# The Prospects for Future Estimation of Mesoscale and Submesoscale Vorticity by Doppler Scatterometry

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# Outline

- Show an example snapshot of energetic submesoscale variability from a model of the California Current System.

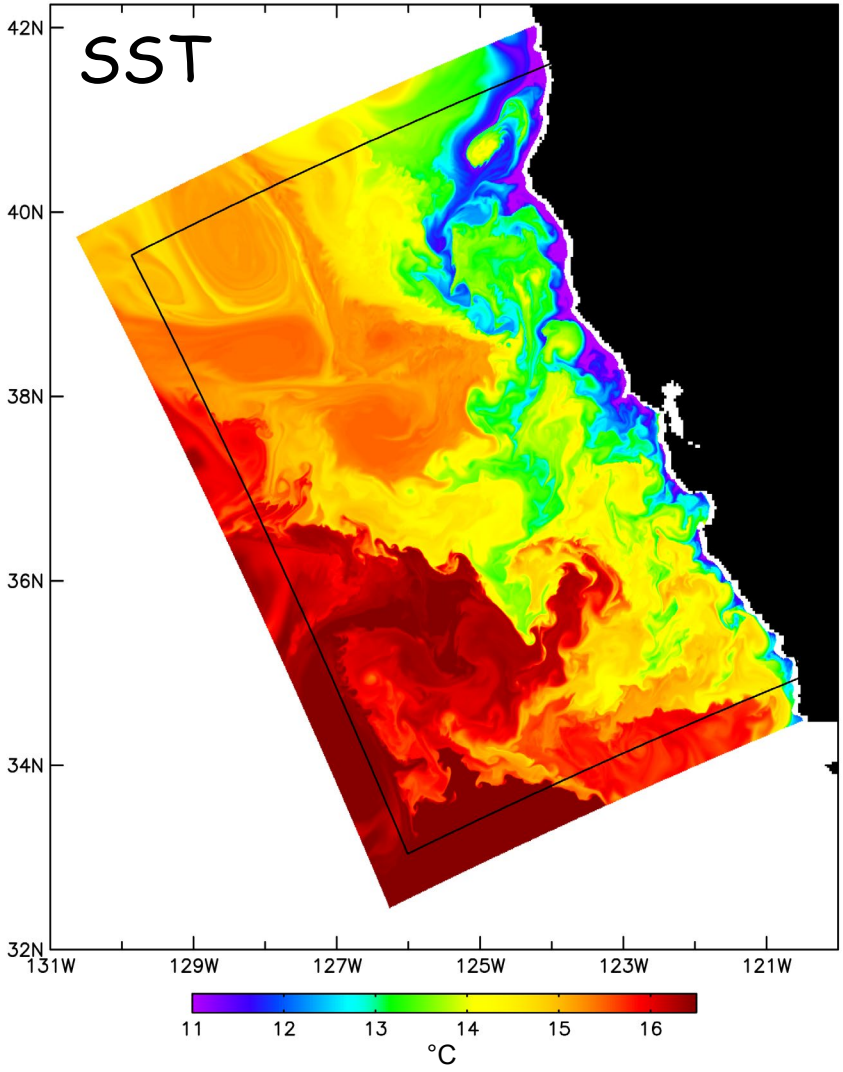
  Compare the submesoscale variability with the resolution capability of about 200 km from presently available satellite data (the SSH fields from AVISO).

- Briefly summarize the sampling characteristics of a Doppler scatterometer concept, tentatively referred to as a "Winds and Currents Mission" (WaCM)

  Contrast with the Surface Water and Ocean Topography (SWOT) mission.

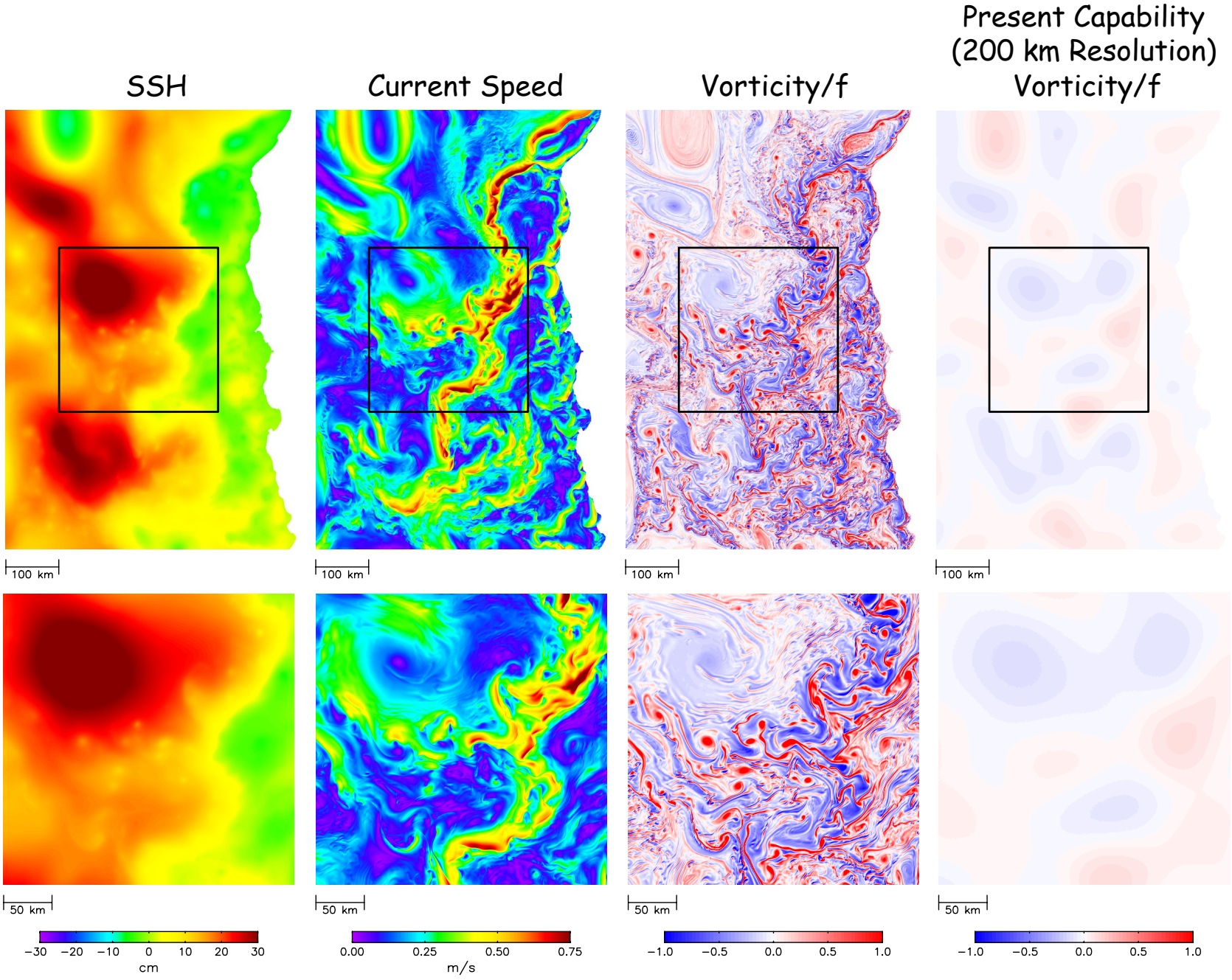
- Compare the resolution capabilities of WaCM and SWOT estimates of surface current speed and relative vorticity.

# Simulated Satellite Observations Based on the UCLA ROMS Model of the California Current System (CCS)




## Model Details:

- Forced by QuikSCAT-based seasonal cycle winds.
- Grid spacing 0.5 km in an orthogonal coordinate system rotated 24° from north-south/east-west.
- 40 vertical levels with a resolution of a few meters near the surface.
- 90-second time step.
- The analysis presented here is based on twice-daily snapshots for the 31-day time period 21 May - 21 June.


SSH
Current Speed
Vorticity/f
Present Capability
(200 km Resolution)
Vorticity/f
100 km
100 km
100 km
100 km
50 km
50 km
50 km
50 km
−30 −20 −10 0 10 20 30
cm
0.00 0.25 0.50 0.75
m/s
−1.0 −0.5 0.0 0.5 1.0
−1.0 −0.5 0.0 0.5 1.0

# Future Satellite Instruments for Observations of Mesoscale to Submesoscale Variability

1. Surface Water and Ocean Topography Mission

   SWOT will observe SSH across a swath of width 120 km with a 20 km nadir gap, a footprint size of 1 km and a measurement error of 2.74 cm.

   This requires double differentiation to get geostrophic vorticity $\zeta_g$.

2. Winds and Currents Mission Concept

   WaCM will observe surface winds and surface ocean velocity across a swath of width 1300 km with a 100 km nadir gap and a footprint size of 5 km. The expected measurement errors are 1.5 m/s for winds and 0.5 m/s for surface currents.

   This requires single differentiation to get vorticity $\zeta$ and is not subject to limitations of the geostrophic approximation.

# Velocity and Vorticity Errors from WaCM and SWOT

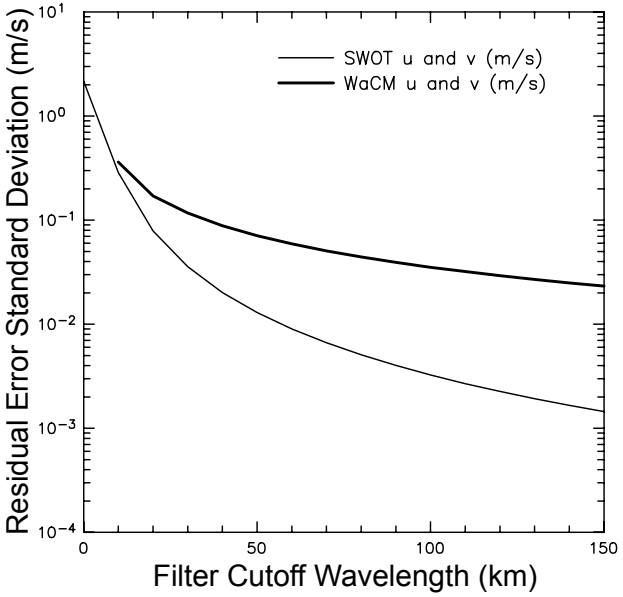
The speed uncertainty for WaCM with a footprint size of 5 km is 0.5 m/s, which corresponds to an uncertainty of 0.354 m/s in each velocity component.

The uncertainty of each geostrophic velocity component for SWOT with an SSH uncertainty of 2.74 cm is 2.17 m/s for a 1 km footprint and 0.290 m/s when smoothed over 5 km. This corresponds to a speed error of 0.410 m/s.

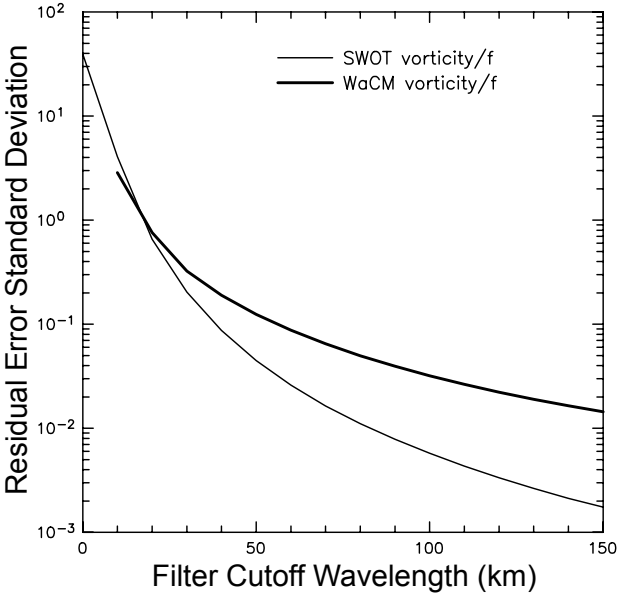
The corresponding noise levels for unitless normalized vorticity $\zeta/f$ with 5 km smoothing are 2.86 for WaCM and 4.08 for SWOT.

