# Estimation of Surface Current Vorticity and Divergence from a Future Winds and Currents Mission (WaCM)

Dudley Chelton
Oregon State University, College of Earth, Ocean & Atmospheric Sciences
and
Ernesto Rodriguez
Jet Propulsion Laboratory, California Institute of Technology

with help from Michael Schlax, Roger Samelson, Tom Farrar, Jeroen Molemaker, Jim McWilliams and Jonathan Gula

Oregon State University
College of Earth, Ocean, and Atmospheric Sciences


Jet Propulsion Laboratory
California Institute of Technology

Chelton et al. (2019, Progress in Oceanography - 95 pages!)

# The Winds and Currents Mission (WaCM)
## Measurement Concept and Sampling

- **Ka-Band Rotating Pencil-Beam Doppler Scatterometer**

  Provides simultaneous measurements of ocean surface currents and vector winds.

- **Daily or Better Sampling Globally**

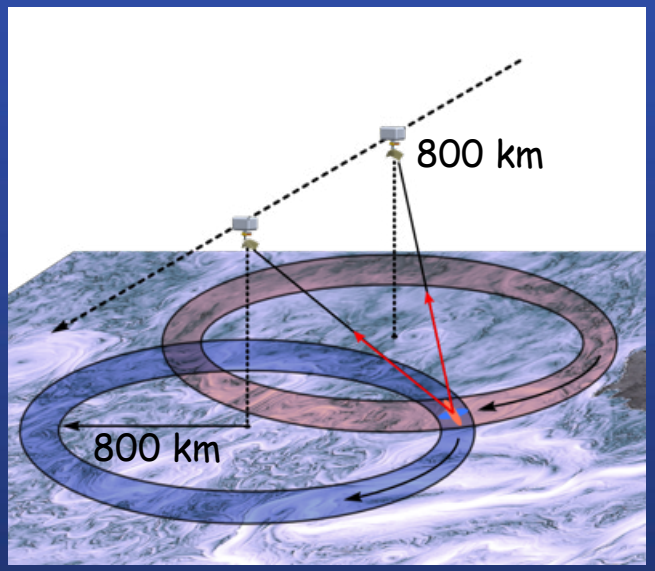
  The wide 1600-km swath enables 2x/day sampling in many places and 1x/day globally. This reduces aliasing from rapidly evolving ocean signals.

- **High Spatial Resolution**

  5 km footprint enables wind measurements very close to the coast, reduces land contamination, and improves sea ice measurements.

- **Expected Performance**

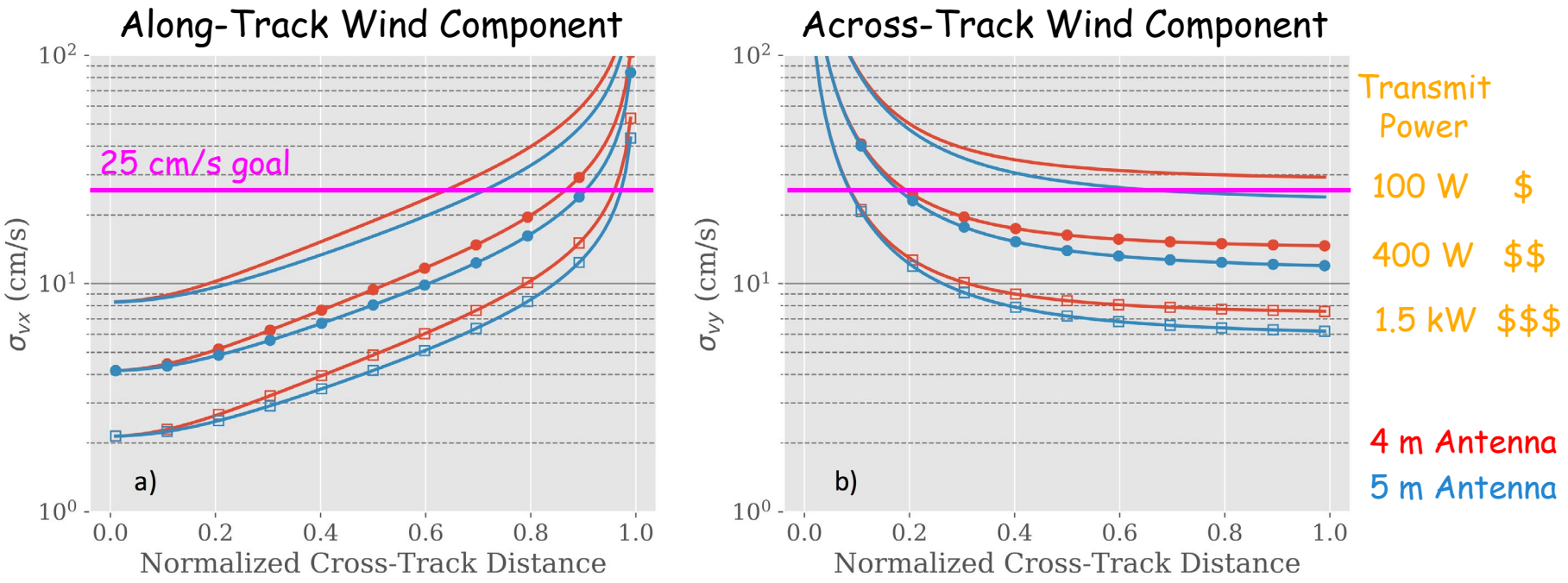
  < 1.5 m/s wind speed noise at 5-km resolution.
  < 0.25 m/s current speed noise at 5-km resolution
  (equivalent to 0.05 m/s at 25-km resolution)




WaCM spaceborne measurement concept

# WaCM Wind Component Noise Standard Deviations for a Footprint Size of 5 km

## Dependencies on Swath Location, Antenna Size and Transmit Power




Velocity component error as a function of the normalized cross-track distance from nadir in the (a) along-track ($\sigma_{vx}$) direction (roughly North) and (b) across-track ($\sigma_{vy}$) direction (roughly East), for antenna lengths of 4 m (red) and 5 m (blue). The peak output power is 100 Watts (solid line), 400 Watts (circles), and 1.5 kWatts (squares).

From Rodriguez, E., 2018: On the Optimal Design of Doppler Scatterometers. *Remote Sensing*, **10**. doi:10.3390/rs10111.

# The Winds and Currents Mission (WaCM)
## Status

- **Winds and Currents were Selected as Targeted Variables by the Decadal Survey for Earth Science from Space**

  WaCM is one of 7 candidate "Earth System Explorer" missions. The Decadal Survey recommends funding of 3 of the 7 missions.

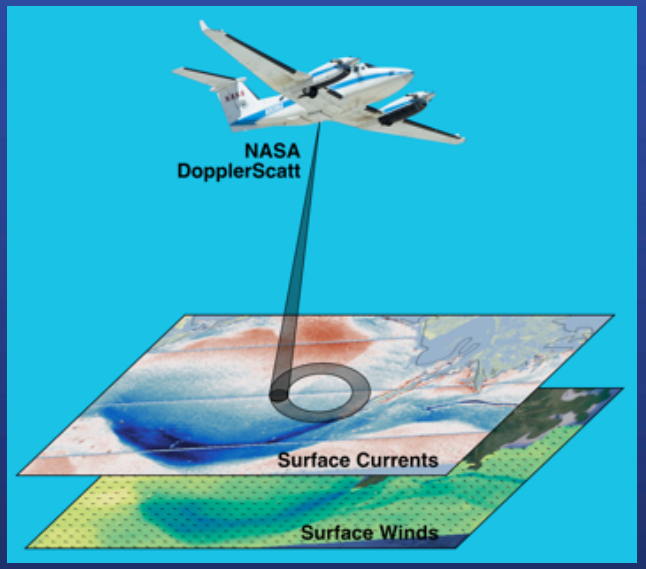
  Community support will be needed!

- **Measurement Maturity**

  The Ka-Band measurement concept has been demonstrated using the airborne DopplerScatt instrument developed at JPL with funding from the NASA Instrument Incubator Program.

- **Complementary Activities**

  The Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) (T. Farrar, PI): A NASA Earth Ventures Suborbital Mission using the airborne DopplerScatt will begin later in 2019.




JPL DopplerScatt
Airborne Demonstrator for
WaCM

# The Winds and Currents Mission (WaCM)

## Science Goals

### Additional input welcome!

- **Ocean-Atmosphere Interactions**

  Measure non-geostrophic equatorial oceans; improve the understanding of wind- and current-driven ocean upwelling mechanisms; estimate ocean vorticity, divergence, wind work and the influence of surface currents on the atmosphere.

- **Ocean-Atmosphere-Biosphere Interactions**

  Study the effects of wind- and current-driven ocean upwelling on ocean productivity, complimenting satellite measurements of ocean color.

- **Ocean-Atmosphere-Cryosphere Interactions**

  Study the space-time evolution of the cryosphere from simultaneous measurements of currents, winds, and ice motion measurements.

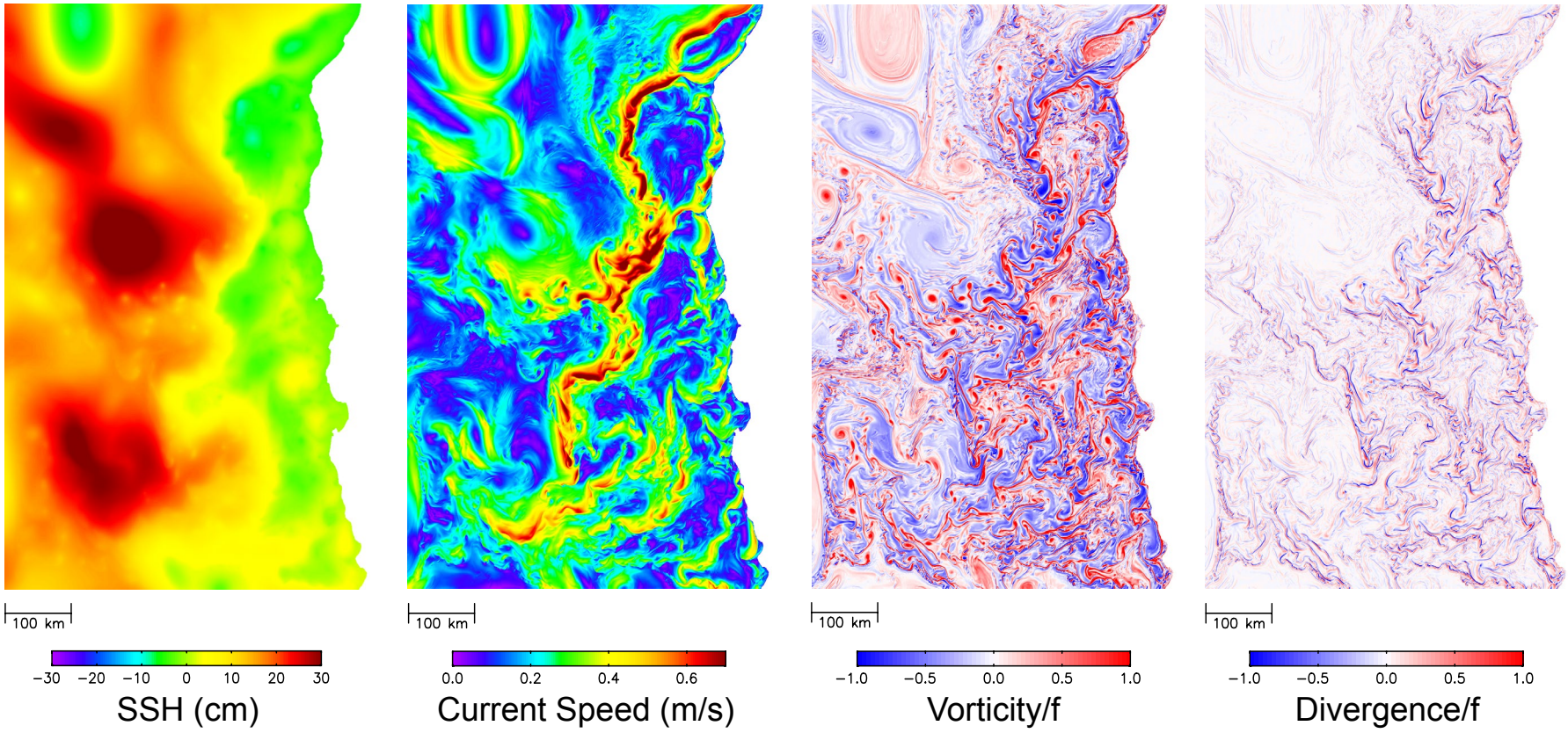
- **Applications**

  Aid in the study of the dispersal of marine debris and pollution; contribute to iceberg tracking; aid in planning and forecasting of coastal environmental issues.

