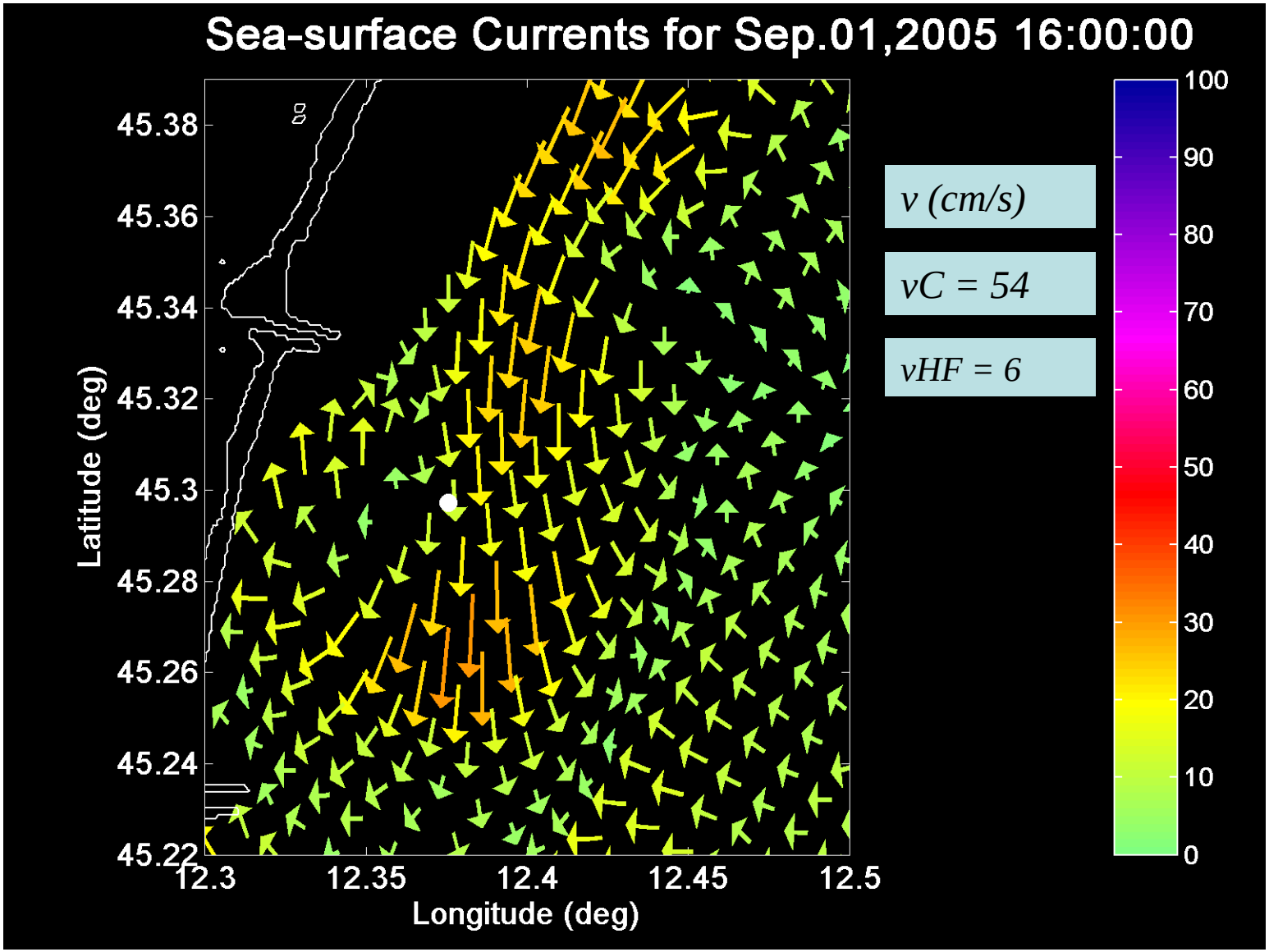
$$u = cx$$

$$v = cy$$

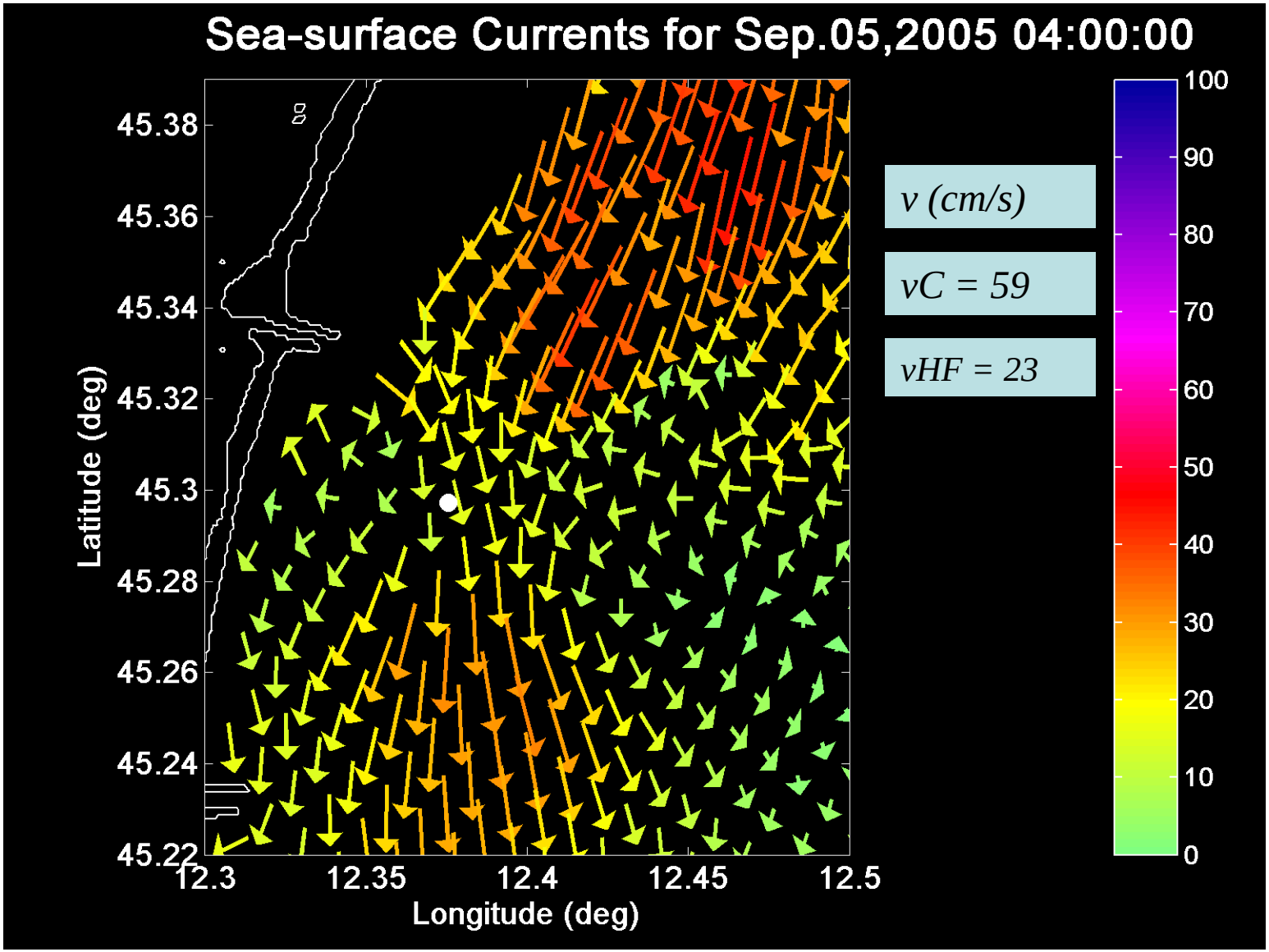
Errors proportional to c

No systematic under/over estimate

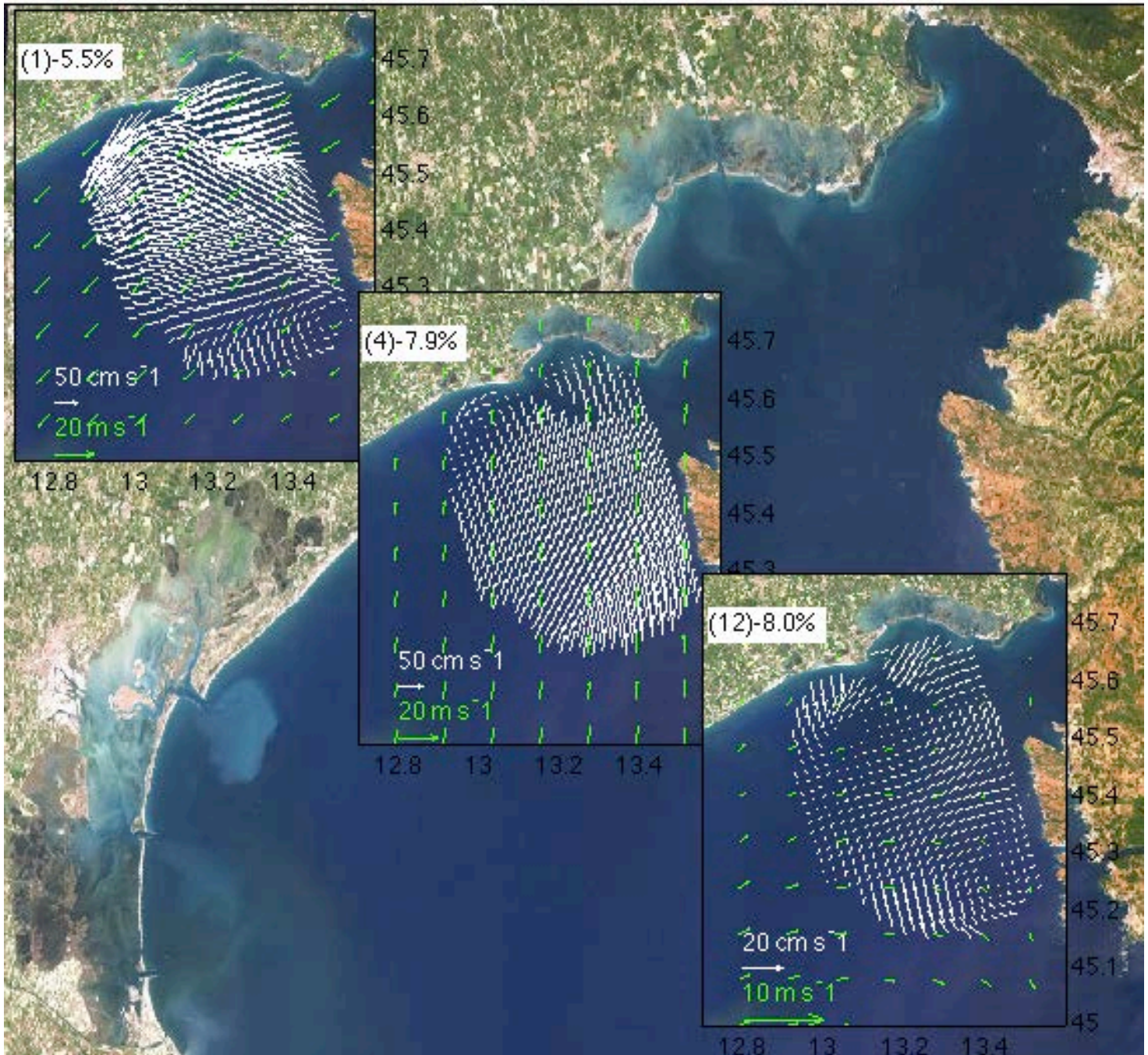
Level-2 Error Analysis: not only an exercise!



Level-2 Error Analysis: not only an exercise!



Level-2 Error Analysis: not only an exercise!



Summary and Conclusions

- HF radars do a great job in measuring and resolving complex patterns

- Well established procedures for system calibration and data validation for both DF and BF systems

- Accuracy and limitation of HF radar measurements (radials – totals) are known

- Standard protocols for data management exist – not for qaqc

- Proposal for qaqc (for commercial DF systems): snrqaqc at Doppler velocity level

  snr is an objective criterion for data quality

  snr of radial velocity can be used as weight in total vector computation

  the procedure is efficient, effective, and fast (less than .5 min on a 1.33GHz PowerPc G4 MacIntosh, 768 MB ram, for 1 radial map)
  can be run in near-real-time and offline

- Next step: direct inversion Doppler spectra – radial currents

Summary and Conclusions

- Errors on radial maps for DF systems depend on snr

- Errors on surface current maps depend (also) on:
  - network geometry (GDOP – GDOSA)
  - on the mapping algorithm
  - on the current pattern

- Open problems:
  - which is the “acceptable” level of error?
  - optimization of the mapping procedure: pattern recognition and iterative correction – worth the try?
  - need for a theoretical explanation for the LS fit bias VS velocity observations and their derivatives

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