WaCM and SWOT data clearly must be smoothed to reduce these large errors.

Velocity Component Noise




Vorticity/f Noise



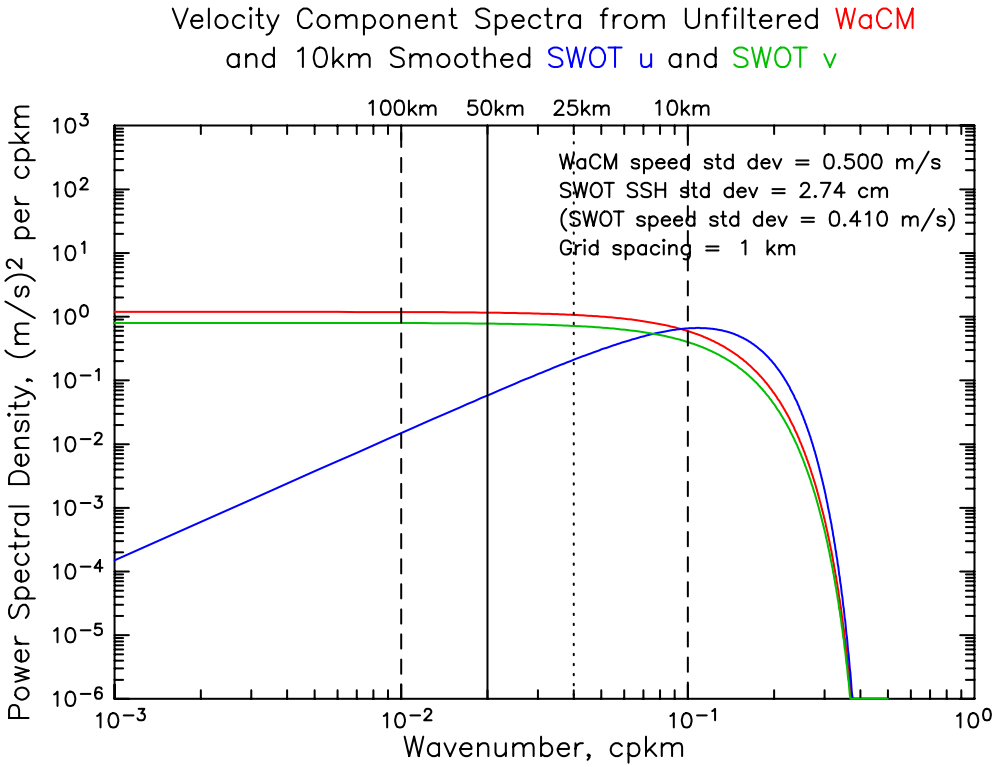

The faster reduction of errors for SWOT is because of the very different spectral characteristics of its velocity errors from the response function for centered difference estimates of the derivatives.

# Comparison of Velocity Errors from WaCM versus SWOT

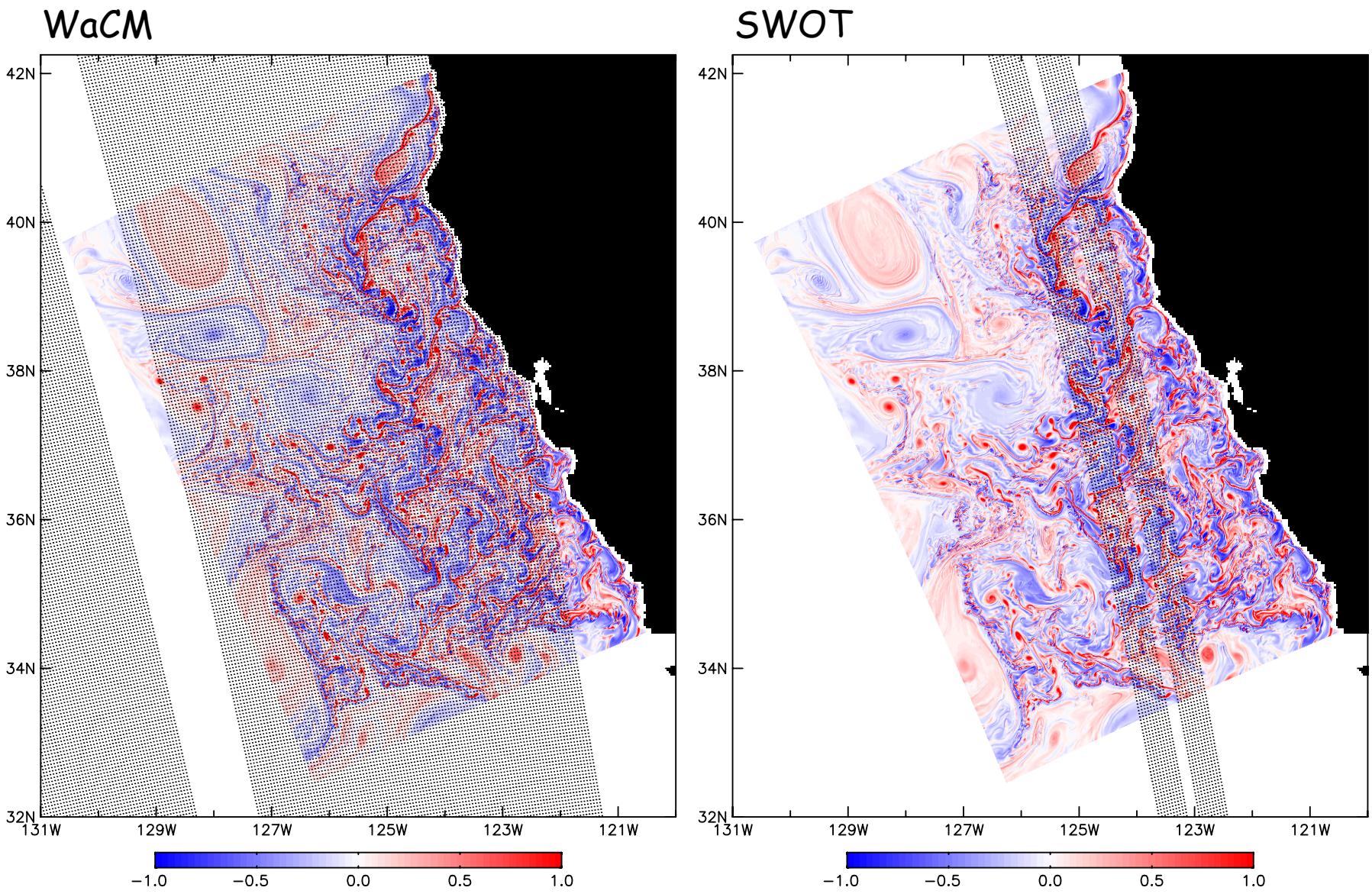
When smoothed with a filter cutoff of 10 km to match the 5 km footprint size of WaCM, the errors of geostrophic speed from 1x1 km SWOT with a 2.74 cm std dev of SSH measurement errors are 0.41 m/s.

The along-track spectra of errors of both components of WaCM estimates of velocity and SWOT estimates of along-track geostrophic velocity are very similar.

However, the centered differencing to get SWOT estimates of cross-track geostrophic velocity results in a "blue" along-track spectrum of errors.



# WaCM versus SWOT Measurement Swaths



# Orbit Characteristics for WaCM and SWOT

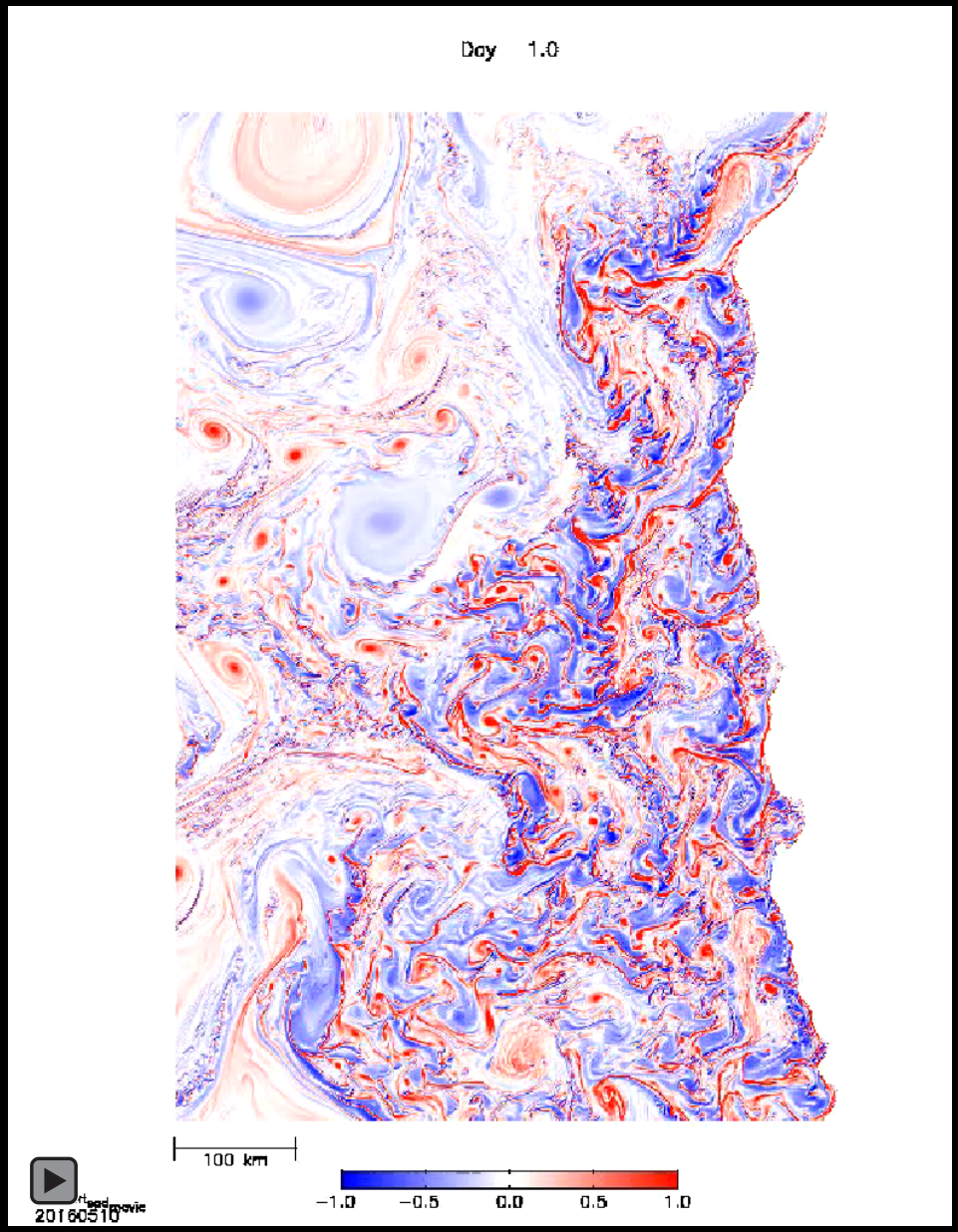
1. The SWOT orbit will have an exact repeat period of 21 days.

   For the CCS region, there are two 4-day subcycles within a 14-day period during each 21-day repeat.