# Objectives of the Rest of this Talk

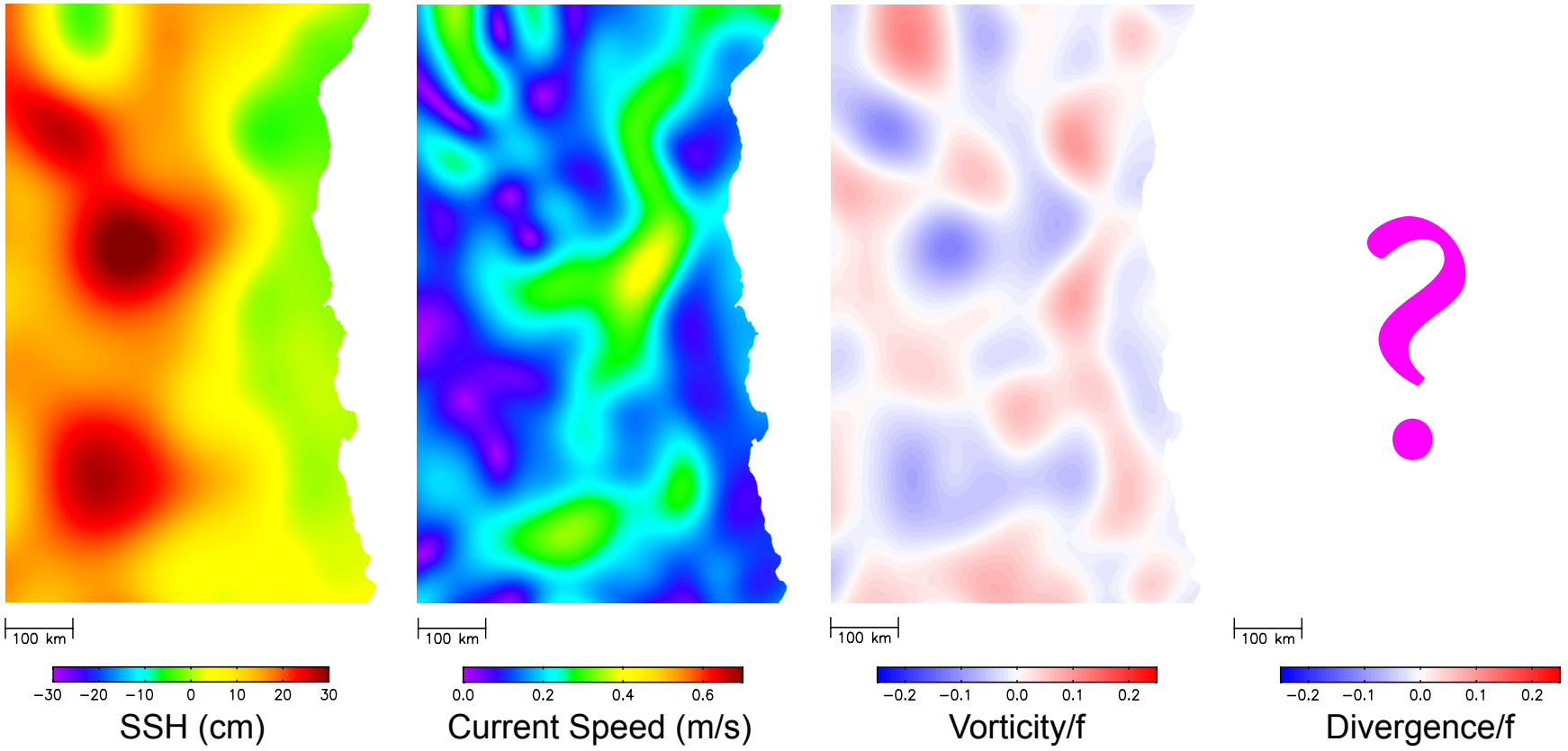
Extend our previous assessment of the resolution capability of WaCM estimates of ocean current vorticity to include SKIM and the resolution capability of WaCM estimates of divergence.

# Snapshots of SSH, Current Speed, Vorticity and Divergence from a ROMS Model of the California Current System with 0.5 km x 0.5 km Grid Resolution




The coordinate system of the ROMS model is rotated 24° CCW from north-south/east-west.

# Space-Time Smoothed SSH, Current Speed and Vorticity: Present Capabilities from AVISO SSH Fields (Geostrophic with 200 km x 1 month Smoothing)




The coordinate system of the ROMS model is rotated 24° CCW from north-south/east-west.

# Example Swaths for WaCM, SKIM and SWOT

WaCM, 1800 km swath
(one of two sides)

SKIM, 320 km swath
(full swath with no nadir gap)

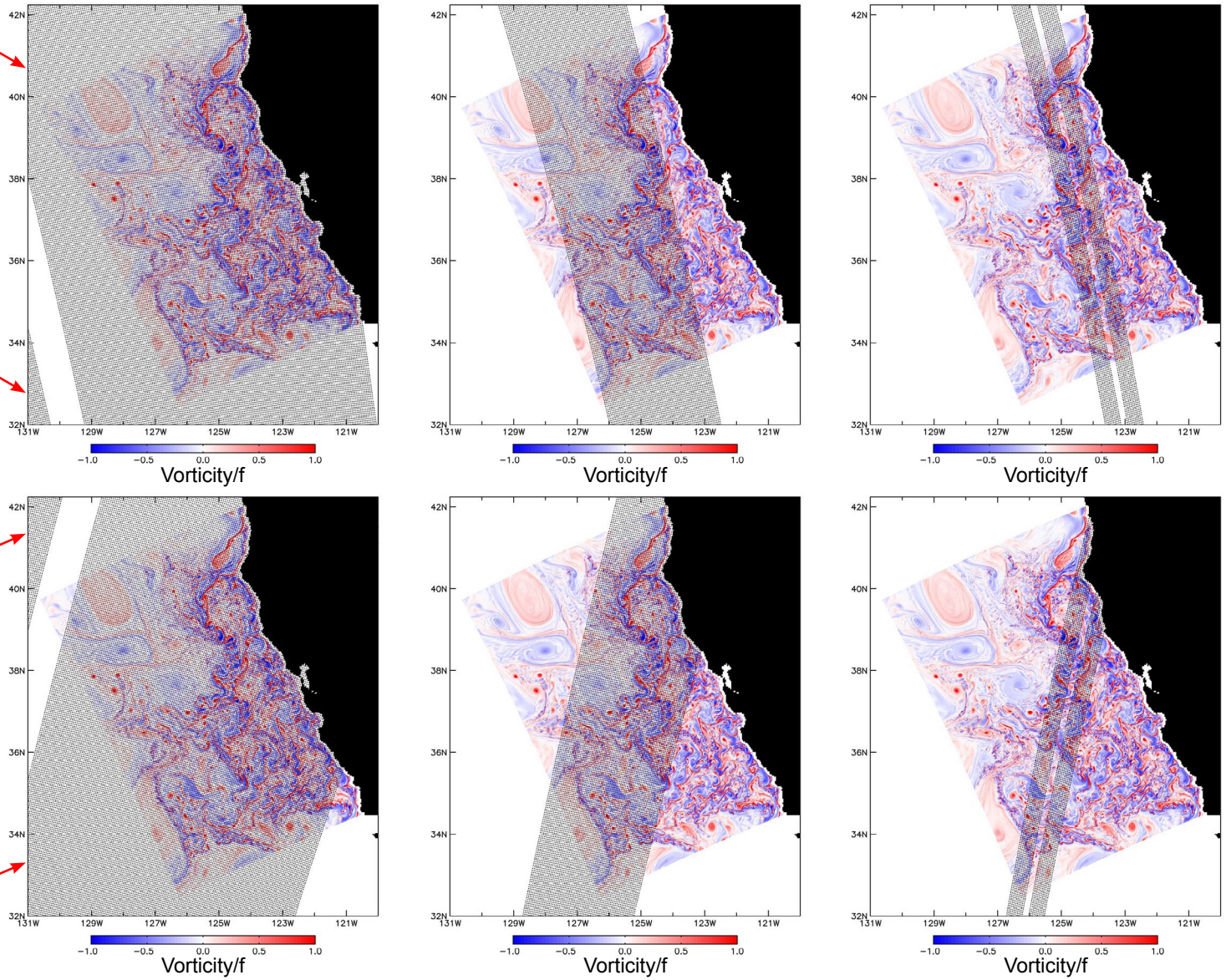
SWOT, 120 km swath
(both sides)

Starboard swath

Small portion of port swath

Small portion of starboard swath

Port swath



# Brief Summary of the Procedure for Defining Resolution Capability

1. Satellite measurements of surface currents were simulated from a high-resolution model with uncorrelated measurement errors added.

2. The simulated satellite data were averaged in time and smoothed spatially to reduce the effects of measurement and sampling errors.

5. For a given time averaging*, the resolution capability was defined to be the filter cutoff wavelength above which the Signal-to-Noise (S/N) standard deviation ratio exceeds a specified threshold value.

* In this presentation, we consider the case of 4-day averages for vorticity, and the cases of 4, 16 and 31 day averages for divergence.

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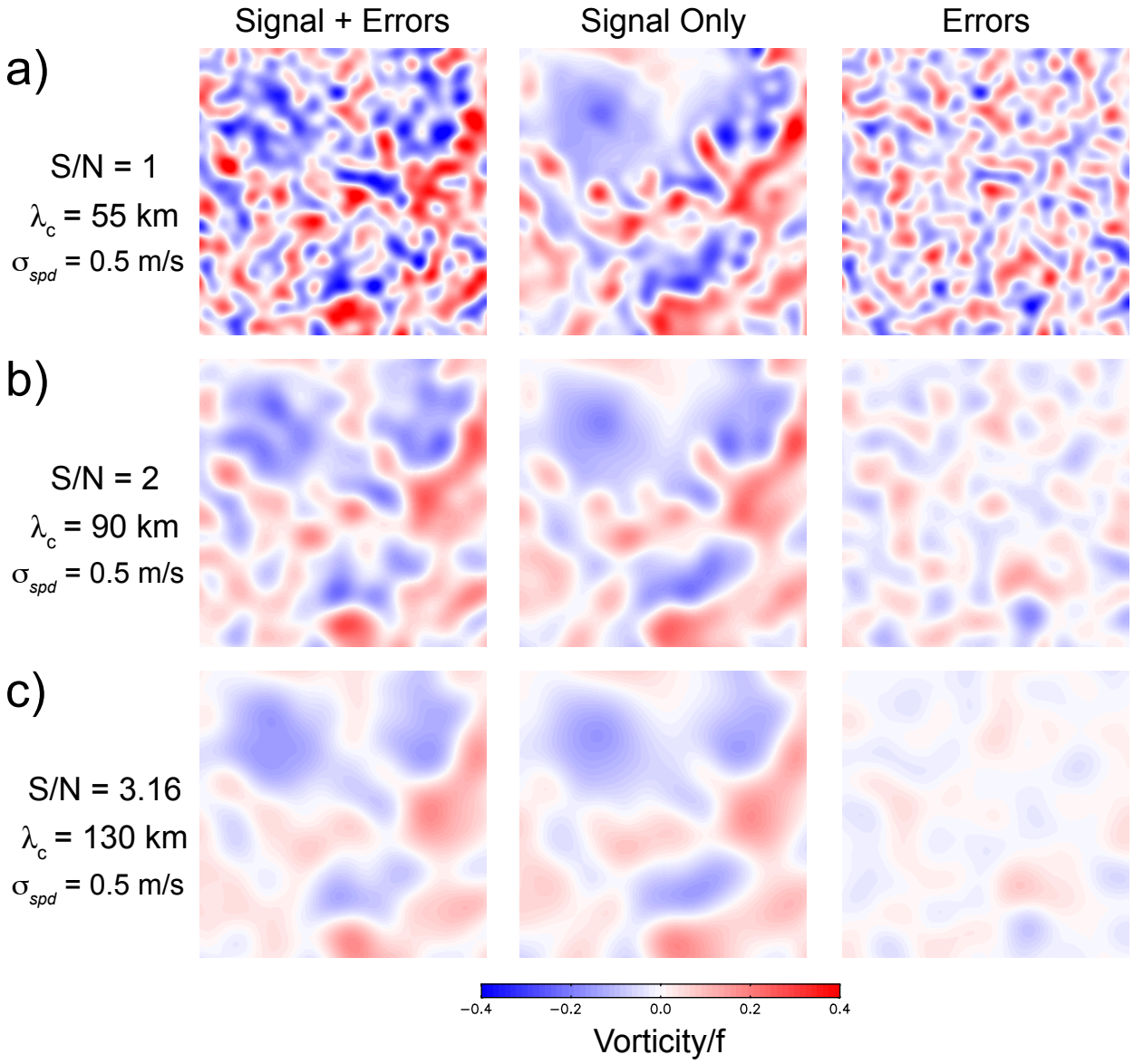
What threshold S/N value should be used?

* In this presentation, we consider the case of 4-day averages for vorticity, and the cases of 4, 16 and 31 day averages for divergence.