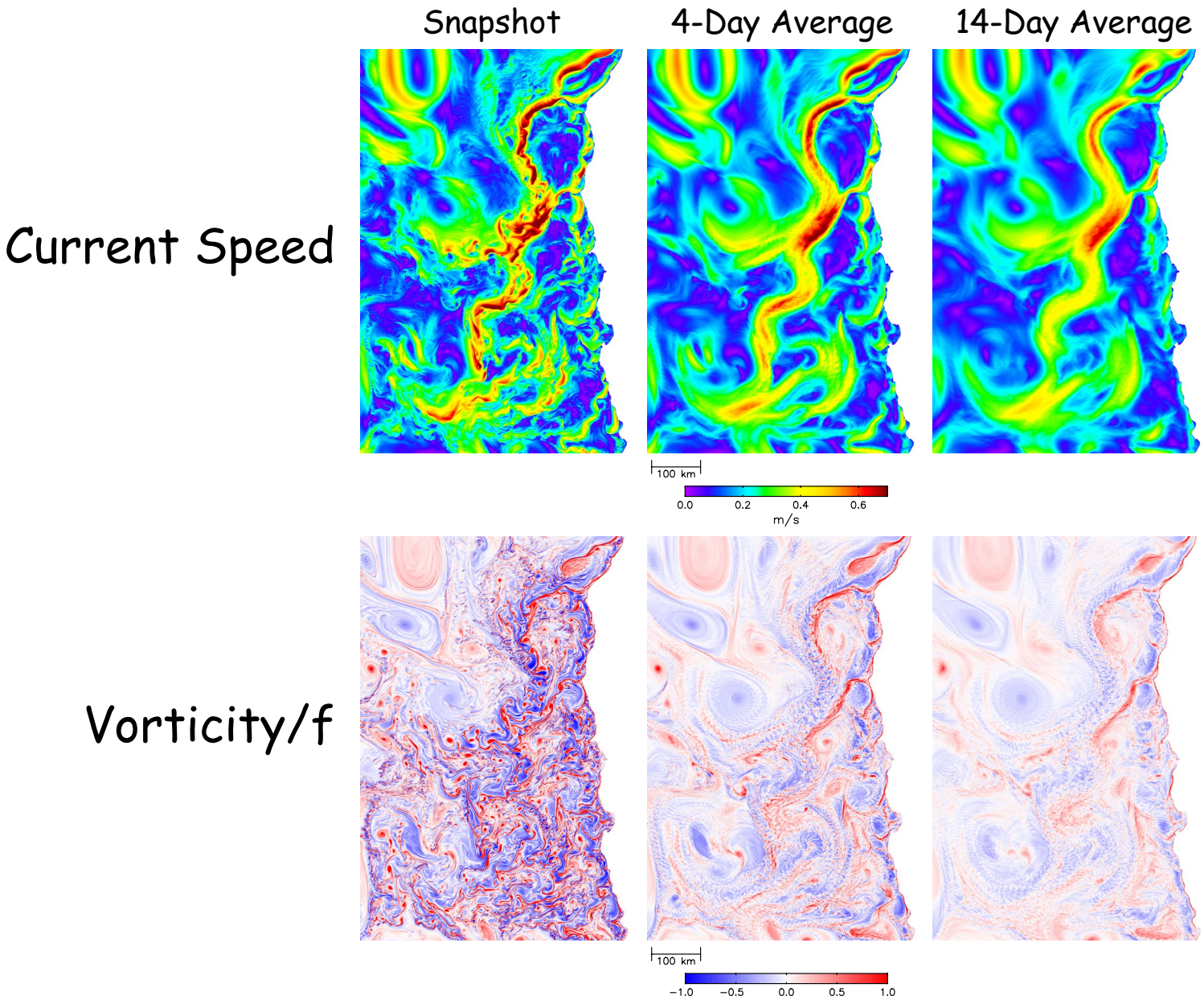
2. The WaCM orbit would likely have an exact repeat of 4 days.

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

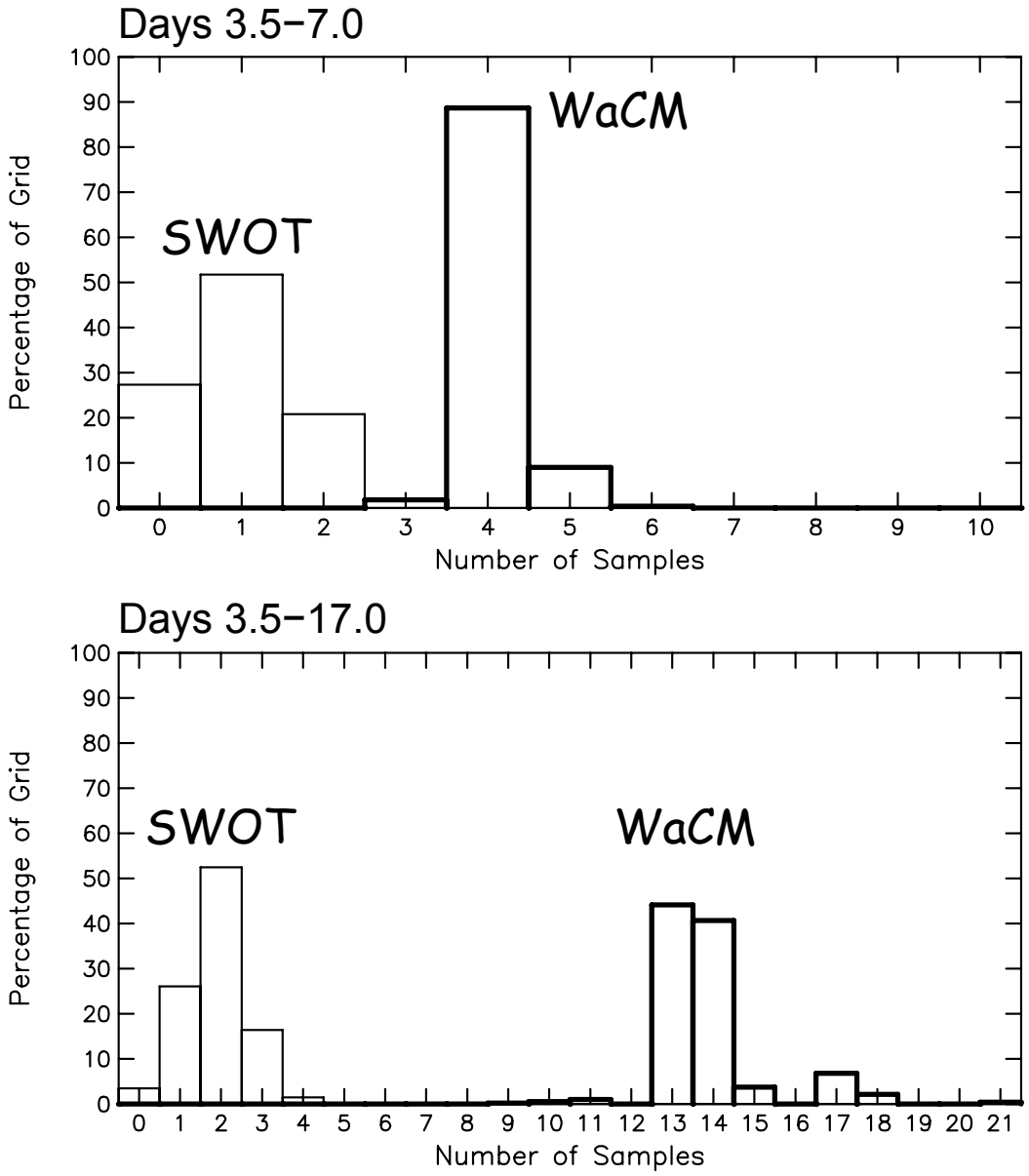
# 31-Day Animation of ζ/f from ROMS Model of the CCS



# Error-Free Time-Averaged Maps



# 4-Day and 14-Day Sampling by WaCM and SWOT



# Criterion for Defining Resolution Capability

1. Space-time averaged maps were constructed 3 different ways:
   - Signal over the full *CCS* domain = "signal only".
   - Noise over the full *CCS* domain = "noise only".
   - Signal sampled only within the measurement swaths = "sampling errors only".
   - Noise sampled only within the measurement swaths = "noise + sampling errors".

2. The 3 space-time averaged fields were smoothed isotropically with half-power filter cutoff wavelengths ranging from 20 km to 200 km.

3. The spatial variance was computed for each of the quadruplet sets of smoothed fields.

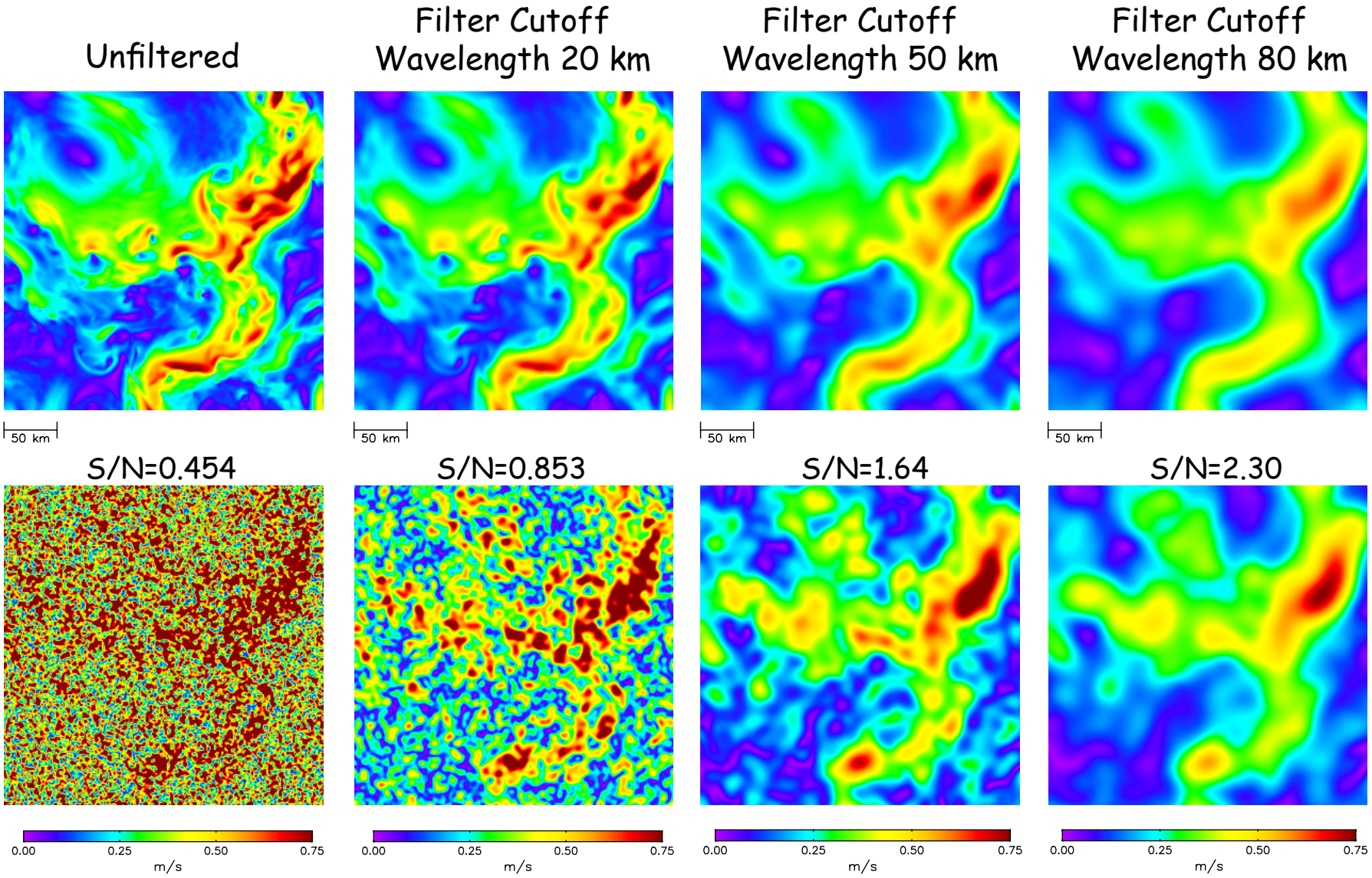
4. The resolution capability was defined to be the filter cutoff wavelength at which the Signal-to-Noise variance ratio is >10.
   - This corresponds to a standard deviation ratio of 3.16.

# WaCM Estimates of Current Speed and Vorticity with 0.5 m/s Velocity Measurement Noise

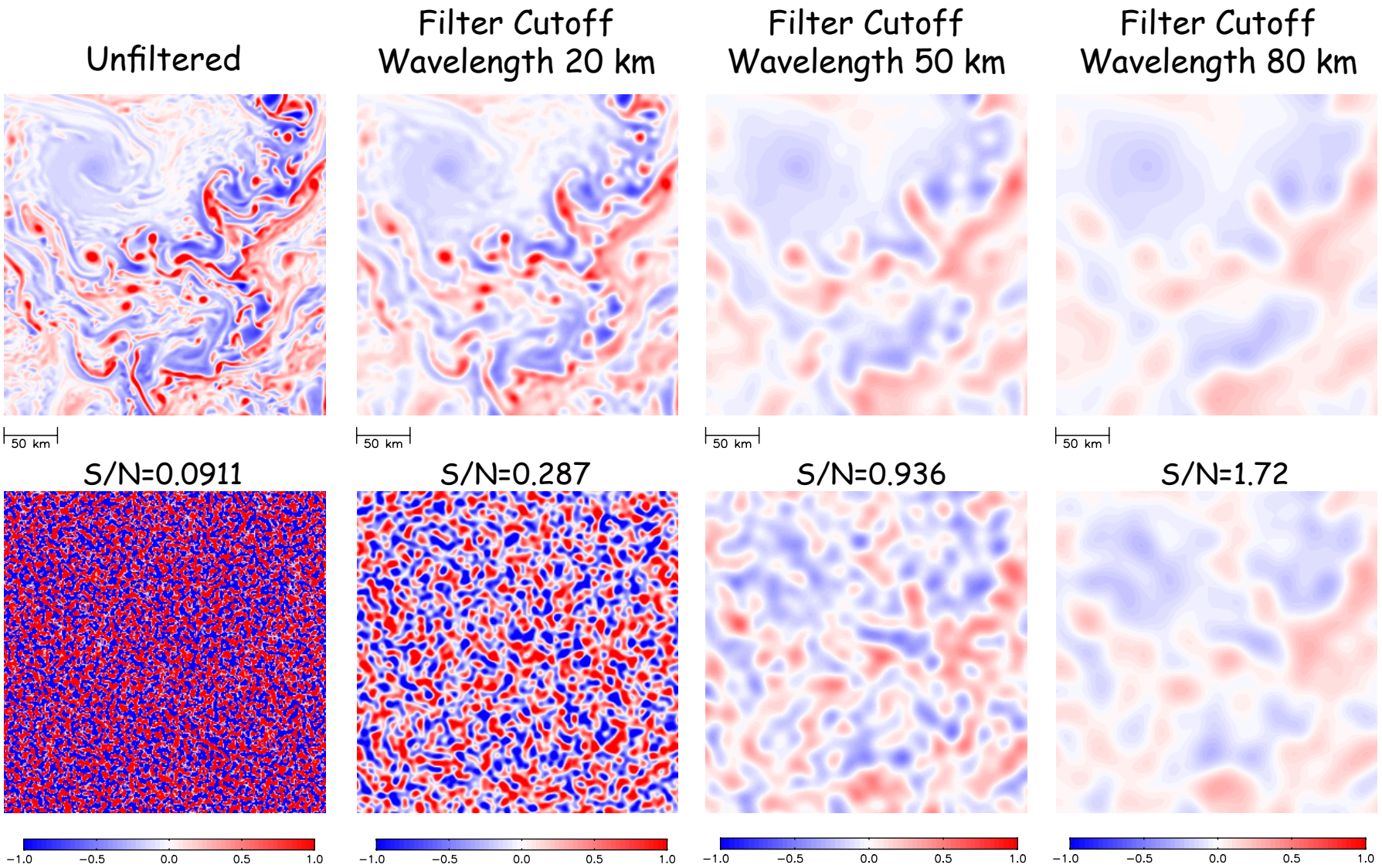
## Part 1:

Smoothed maps constructed from a snapshot of error-free and noisy velocity during a single WaCM overflight of the Central CCS region

# Smoothed WaCM Maps of Current Speed
# Error-Free and with 0.5 m/s Uncorrelated Noise



# Smoothed WaCM Maps of Vorticity/f
# Error-Free and with 0.5 m/s Uncorrelated Noise



# WaCM Estimates of Current Speed and Vorticity with 0.5 m/s Velocity Measurement Noise

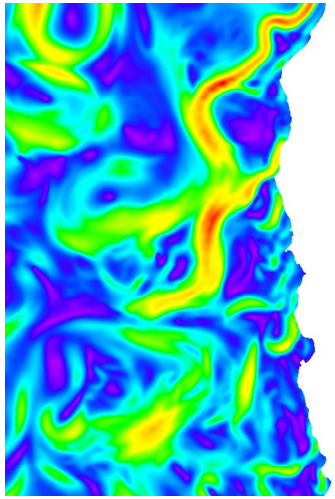
## Part 2:

Smoothed maps constructed from 4-day and 14-day averaged error-free and noisy velocity over the full CCS domain and sampled within just the WaCM measurement swaths

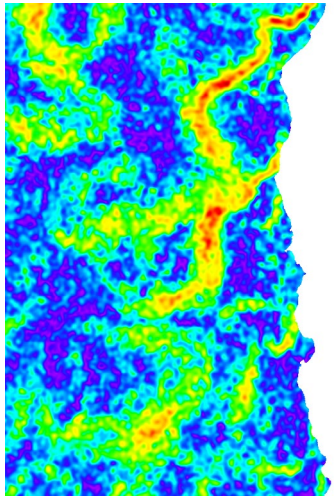
# WaCM Current Speed Smoothed with Filter Cutoff Wavelength 25 km

## 4-Day Average

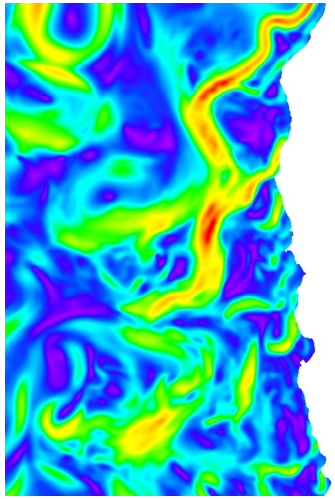
Error Free
Full CCS Domain



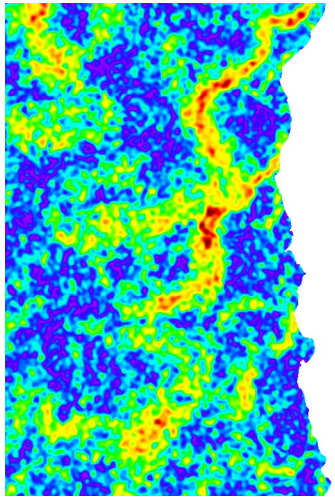
0.5 m/s Measurement Errors
Full CCS Domain

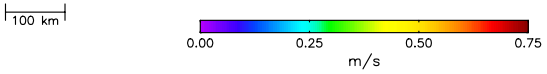


Error Free
WaCM Sampled



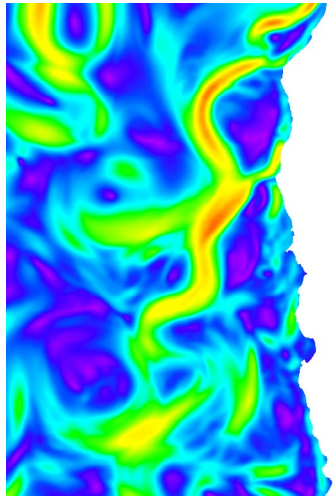
0.5 m/s Measurement Errors
WaCM Sampled



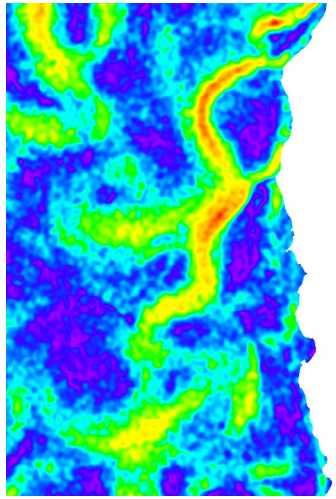



## 14-Day Average

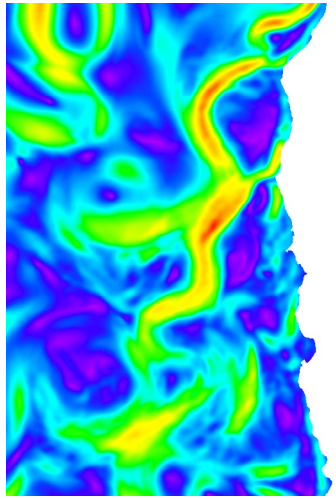
Error Free
Full CCS Domain



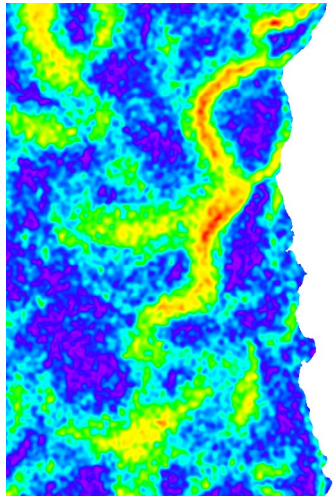
0.5 m/s Measurement Errors
Full CCS Domain