# Simulated Noisy Estimates of Snapshot of Vorticity with S/N Standard Deviation Ratios of 1, 2 and 3.16



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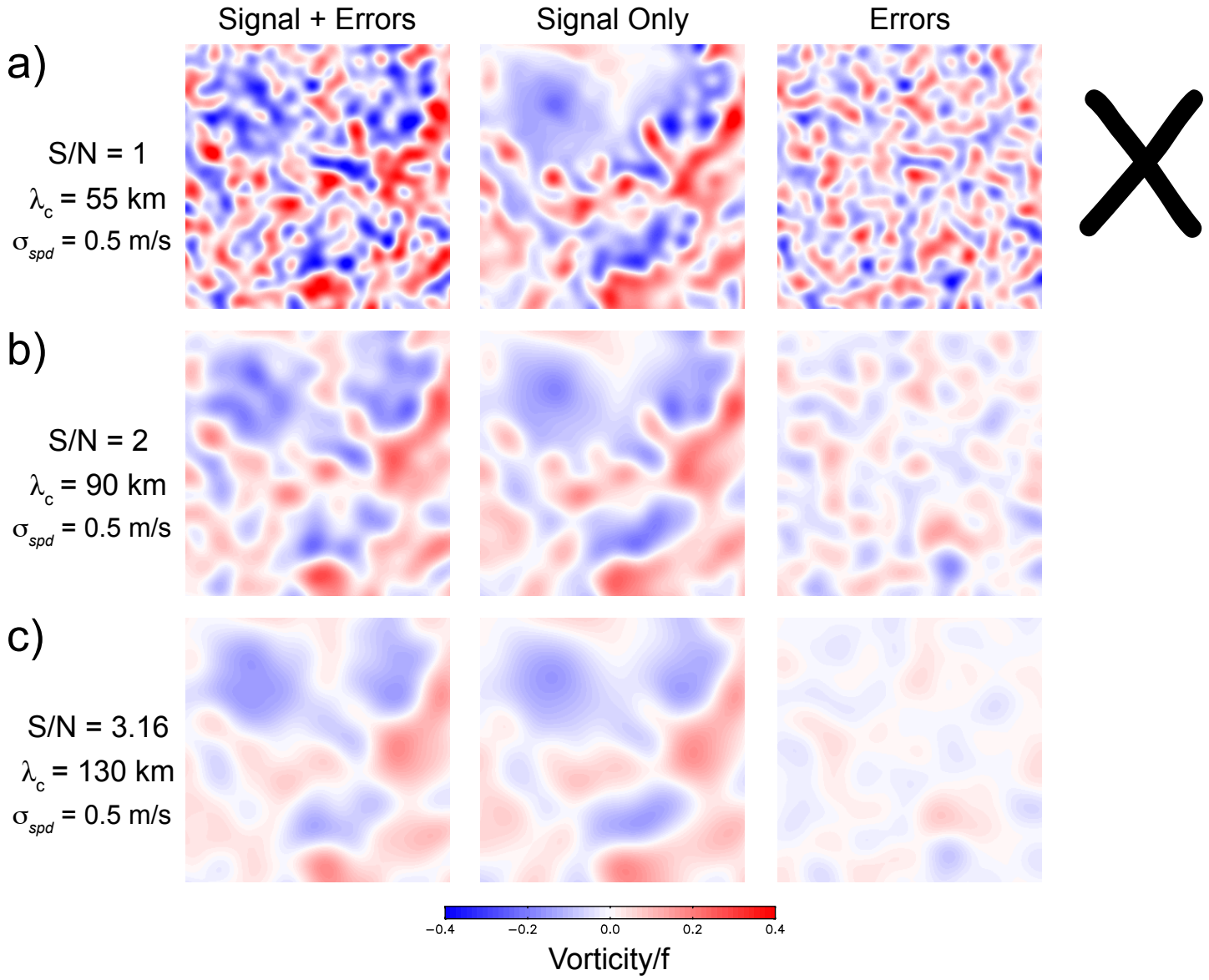

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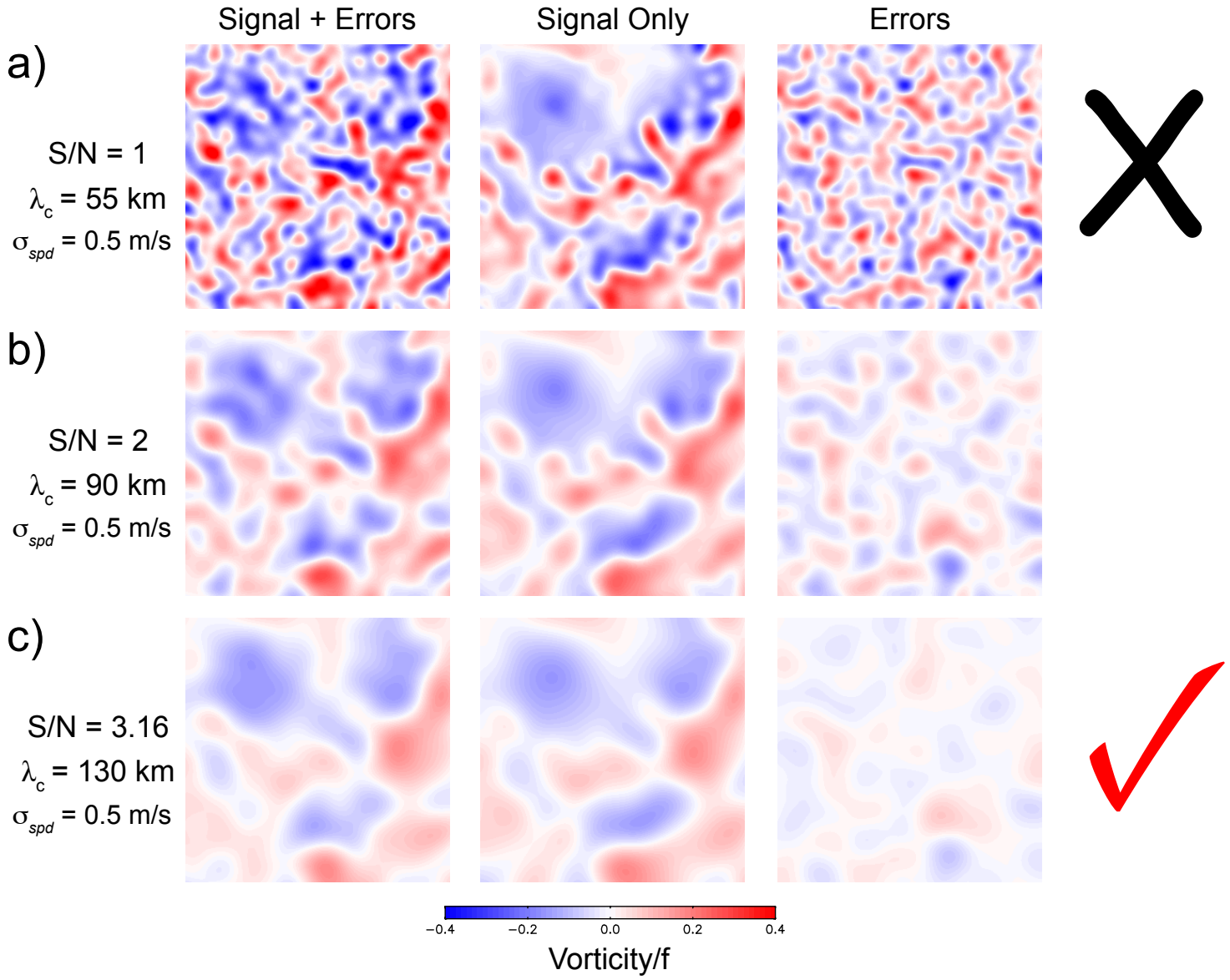

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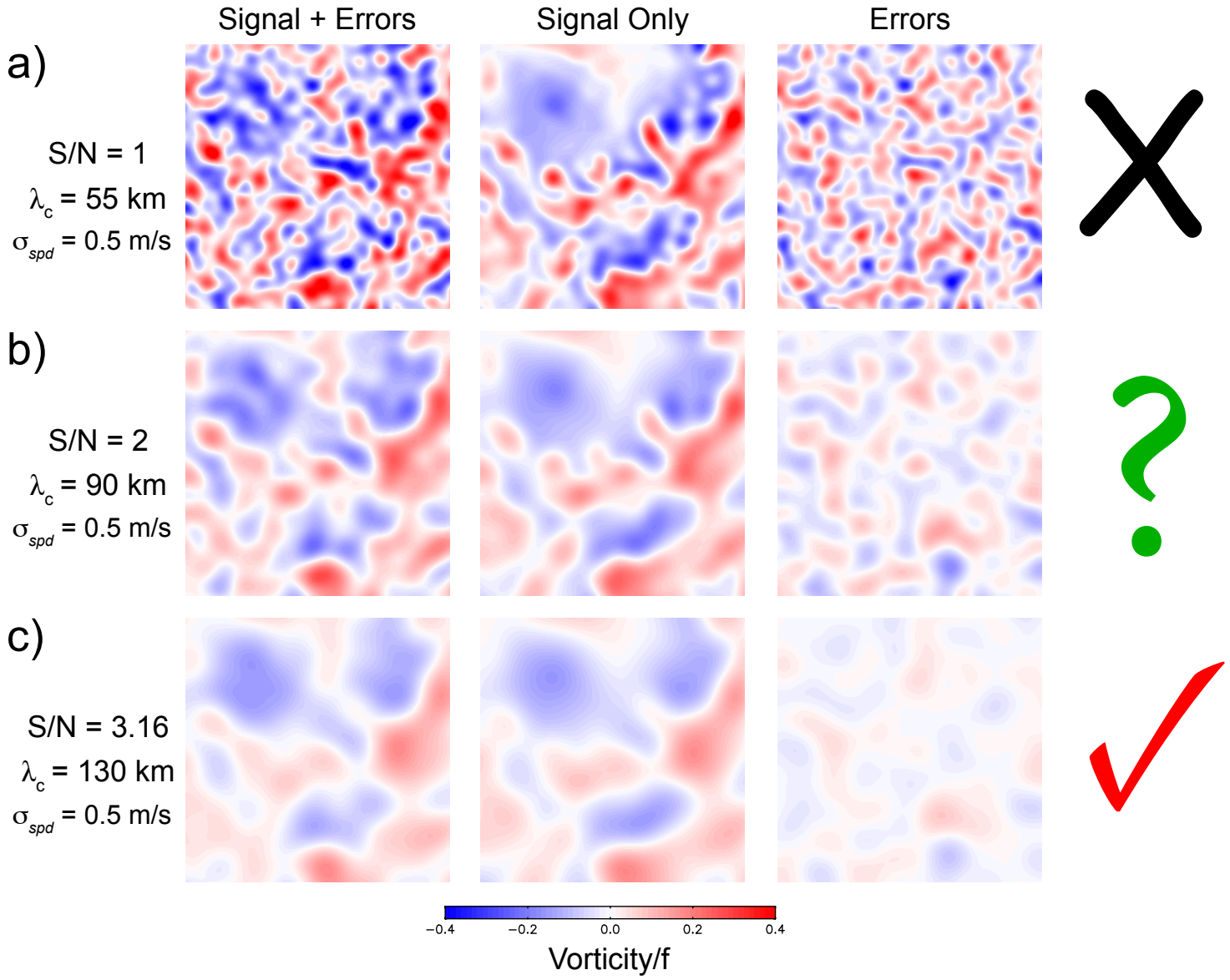
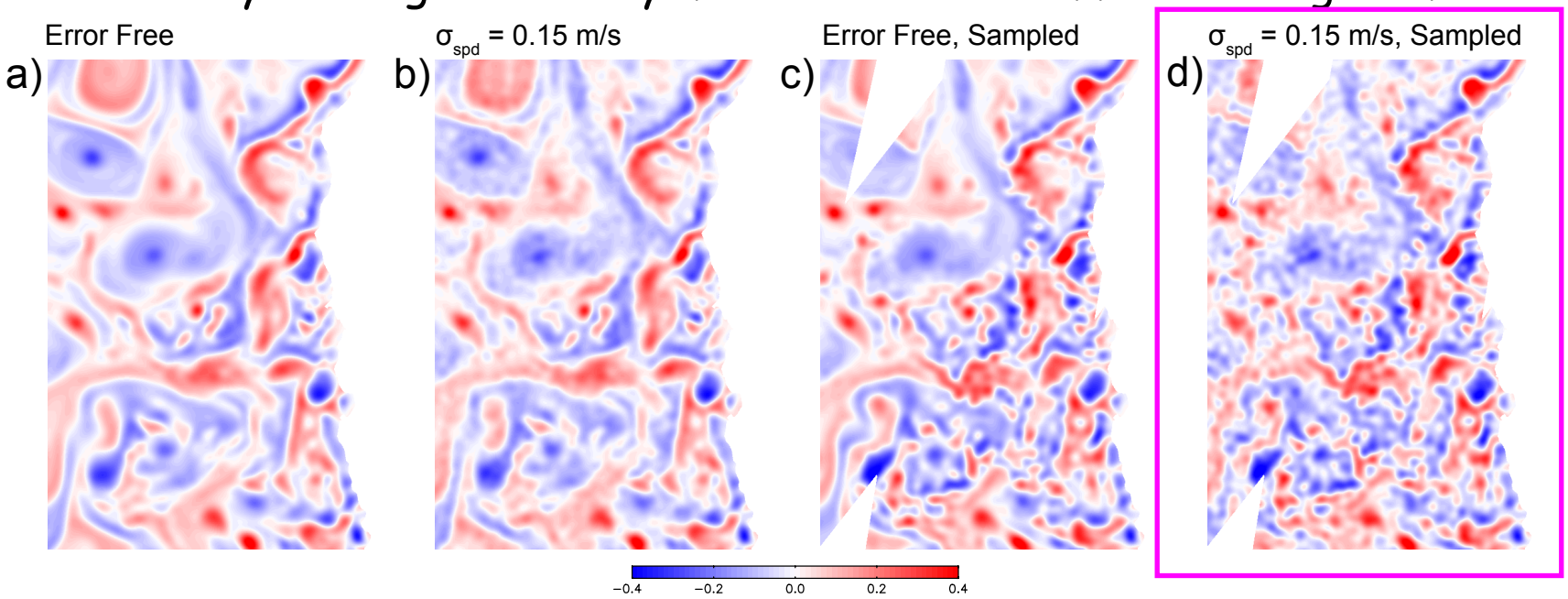


# Example Maps from Simulated WaCM and SKIM Data with Measurement and Sampling Errors Individually and Together

## 4-Day Averages with 50-km Smoothing

# SKIM 4-Day Average Vorticity/f with Filter Cutoff Wavelength of 50 km



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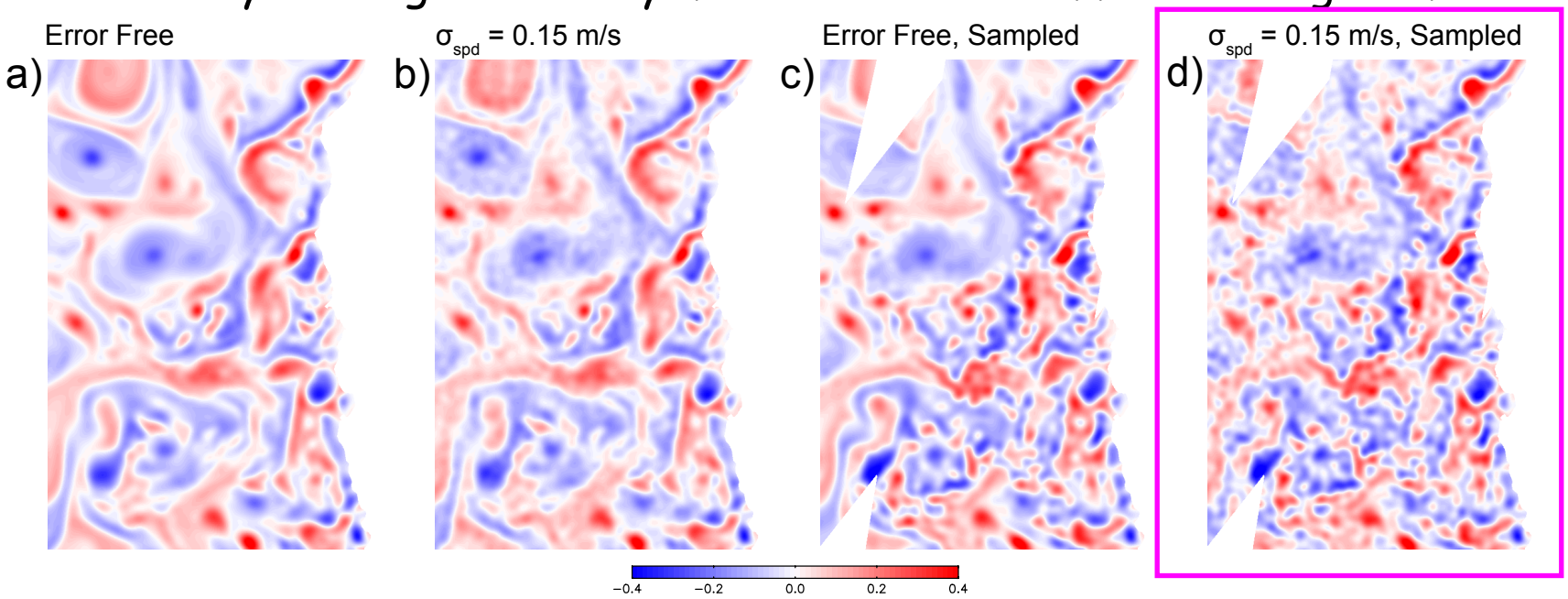
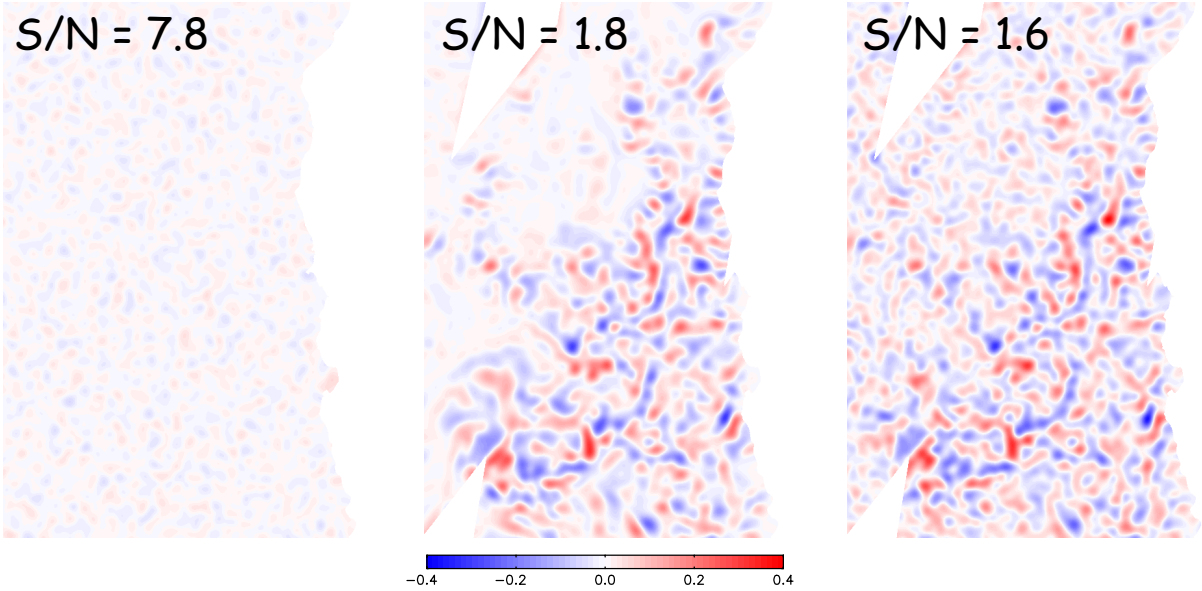


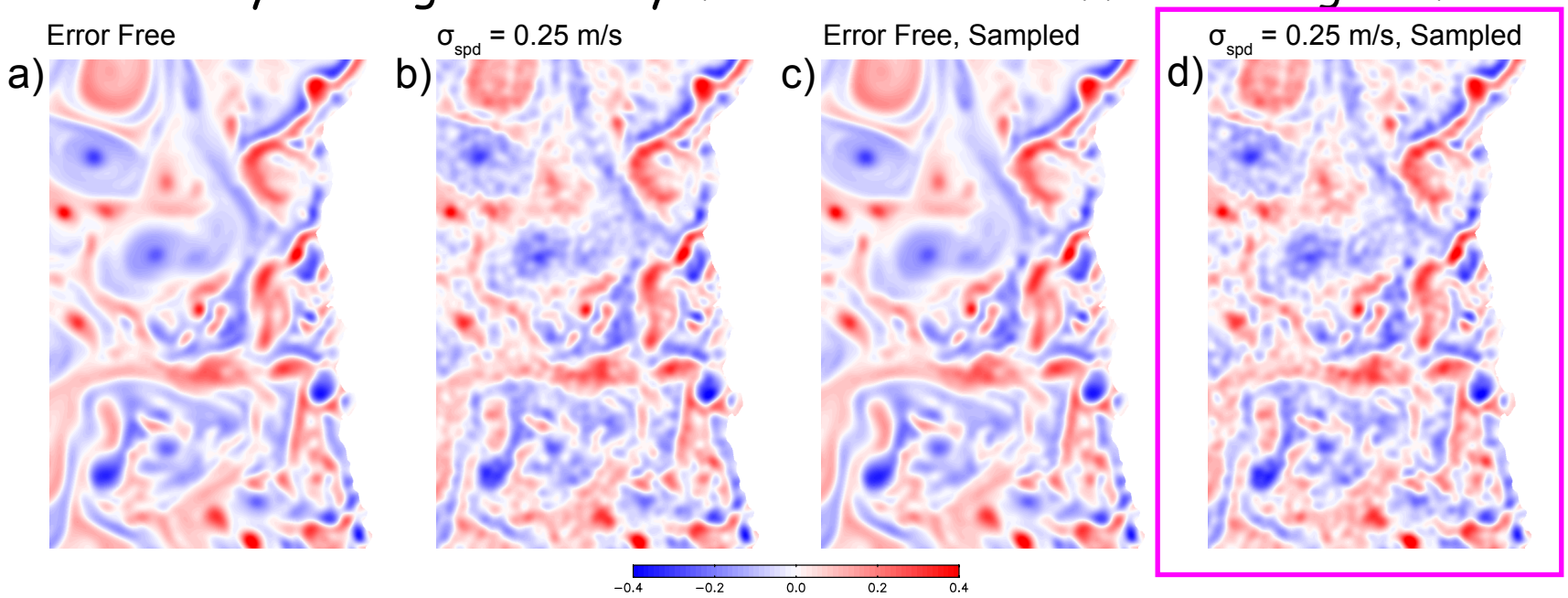

Error Maps

(Differences from top left panel)

The total errors are dominated by sampling errors, although measurement errors also have an effect



# WaCM 4-Day Average Vorticity/f with Filter Cutoff Wavelength of 50 km

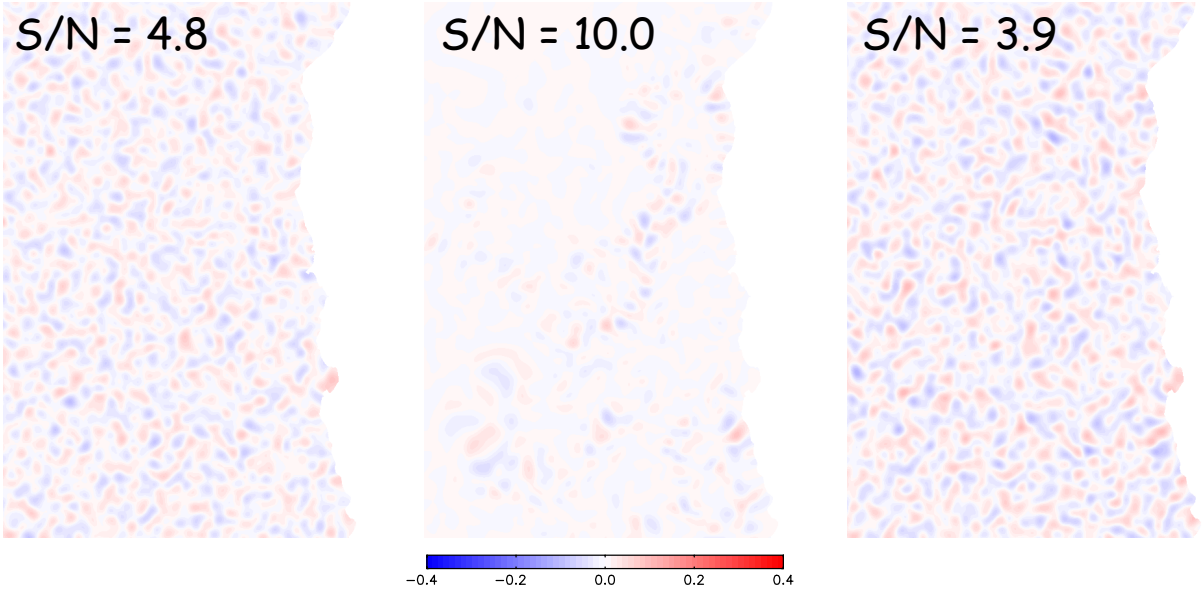



Error Maps

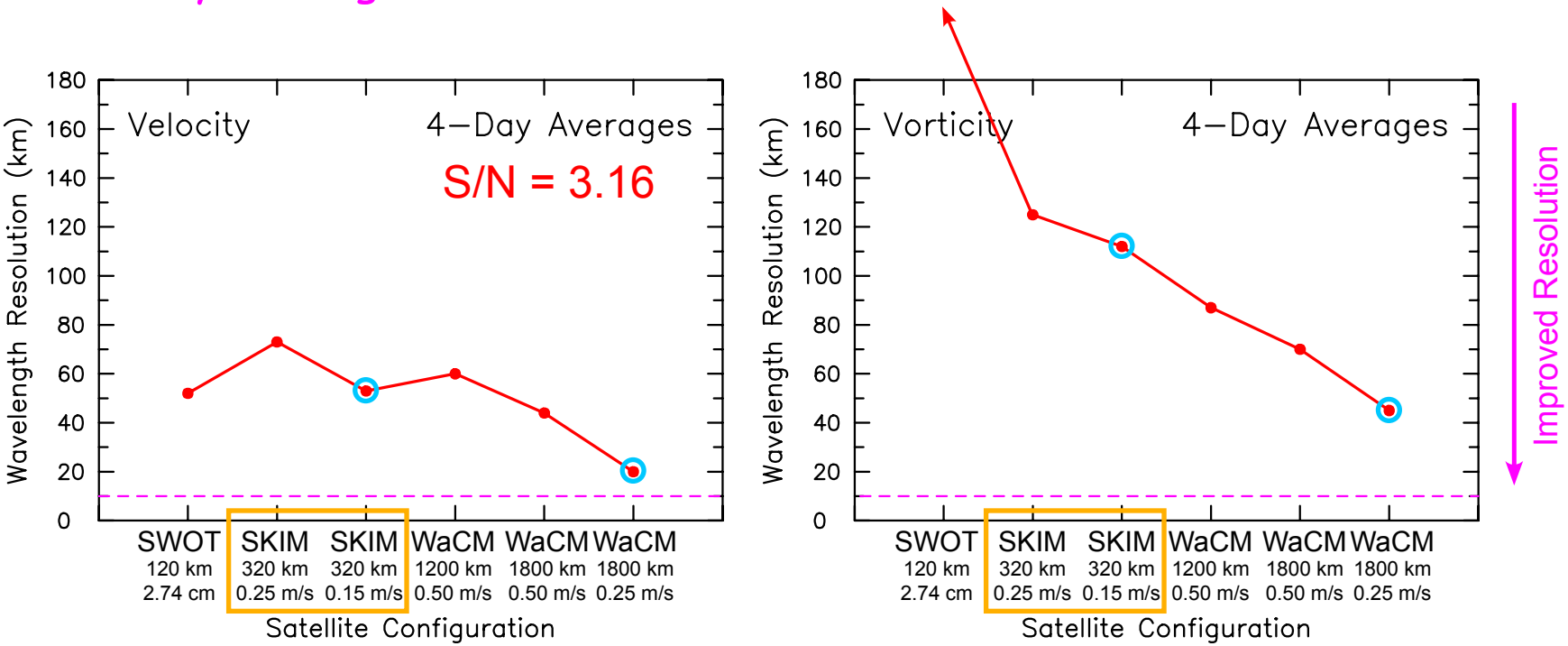
(Differences from top left panel)

The total errors are almost completely controlled by measurement errors

(the errors are too small to see this with 1800 km swath and 0.25 m/s noise)