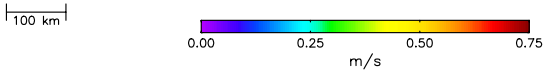


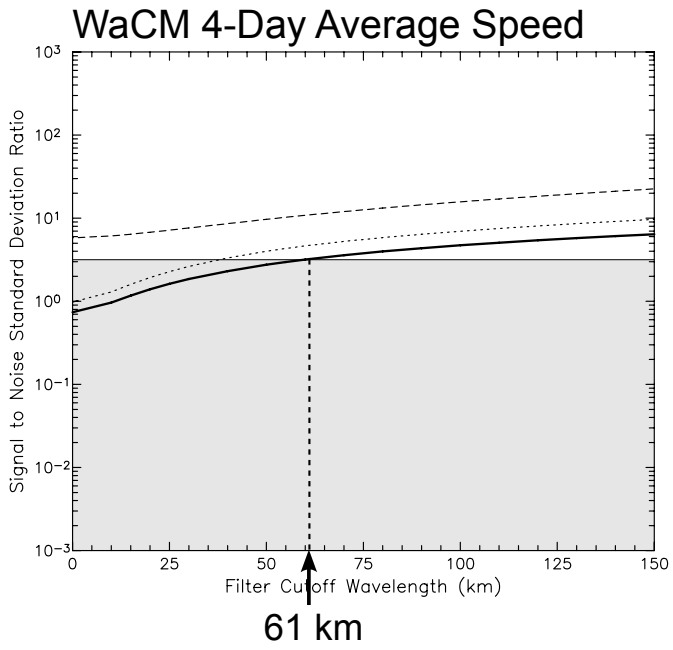
Error Free
WaCM Sampled

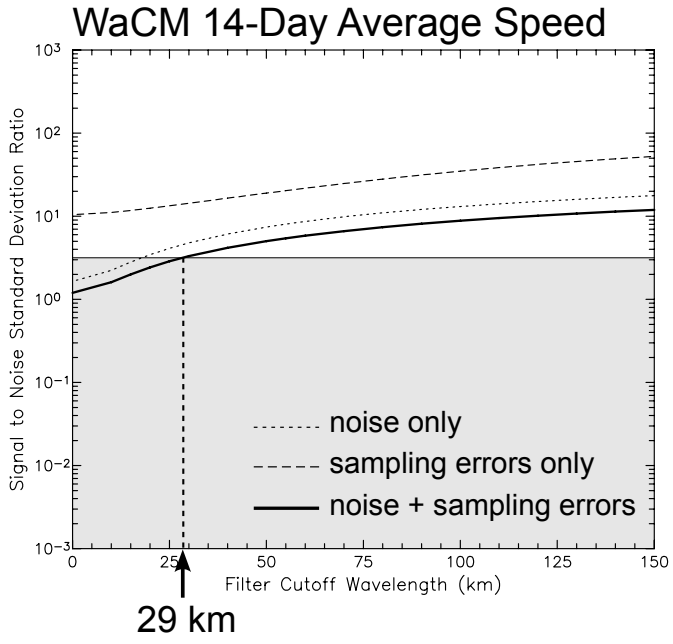


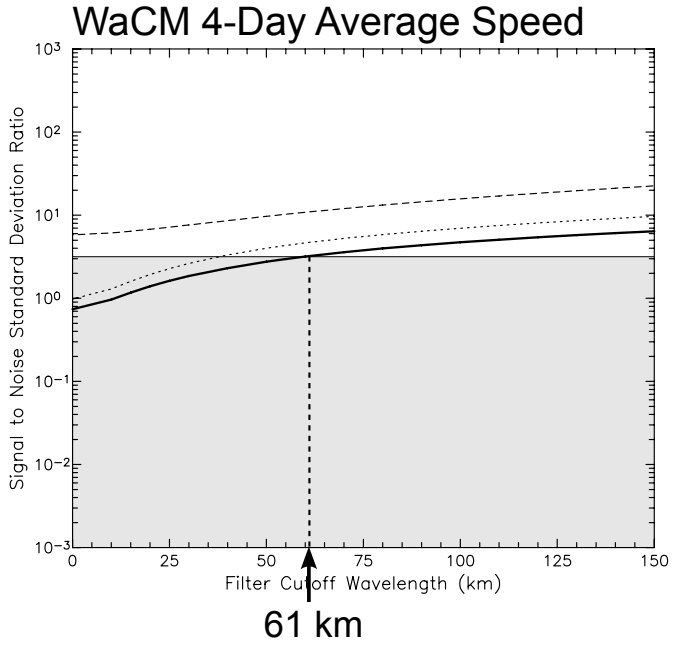
0.5 m/s Measurement Errors
WaCM Sampled

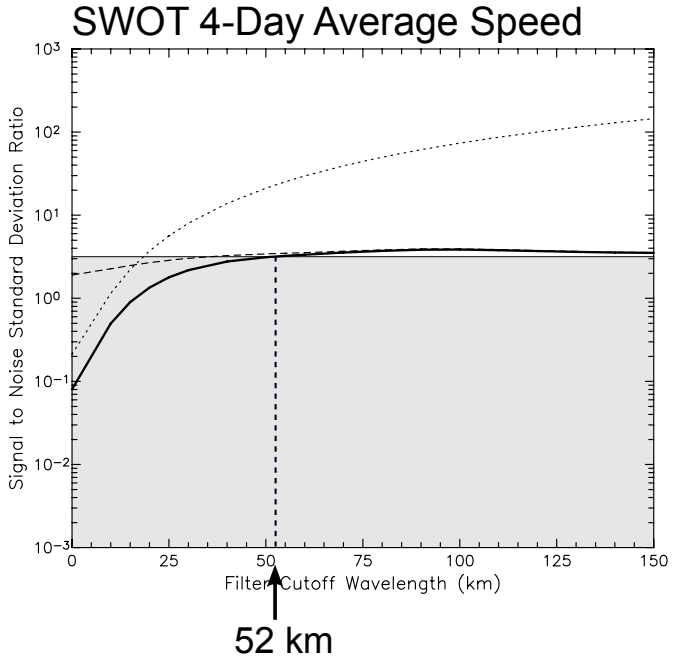


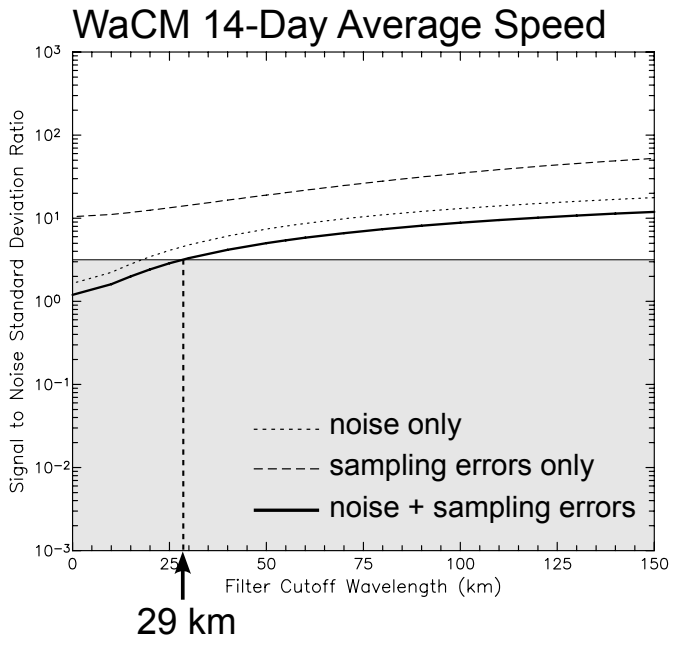


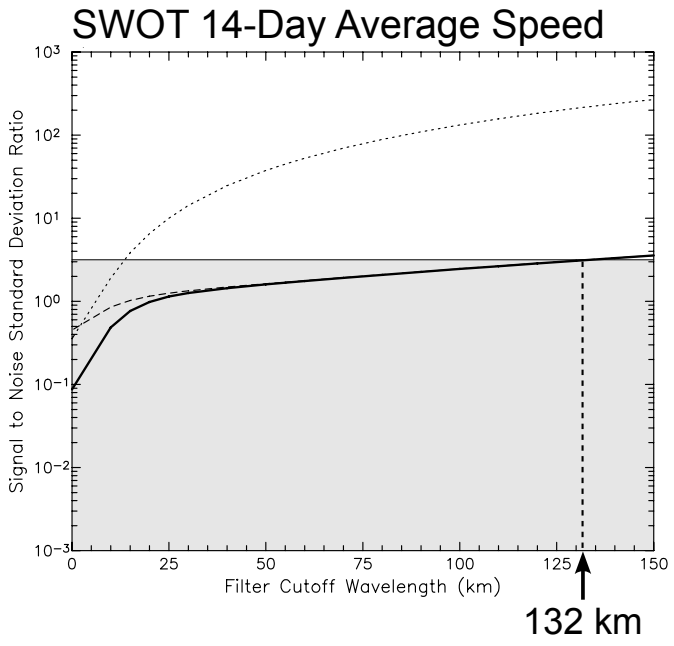

WaCM 4-Day Average Speed
Signal to Noise Standard Deviation Ratio
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
25
50
75
100
125
150
Filter Cutoff Wavelength (km)
61 km


WaCM 14-Day Average Speed
Signal to Noise Standard Deviation Ratio
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
25
50
75
100
125
150
Filter Cutoff Wavelength (km)
noise only
sampling errors only
noise + sampling errors
29 km


WaCM 4-Day Average Speed
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
61 km


SWOT 4-Day Average Speed
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
52 km

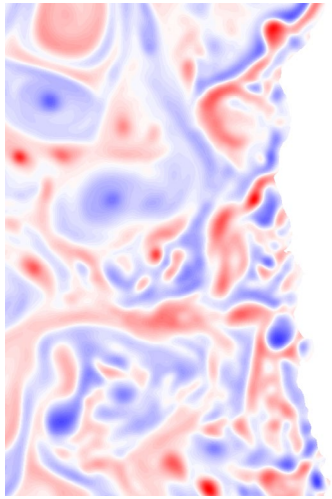

WaCM 14-Day Average Speed
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
noise only
sampling errors only
noise + sampling errors
29 km


SWOT 14-Day Average Speed
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
132 km

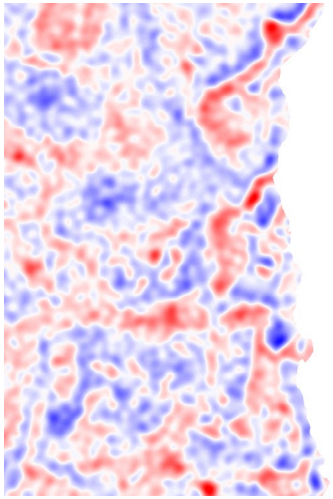
# WaCM Vorticity/f Smoothed with Filter Cutoff Wavelength 50 km

## 4-Day Average

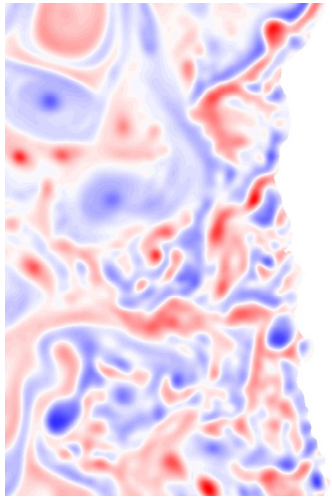
Error Free
Full CCS Domain



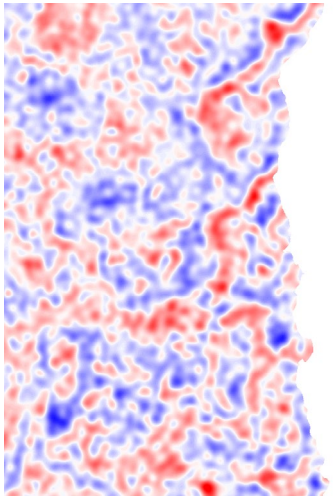
0.5 m/s Measurement Errors
Full CCS Domain

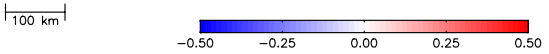


Error Free
WaCM Sampled



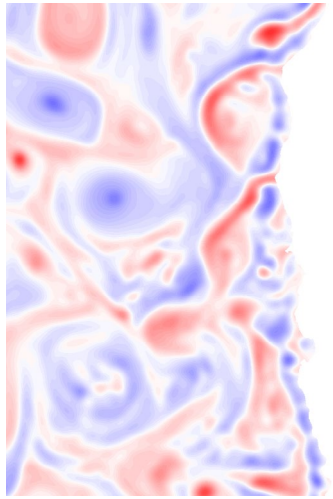
0.5 m/s Measurement Errors
WaCM Sampled



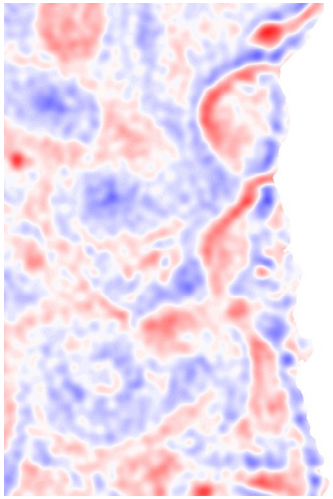



## 14-Day Average

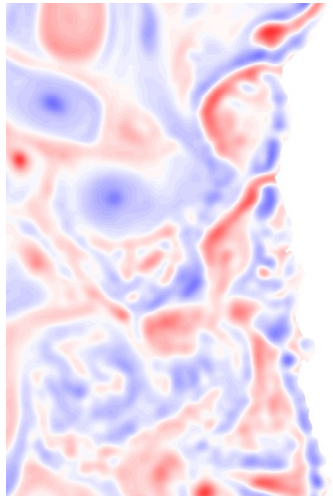
Error Free
Full CCS Domain



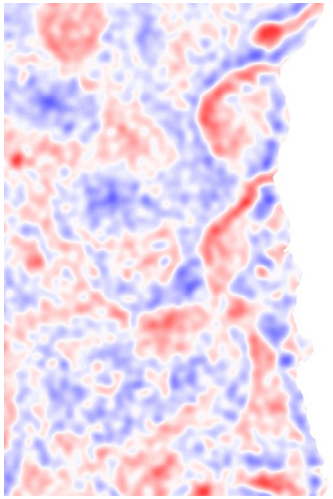
0.5 m/s Measurement Errors
Full CCS Domain