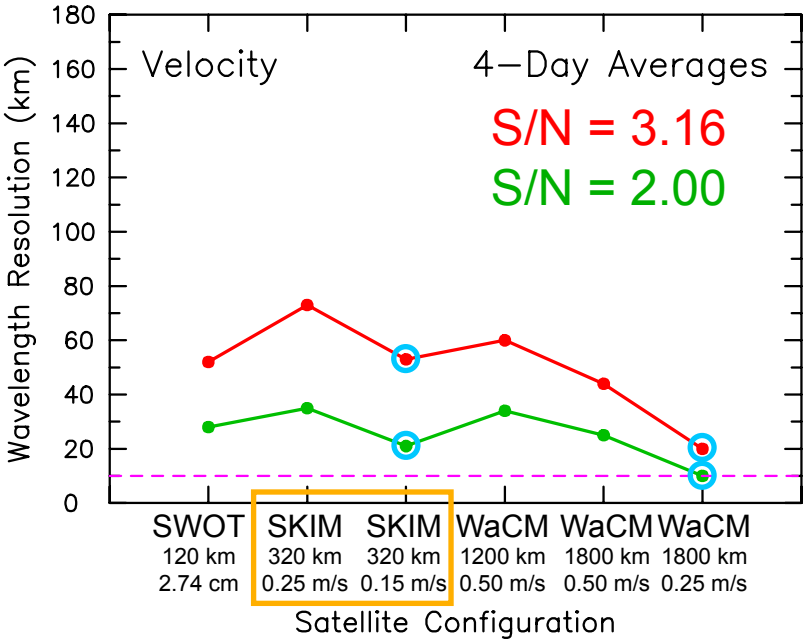
# Summary of WaCM and SKIM Wavelength Resolution Capabilities in 4-Day Averages for S/N Standard Deviation Ratios of 3.16

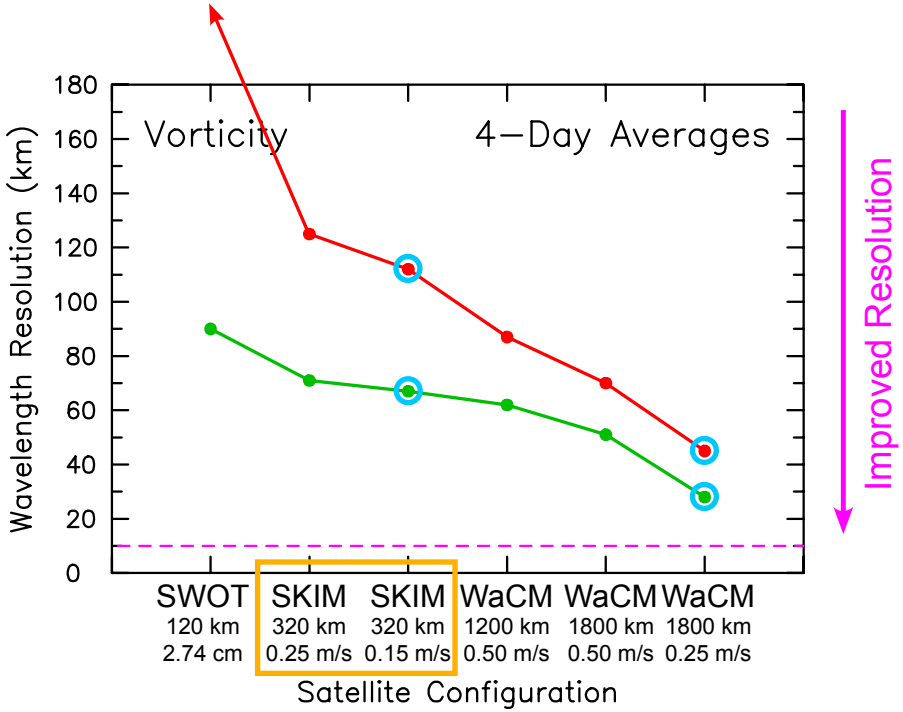



Dashed lines are the 10 km wavelength resolution for the 5 km footprint assumed for WaCM and SKIM

SKIM (Sea surface KInematics Multiscale mission) is a proposed European Space Agency Doppler radar mission to measure surface currents and waves across a swath width of 320 km.

# Summary of WaCM and SKIM Wavelength Resolution Capabilities in 4-Day Averages for S/N Standard Deviation Ratios of 3.16 and 2.00

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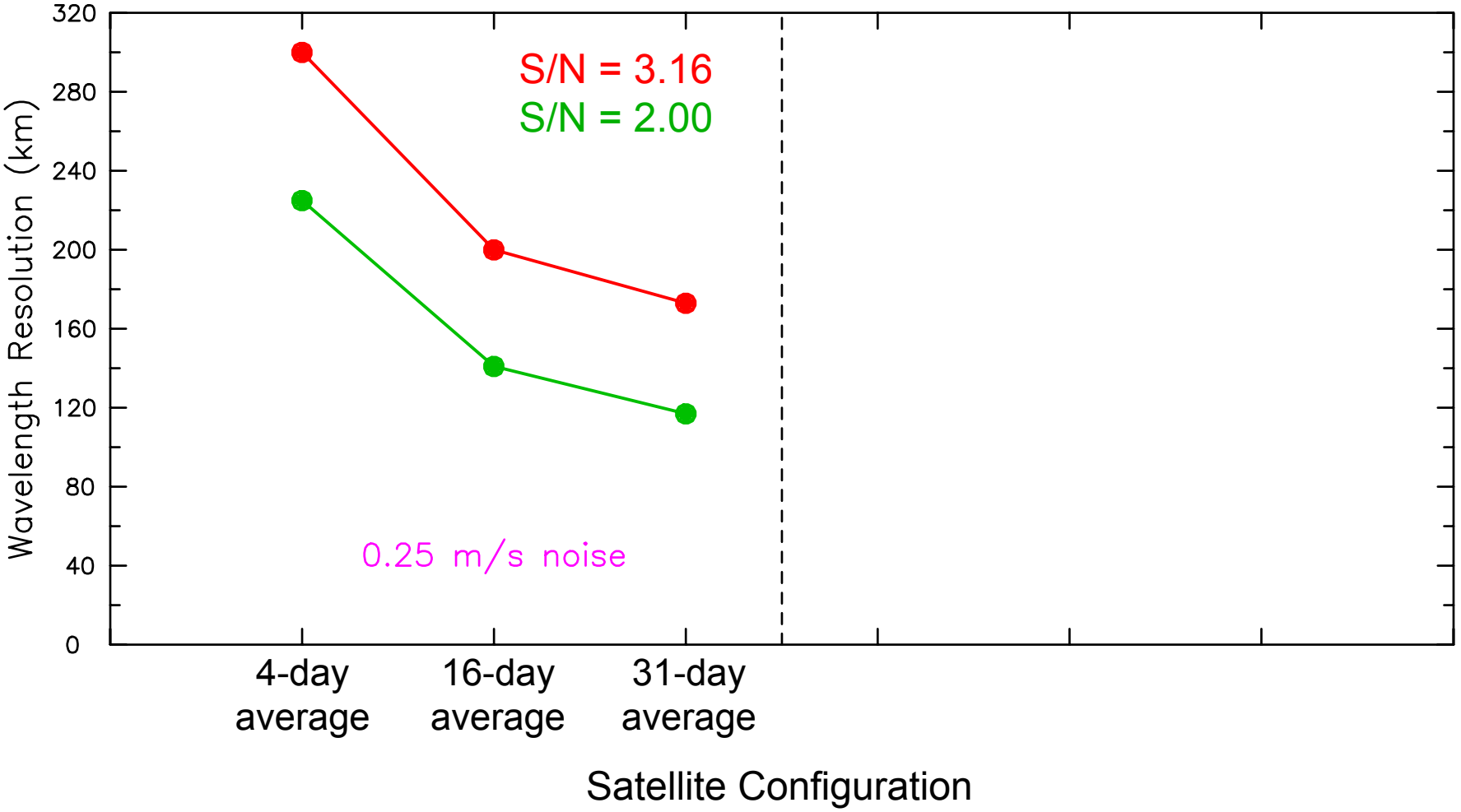
# The Challenge of WaCM Estimation of Surface Current Divergence

Since the velocity field is nearly geostrophic on the scales that will be resolvable by WaCM, divergence is about 10x weaker than vorticity. Estimation of surface current divergence, and hence vertical velocity, will therefore be challenging.

- Divergence and vorticity both involve 1st derivatives of velocity. The residual noise variance for a given amount of smoothing will therefore be about the same for divergence as for vorticity.
- The signal-to-noise ratio will therefore be smaller for divergence than for vorticity.

The resolution capability of WaCM estimates of divergence will thus be coarser than that of vorticity.

# Wavelength Resolution Capabilities of WaCM Estimates of Divergence for 1800-km Swath Width and S/N Standard Deviation Ratios of 3.16 and 2.00



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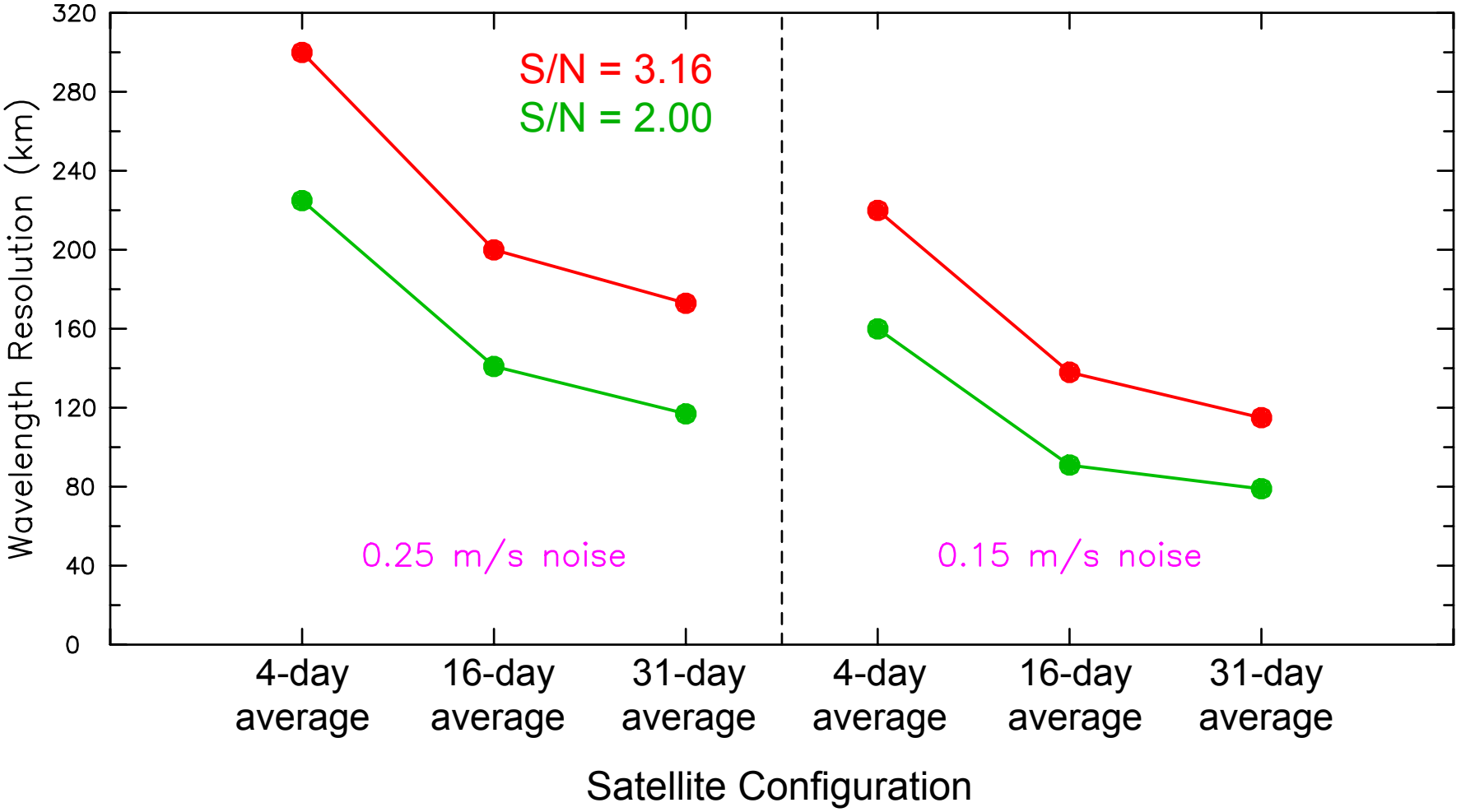

# Summary

- The relative importance of measurement and sampling errors differ for WaCM and SKIM:
  - WaCM is limited almost entirely by measurement errors.
  - SKIM is limited mostly by sampling errors, but the effects of measurement errors are also significant.

- With an 1800-km swath, 0.25 m/s noise and S/N ratios of 3.16/2.00, WaCM would provide 4-day average maps of vorticity with wavelength resolutions of 45/28 km.

- Estimation of divergence is much more challenging. WaCM would provide 16-day average maps of divergence with wavelength resolutions of 200/141 km.
  - WaCM would thus provide the first satellite estimates of mesoscale surface current divergence and the associated vertical velocity with a resolution that is better than that of present AVISO SSH fields that have proven very useful for studies of mesoscale dynamics.

# Final Comments on the Uniqueness of the WaCM Doppler Scatterometer Mission

Whereas conventional scatterometry measures the wind forcing and altimetry measures the (geostrophic) ocean response, WaCM will measure both the wind forcing and the ocean response from a single instrument.

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See Thursday afternoon presentation by Larry O'Neill.

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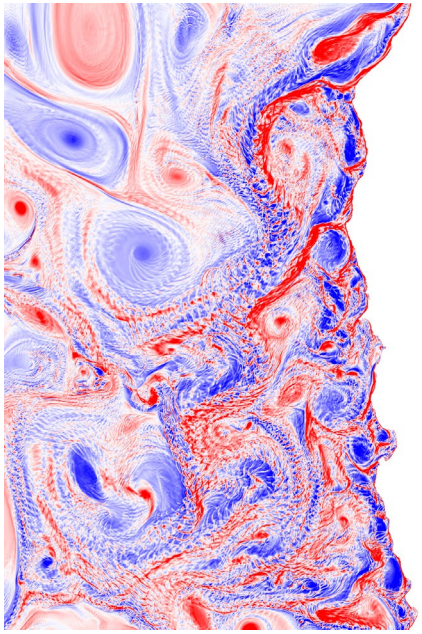
See Thursday afternoon presentation by Larry O'Neill.

Imagine a single satellite instrument that provides estimates of surface winds, currents and SSH across a swath width of 1800 km . . .

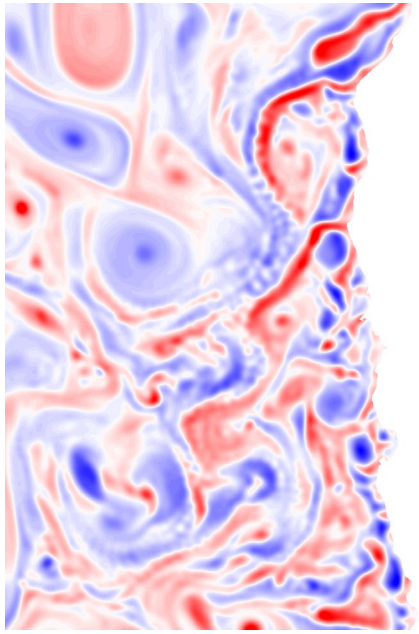
# Error-Free 4-Day Average Maps of Vorticity with Various Smoothing for 0.25 m/s Noise

4-Day Average
Unsmoothed



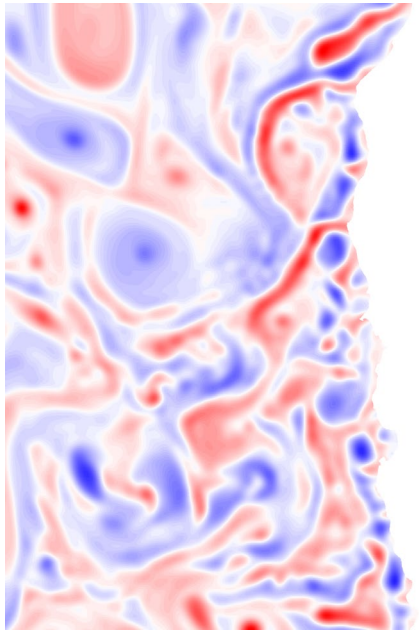

WaCM with S/N = 2.00
(1800 km, 0.25 m/s)

4-Day Average
with 28 km Smoothing



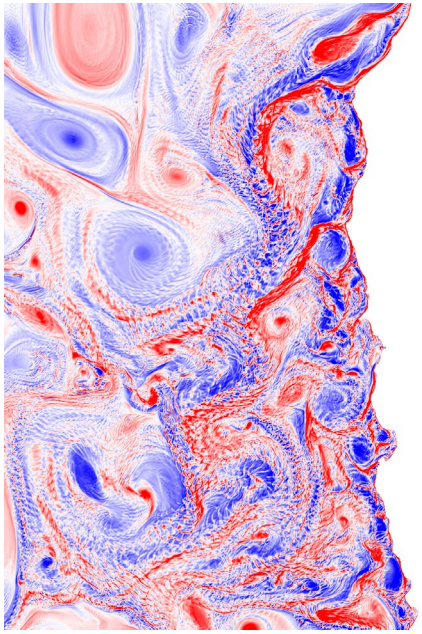

WaCM with S/N = 3.16
(1800 km, 0.25 m/s)

4-Day Average
with 45 km Smoothing



# Error-Free 4-Day Average Maps of Vorticity with Various Smoothing for 0.25 m/s Noise

4-Day Average
Unsmoothed




WaCM with S/N = 2.00
(1800 km, 0.25 m/s)
4-Day Average
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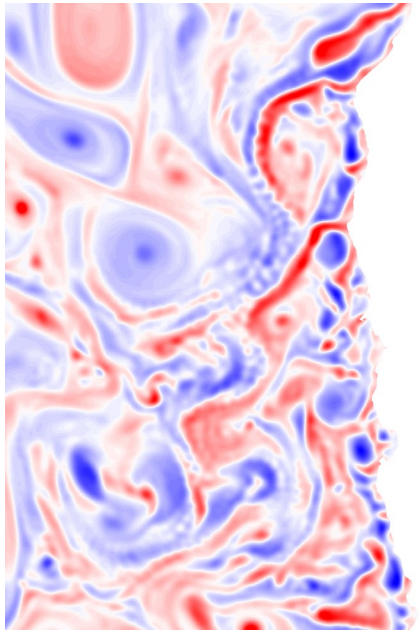
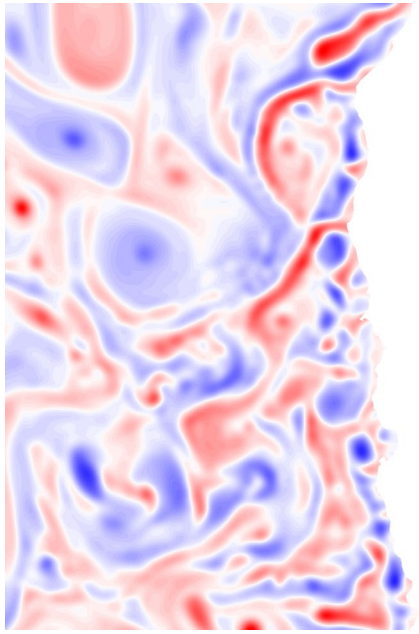
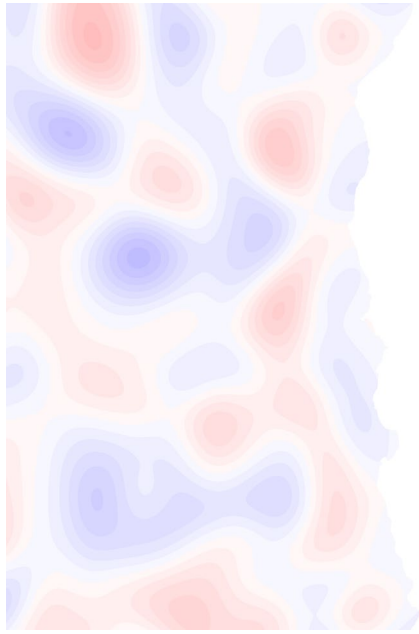



WaCM with S/N = 3.16
(1800 km, 0.25 m/s)
4-Day Average
with 45 km Smoothing

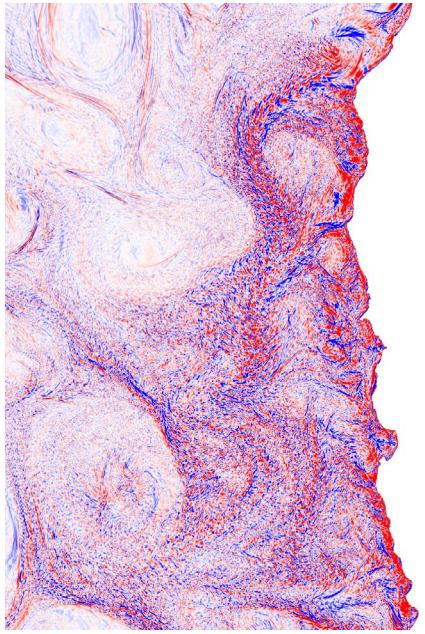



Present Capability
from AVISO SSH
31-Day Average
with 200 km Smoothing

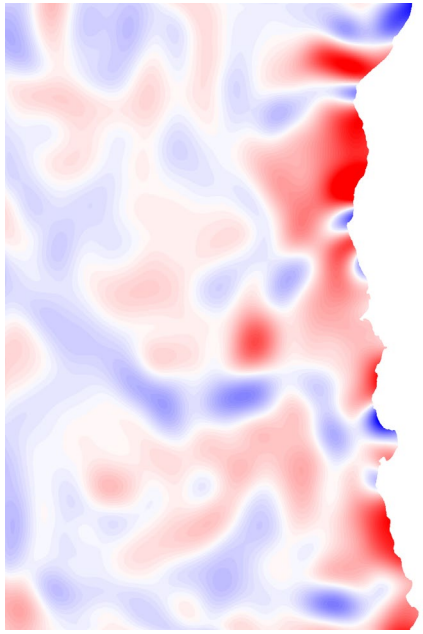


# Error-Free 16-Day Average Maps of Divergence with Various Smoothing for 0.25 m/s Noise

16-Day Average
Unsmoothed




WaCM with S/N = 2.00
(1800 km, 0.25 m/s)
16-Day Average
with 141 km Smoothing




WaCM with S/N = 3.16
(1800 km, 0.25 m/s)
16-Day Average
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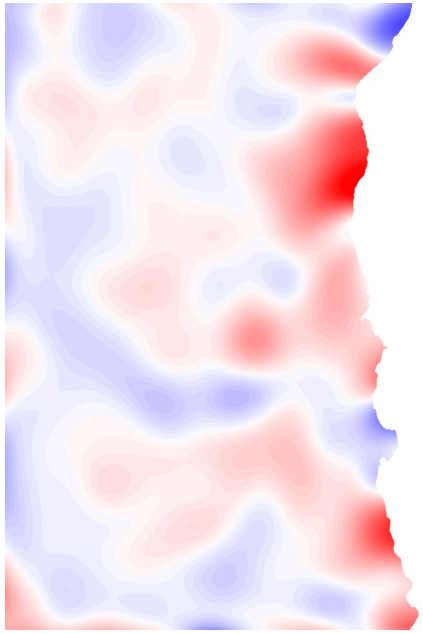
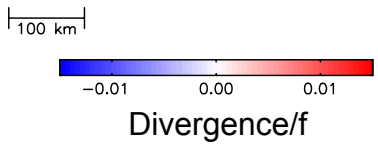



Present Capability

NONE

?




Note 5x wider dynamic range
of color bar for left panel.

# Extra Slides

# Future Satellite Instruments for Observations of Mesoscale to Submesoscale Surface Currents

1. Winds and Currents Mission (WaCM)

   WaCM is one of seven candidate "Earth System Explorer" missions identified in the Decadal Survey for Earth Science from Space, which recommends funding of three of the seven missions.

   WaCM will observe surface winds and ocean currents across a swath of width 1800 km with a 100 km nadir gap and a footprint size of 5 km with measurement errors of ~0.25 m/s for surface currents.

2. Sea surface KInematics Multiscale (SKIM) Mission

   SKIM is one of two proposed European Space Agency's ninth "Earth Explorer" missions, competing with the Far-Infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission.

   SKIM will observe surface currents, ice drift and waves (but not winds) across a swath of width 320 km and a footprint size of ~5 km with measurement errors of ~0.15 m/s for surface currents.

# Orbit Characteristics for WaCM and SKIM

1. For WaCM, we assumed the 4-day exact-repeat orbit of QuikSCAT.

   The CCS model domain is sampled by one of the 1800-km 2-sided swaths on every overpass and there are 8 overpasses (4 ascending and 4 descending) with complete or at least partial swath coverage during each 4-day repeat.

3. For SKIM, we assumed the 29-day exact-repeat orbit of MetOp-B.

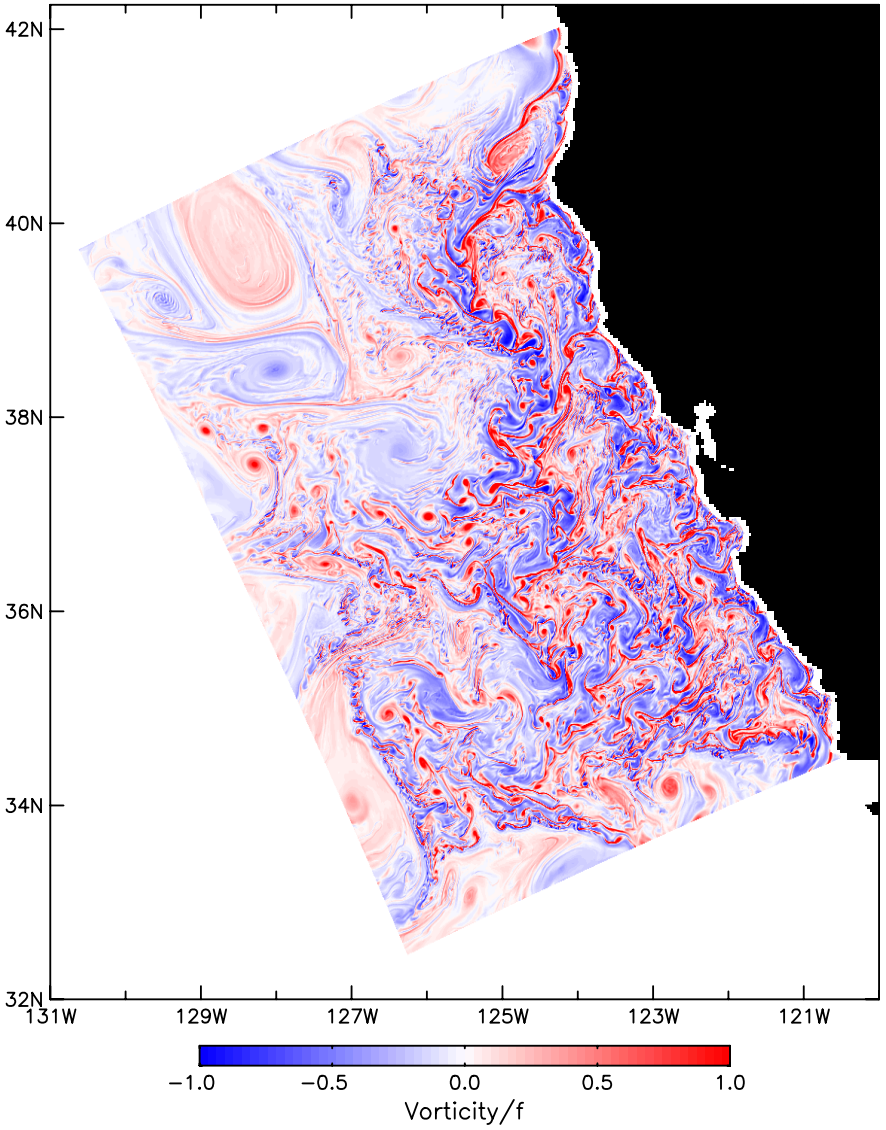
   The ground tracks fill in from west to east with coarse coverage of the full CCS model domain in 4 days and complete coverage in 14 days in the form of overlapping swaths with spatially adjacent swaths separated by 5 days.