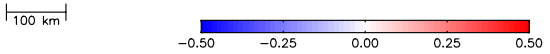


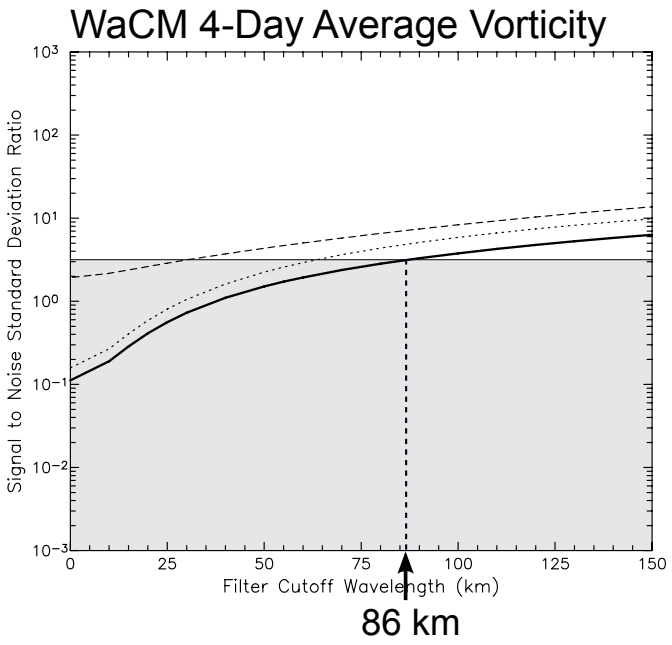
Error Free
WaCM Sampled

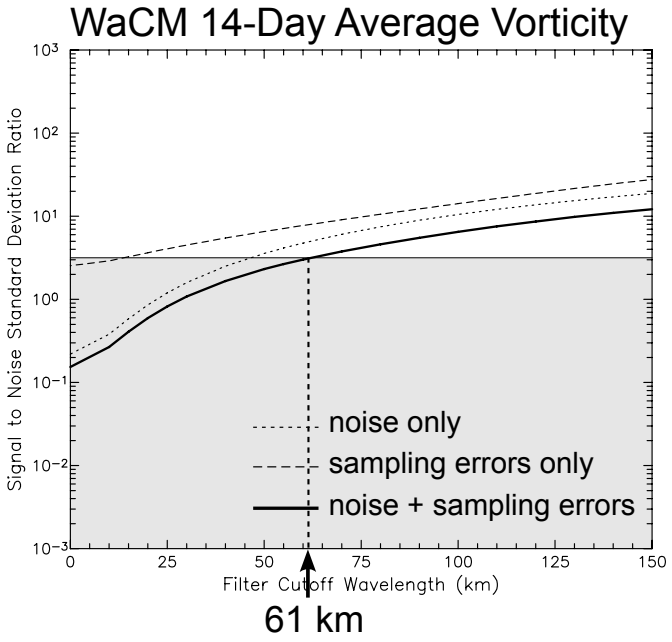


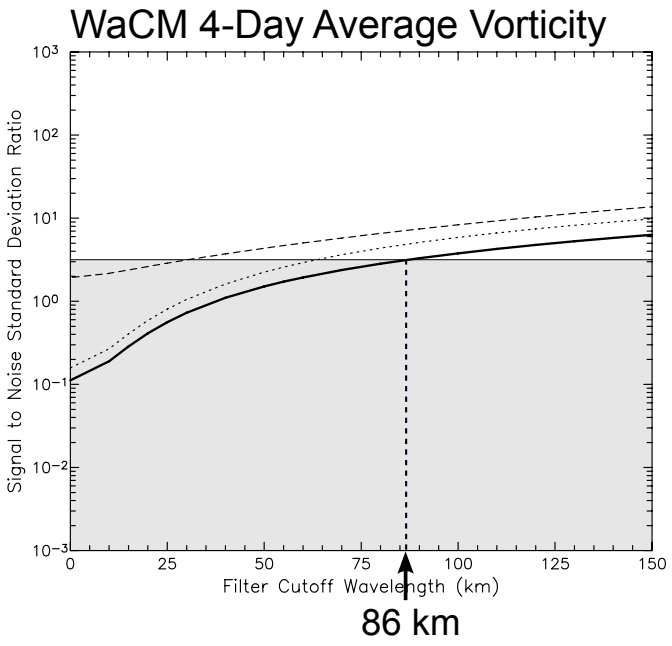
0.5 m/s Measurement Errors
WaCM Sampled

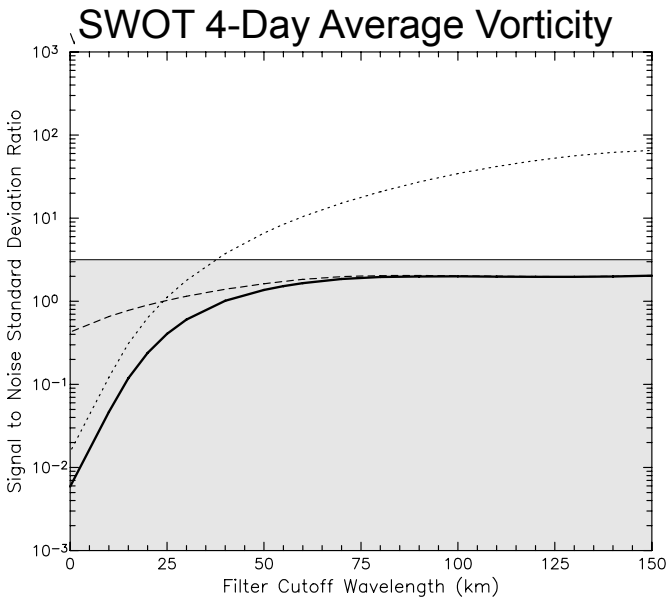


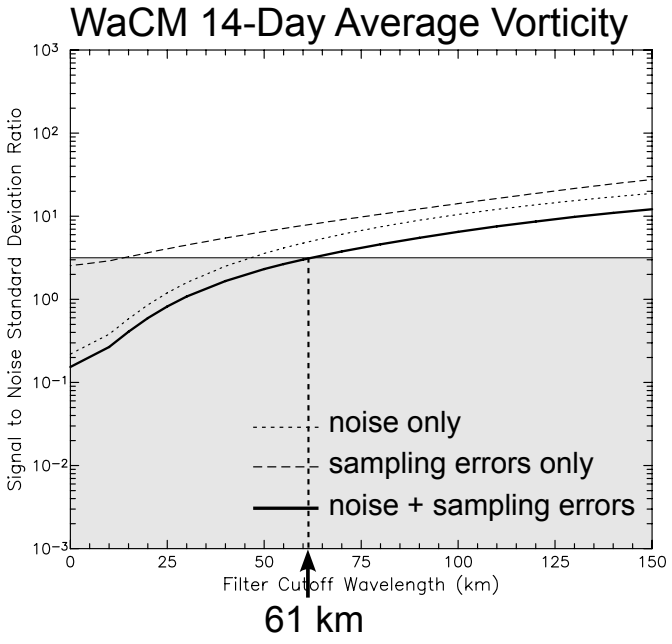


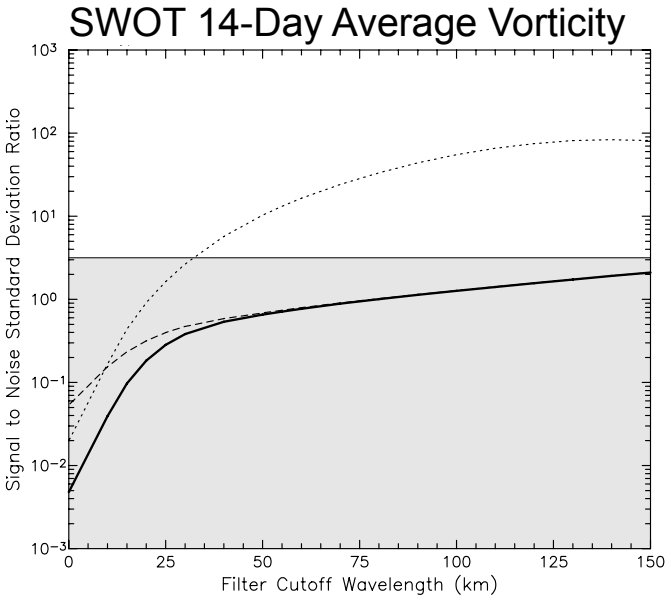

WaCM 4-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
86 km


WaCM 14-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
noise only
sampling errors only
noise + sampling errors
Filter Cutoff Wavelength (km)
61 km


WaCM 4-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)
86 km


SWOT 4-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)


WaCM 14-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
noise only
sampling errors only
noise + sampling errors
Filter Cutoff Wavelength (km)
61 km


SWOT 14-Day Average Vorticity
Signal to Noise Standard Deviation Ratio
Filter Cutoff Wavelength (km)