We have therefore considered the effects of measurement and sampling errors in 4-day and 14-day averages.

Only the 4-day sampling will be considered in this presentation.

# High-Resolution Vorticity/f from a Model of the CCS

## (Molemaker et al, 2015, J. Phys. Oceanogr.)




ROMS Model

Grid: Uniform 0.5 km x 0.5 km

Grid rotated 24° from

north-south/east-west

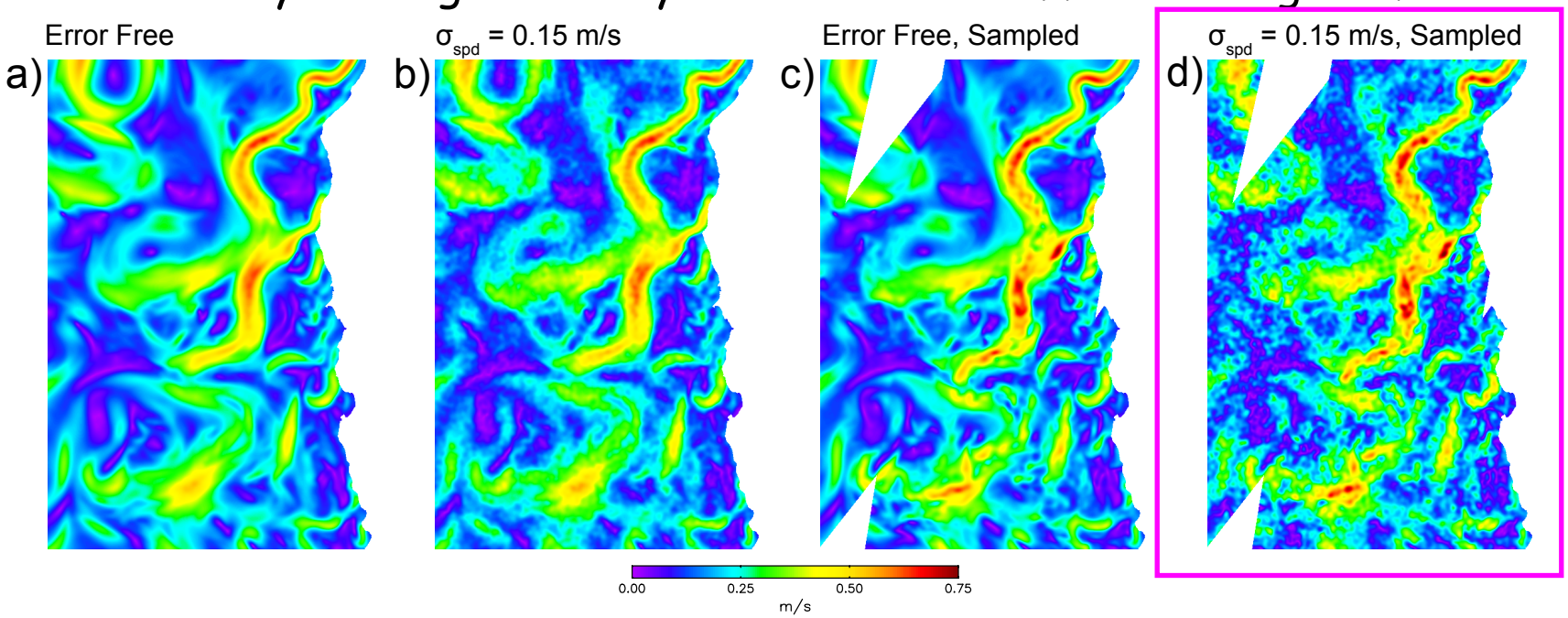
Forcing:

- Seasonal cycle wind stress from QuikSCAT without SST feedback or surface current feedback.
- Climatological heat fluxes.
- Does not include tidal forcing.

The model thus:

- Underestimates the contributions of internal gravity waves and inertial motions to the surface velocity field.
- Does not include $w_{SST}$ or $w_c$, but does include $w_\zeta$ (as do all models).

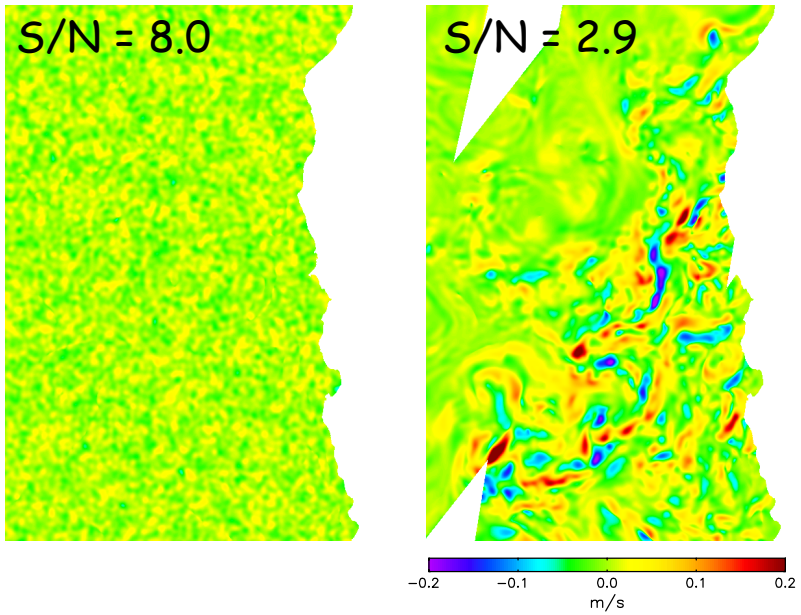
# SKIM 4-Day Average Velocity with Filter Cutoff Wavelength of 25 km




Error Maps

(Differences from top left panel)

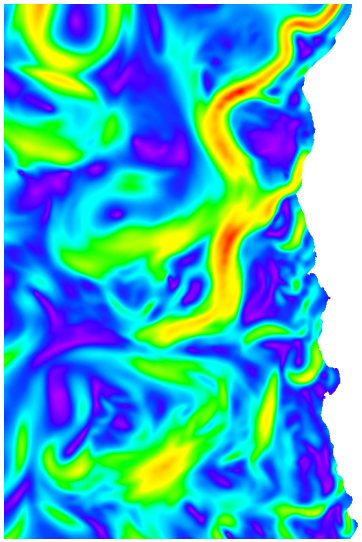
The total errors are dominated by sampling errors, although measurement errors also have an effect



# WaCM 4-Day Average Velocity with Filter Cutoff Wavelength of 25 km

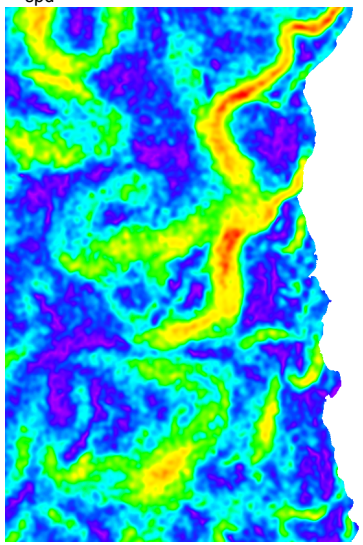
Error Free

a)



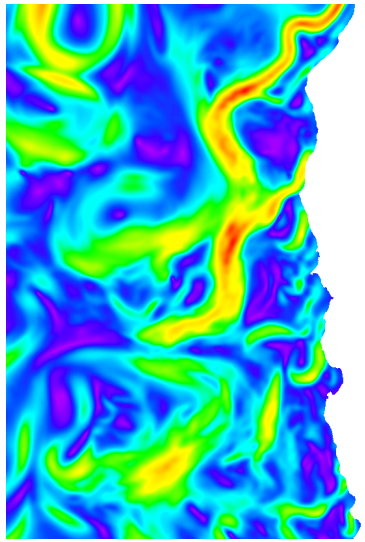
$\sigma_{spd}$ = 0.25 m/s

b)



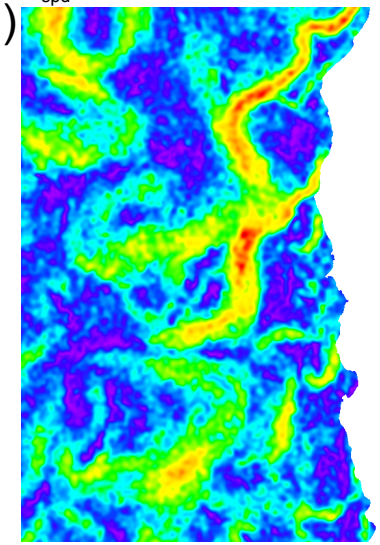
Error Free, Sampled

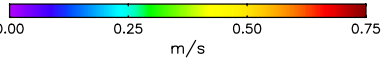
c)



$\sigma_{spd}$ = 0.25 m/s, Sampled

d)



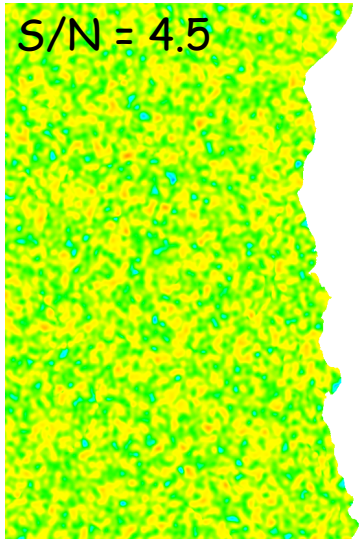



Error Maps

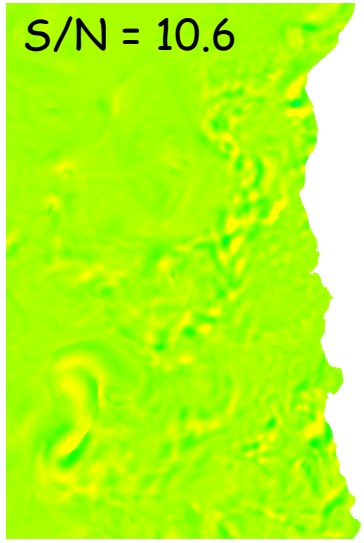
(Differences from top left panel)

The total errors are almost completely controlled by measurement errors

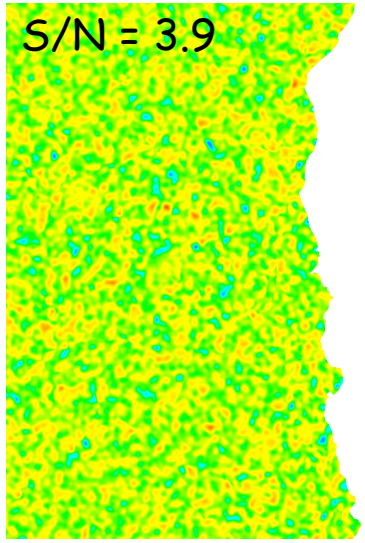
S/N = 4.5

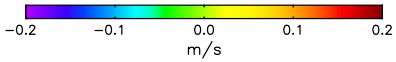


S/N = 10.6



S/N = 3.9





# DopplerScatt Overview

## (Courtesy of Ernesto Rodriguez, Jet Propulsion Laboratory)

### DopplerScatt Programmtic Overview

Scanning Doppler radar developed under NASA's IIP program

Becoming operational under NASA AITT program by 2019

### Data Products:

1.Vector ocean surface currents

2.Vector ocean surface winds

3.Radar brightness maps (sensitive to surfactants such as oil films)

4.. Wave spectra (experimental)

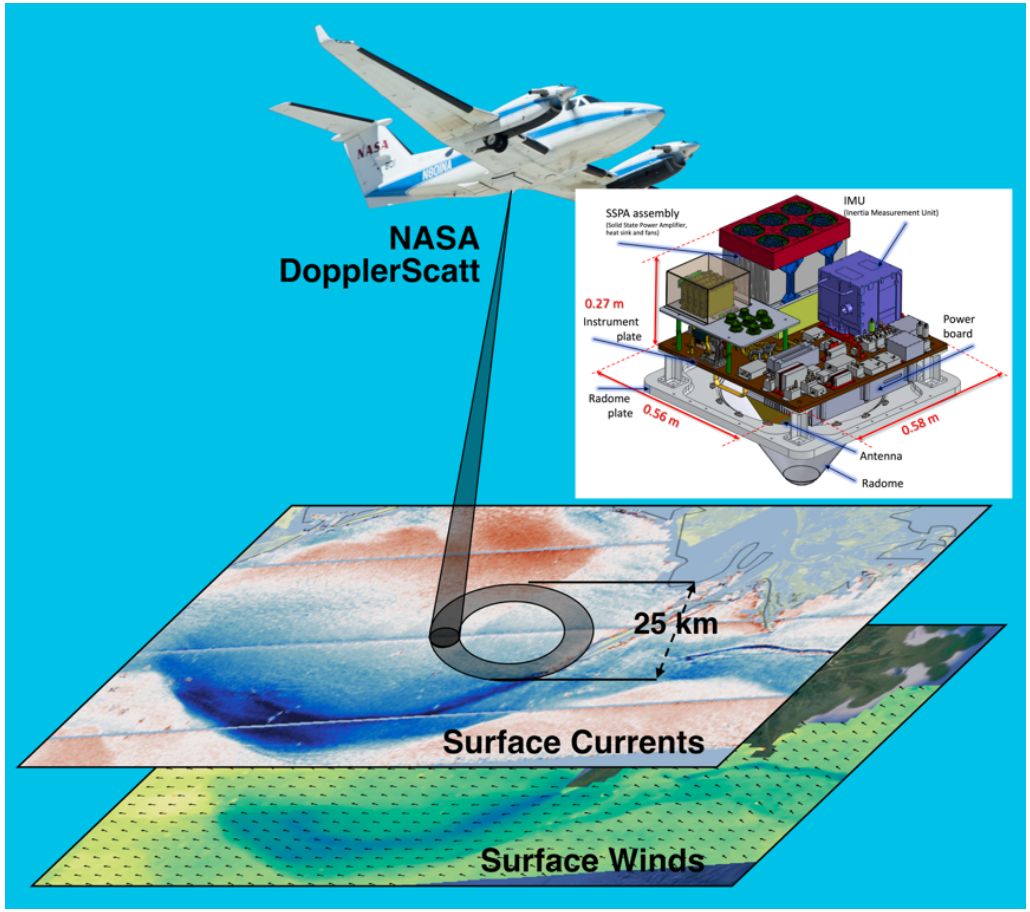
Data products are still being refined under AITT. Will be posted in NASA PODAAC when finished.