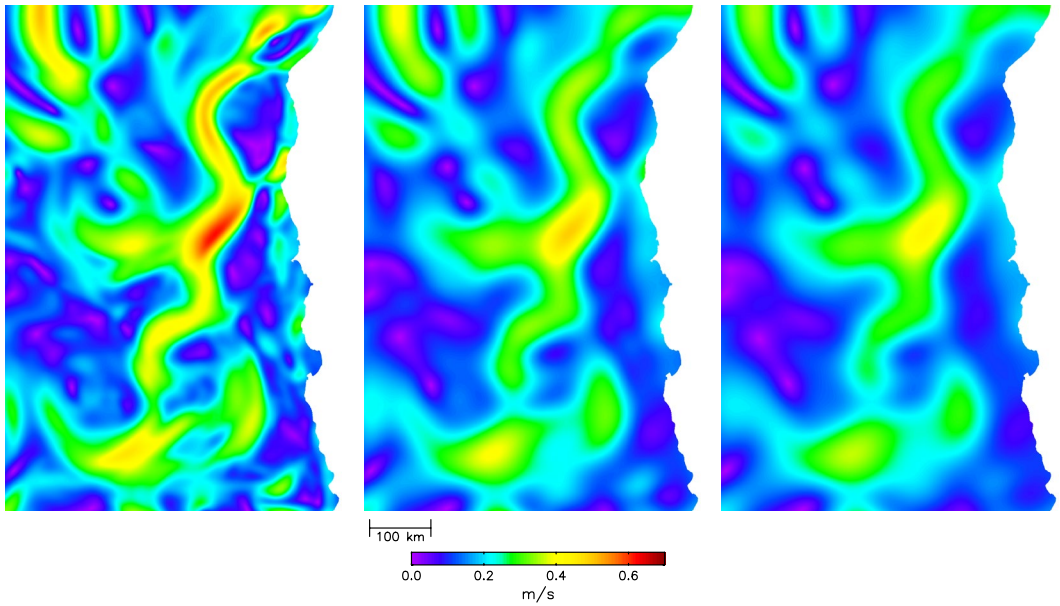
Present Capability

Filter Cutoff Wavelength 50 km

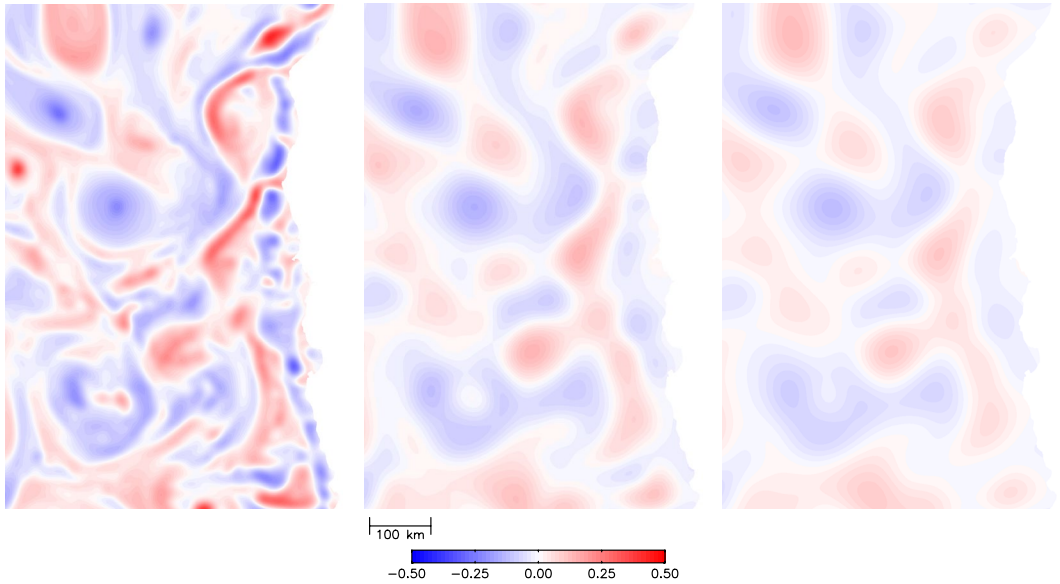
Filter Cutoff Wavelength 150 km

Filter Cutoff Wavelength 200 km

Current Speed




Vorticity/f



# Conclusions

- The effects of measurement and sampling errors are very different for WaCM and SWOT:

  Whereas SWOT is most limited by sampling errors because of its very narrow swath and the rapid evolution of submesoscale variability, WaCM is limited by measurement errors.

- With a noise of 0.5 m/s in surface current measurements, WaCM would provide maps of surface current velocity and relative vorticity with a resolution of roughly 50 km in 14-day averages.

  This is significantly higher resolution than will be achieved from SWOT.

  This would also significantly improve the resolution capability of about 200 km from presently available satellite data.

- Engineering improvements to reduce the baseline measurement noise below 0.5 m/s would push the resolution capability down into the submesoscale regime of wavelengths less than 50 km.

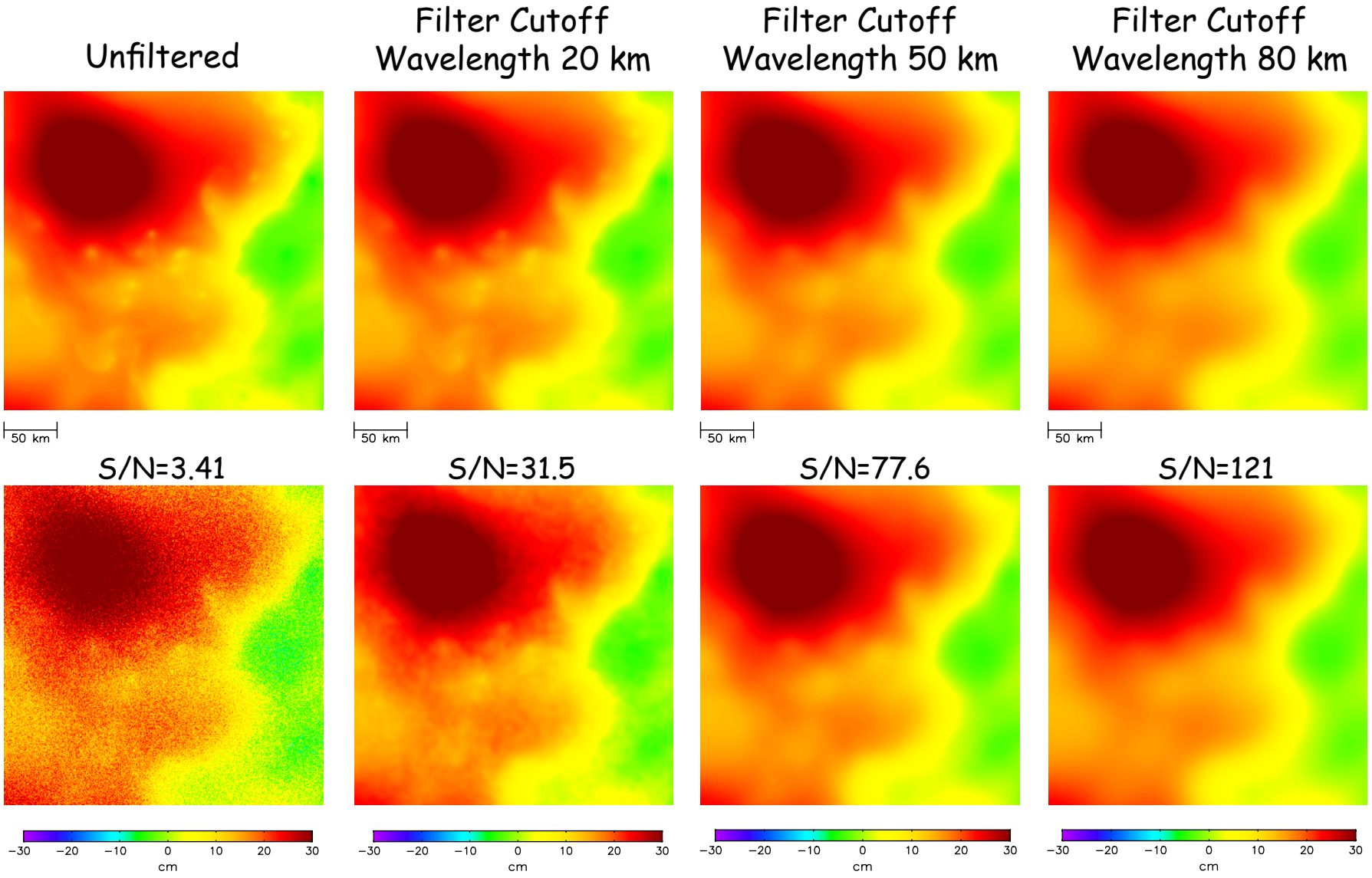
# Extra Figures

# SWOT Estimates of Current Speed and Vorticity with 2.74 cm SSH Measurement Noise

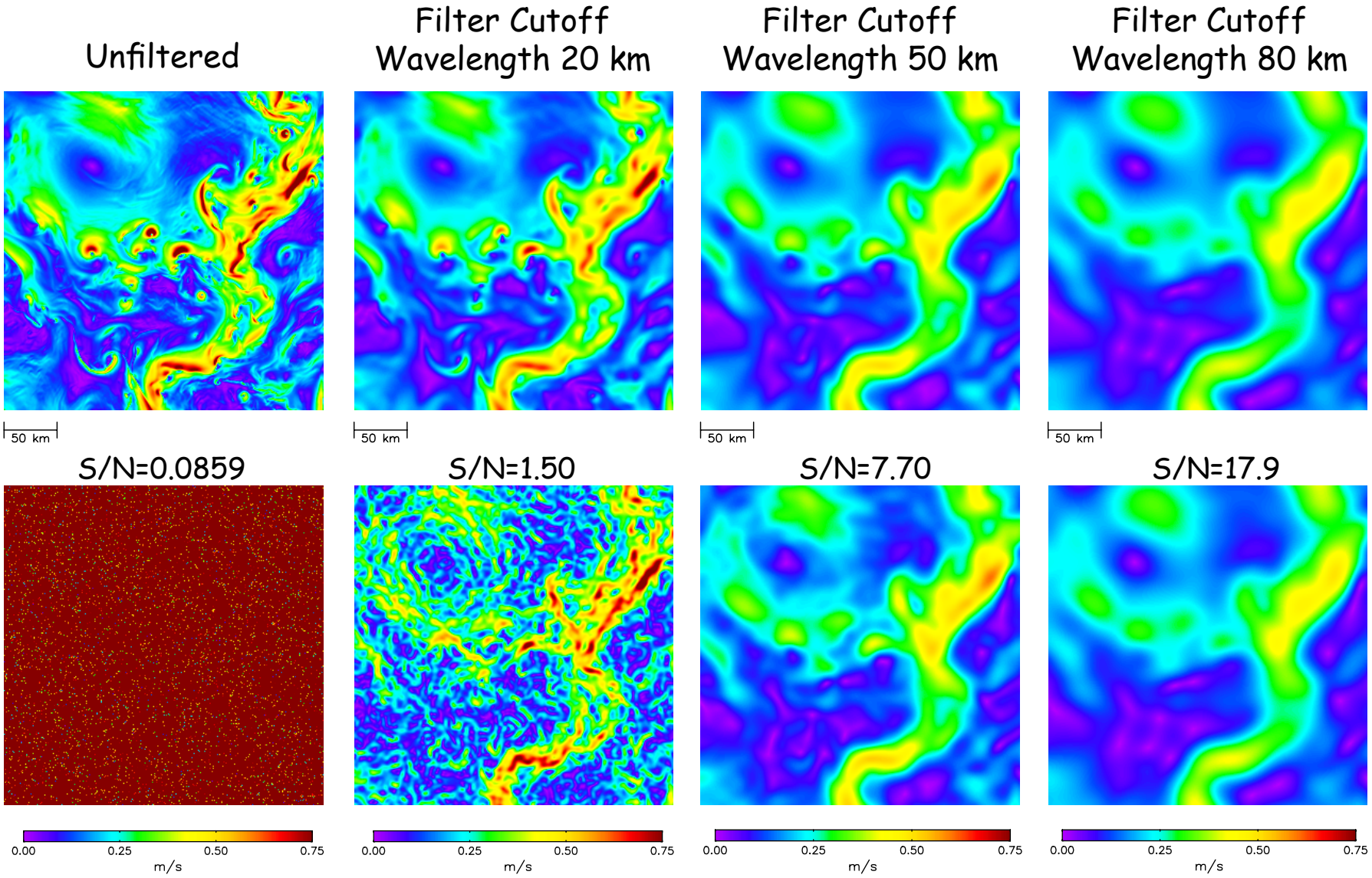
## Part 1:

Smoothed maps constructed from a snapshot of error-free and noisy velocity during a single SWOT overflight for the unrealistic case of sampling the entire Central CCS region