### Mapping capabilities:

- 25 km swath
- maps 200km x 100km area in about 4 hrs
- 200m data product posting
- Mapping within ~600 m of coast
- ~5-10 cm/s radial velocity precision.
- ~ 1 m/s wind speed, <20° wind direction.

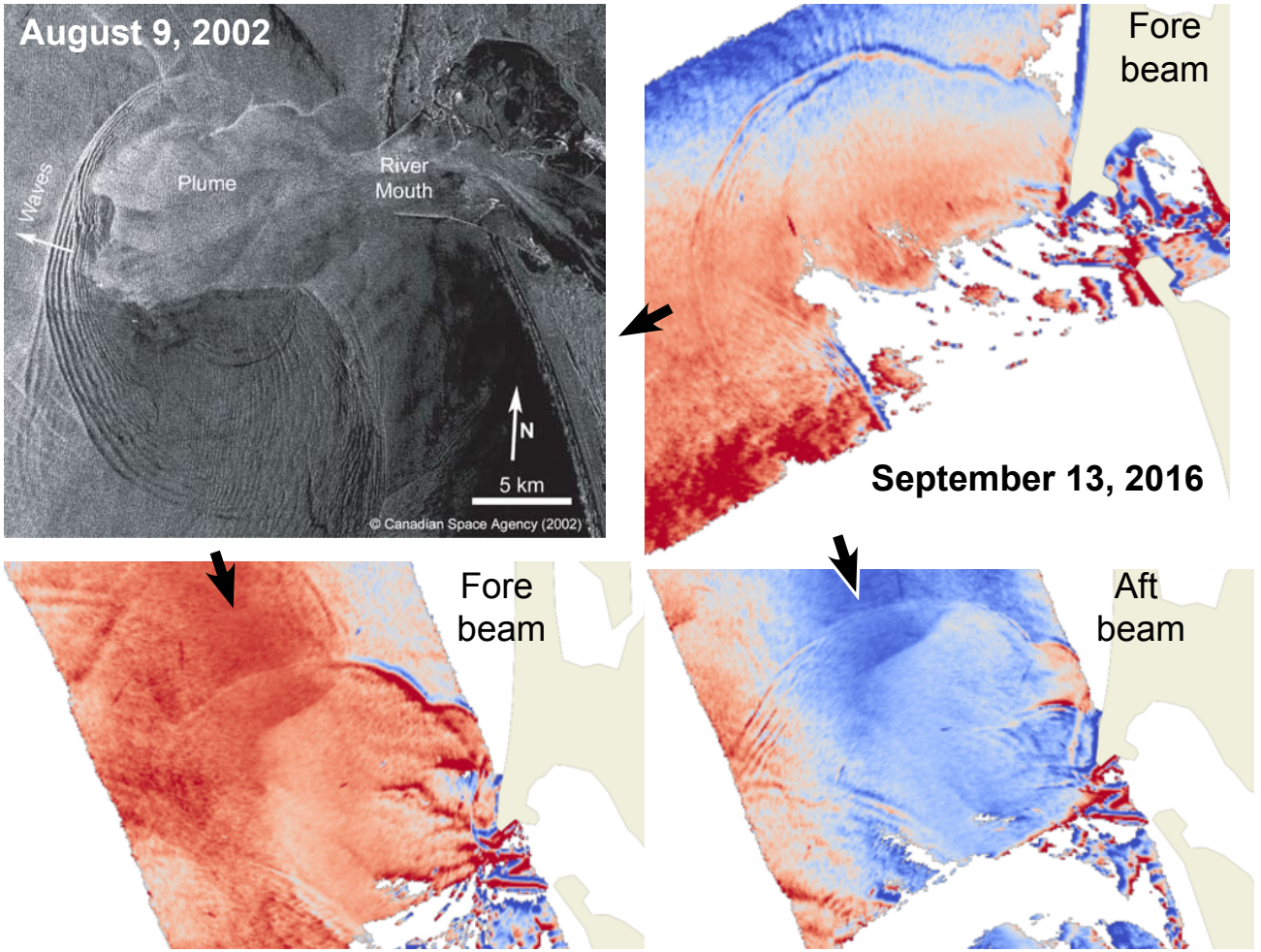
### Campaigns flown/planned:

- Oregon coast (2016)
- SPLASH (Submesoscale Processes and Lagrangian Analysis on the Shelf) in Mississippi River Plume
- KISS-CANON in Monterey Bay May 1-4, 2017.
- Chevron GoM (March, 2018)
- California current (September, 2018)



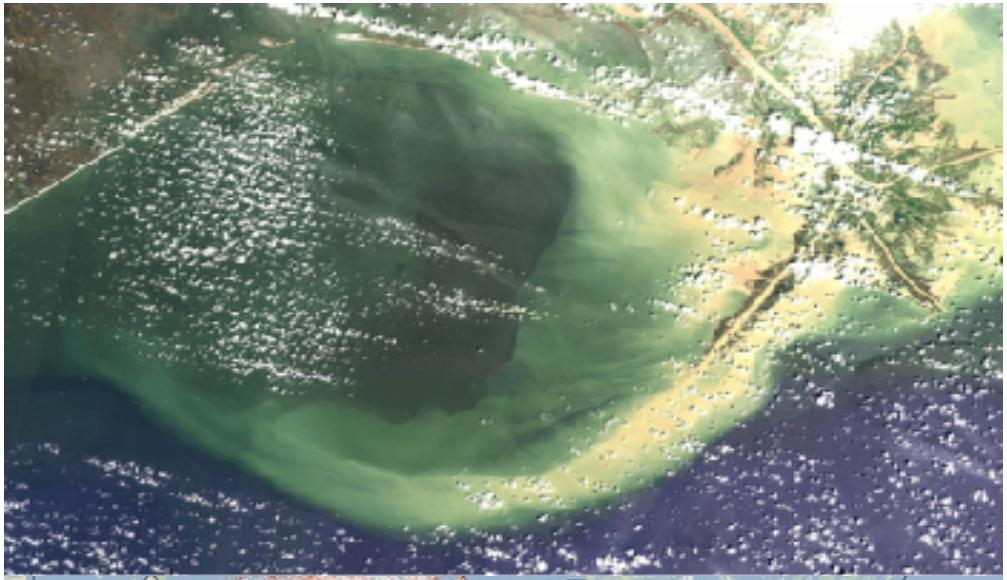
# Columbia River Tidal Plume Front: August 2002 SAR Image and September 2016 DopplerScatt Observations of Radial Velocity

Courtesy of Ernesto Rodriguez, JPL

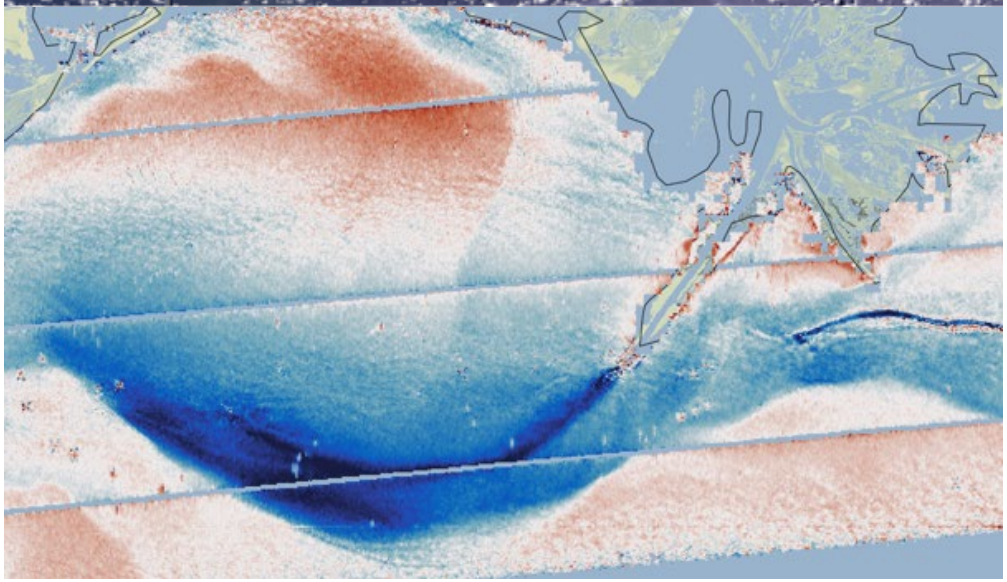



White areas within the measurement swaths are regions of low signal, likely attributable to suppression of Bragg scattering waves by biological surfactants in areas of low wind speeds.

# SPLASH Campaign
## (Submesoscale Processes and Lagrangian Analysis on the Shelf)



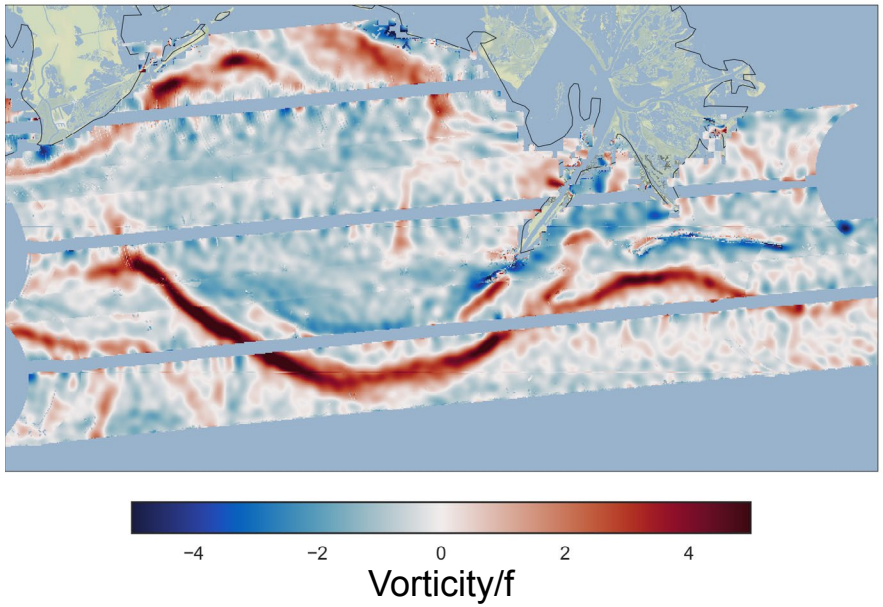
Sentinel 3 2017-04-18
Courtesy of Copernicus Sentinel, processed by ESA

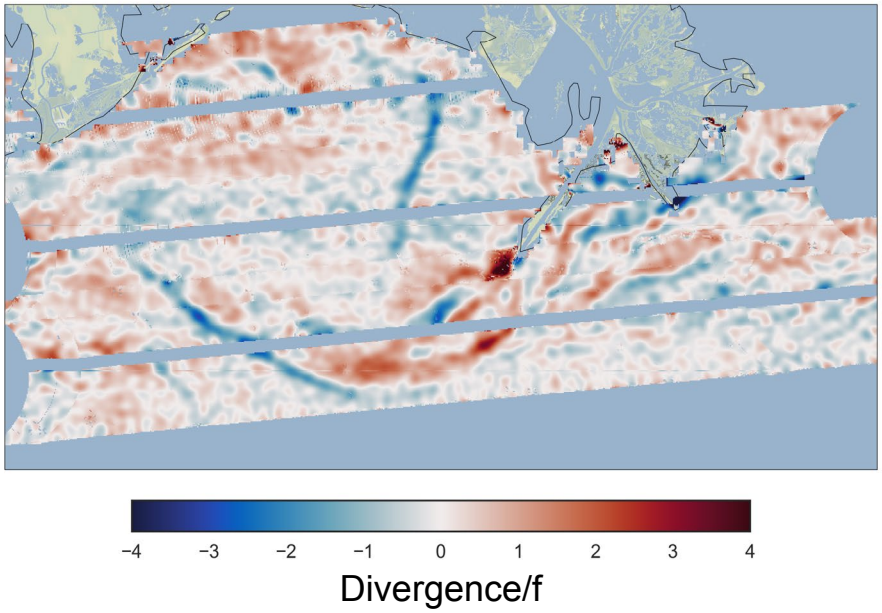


DopplerScatt surface current U component.

Circulation pattern matches Sentinel 3 color pattern very closely.

# DopplerScatt Estimates of Surface Current Vorticity and Divergence




DopplerScatt figures courtesy of the JPL DopplerScatt Team:

Instrument PI:
Dragana Perkovic-Martin

Science Lead:
Ernesto Rodriguez

Team:
T. Gal, N. Majurec
N. Niamsuwan
F. Nicaise
R. Rodriguez
K. Srinivasan
B. Stiles
A. Wineteer