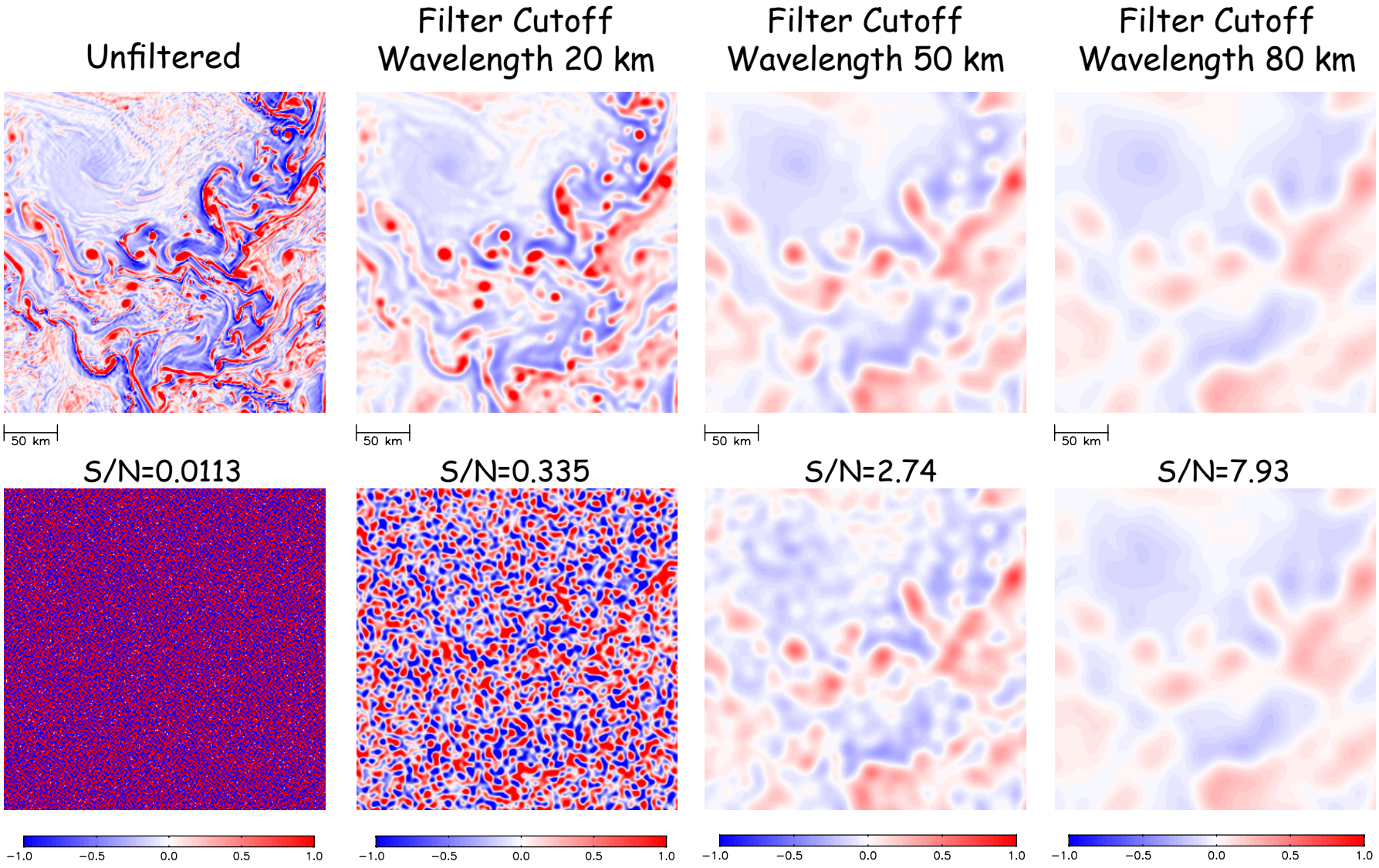
# Smoothed SWOT Maps of SSH
# Error-Free and with 2.74 cm Uncorrelated Noise



# Smoothed SWOT Maps of Current Speed
# Error-Free and with 2.74 cm Uncorrelated Noise



# Smoothed SWOT Maps of Vorticity/f
# Error-Free and with 2.74 cm Uncorrelated Noise



# SWOT Estimates of Current Speed and Vorticity with 2.74 cm SSH Measurement Noise

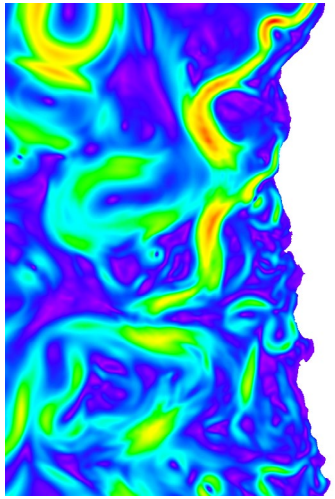
## Part 2:

Smoothed maps constructed from 4-day and 14-day averaged error-free and noisy SSH over the full CCS domain and sampled within just the SWOT measurement swaths

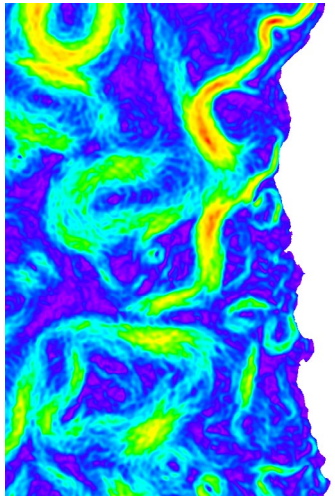
# SWOT Current Speed Smoothed with Filter Cutoff Wavelength 25 km

## 4-Day Average

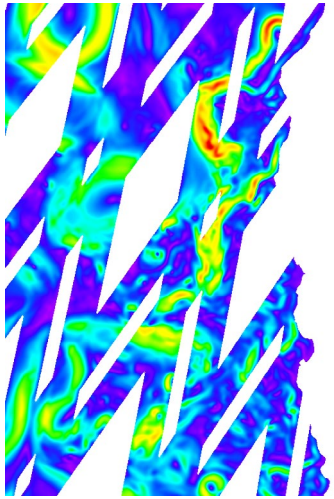
Error Free
Full CCS Domain



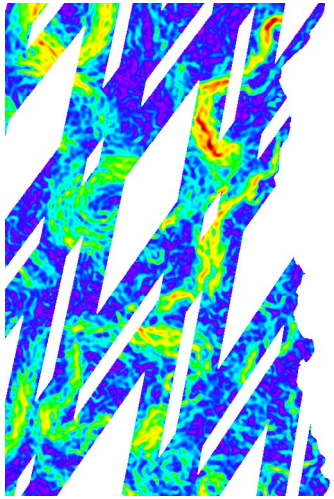
2.74 cm Measurement Errors
Full CCS Domain

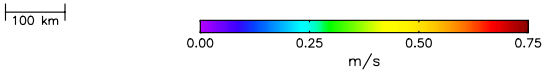


Error Free
SWOT Sampled



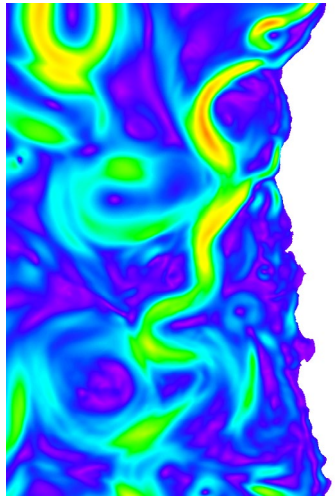
2.74 cm Measurement Errors
SWOT Sampled



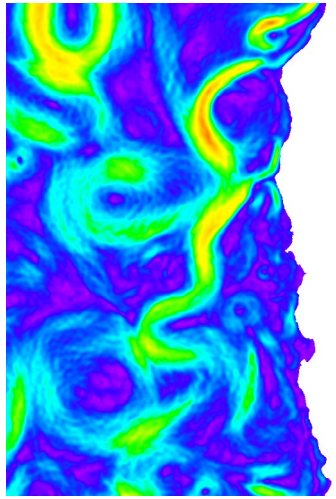



## 14-Day Average

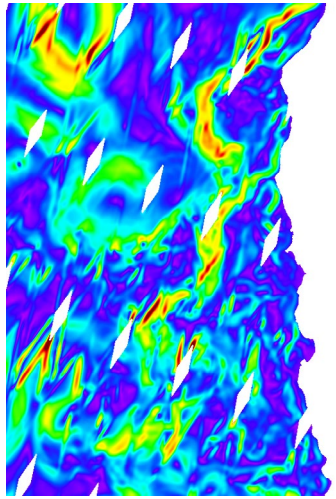
Error Free
Full CCS Domain



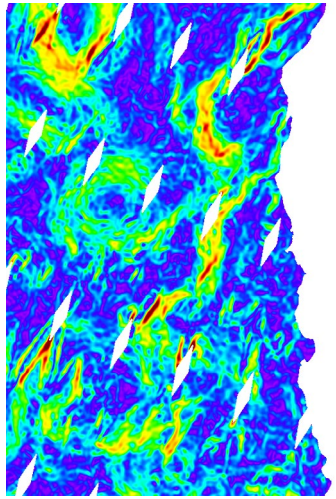
2.74 cm Measurement Errors
Full CCS Domain

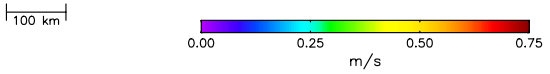


Error Free
SWOT Sampled



2.74 cm Measurement Errors
SWOT Sampled

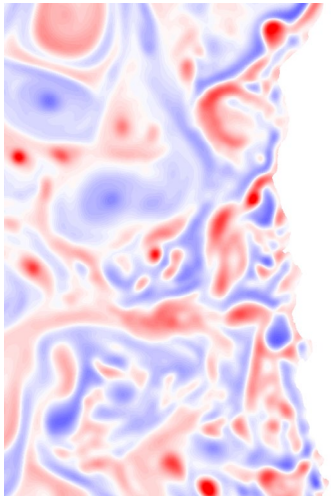




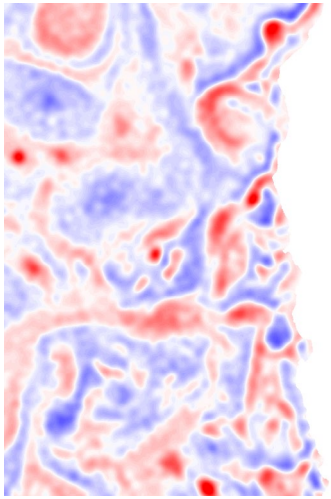
# SWOT Vorticity/f Smoothed with Filter Cutoff Wavelength 50 km

## 4-Day Average

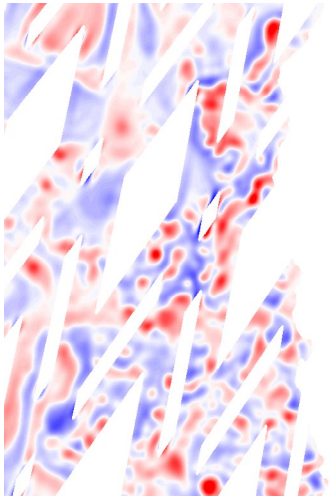
Error Free
Full CCS Domain



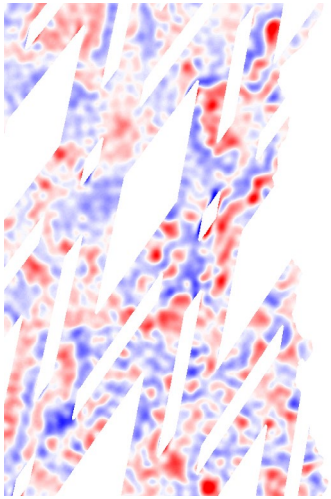
2.74 cm Measurement Errors
Full CCS Domain

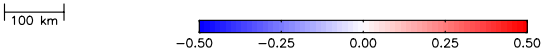


Error Free
SWOT Sampled



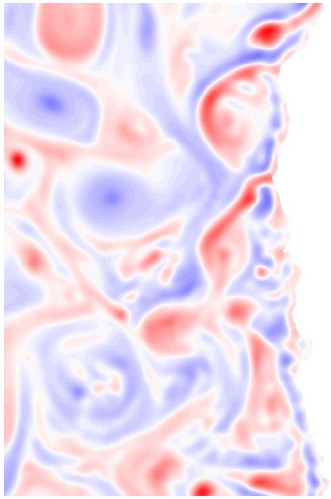
2.74 cm Measurement Errors
SWOT Sampled



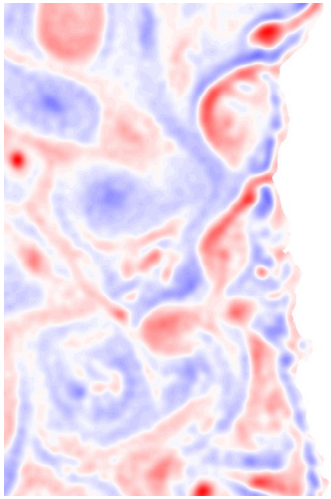



## 14-Day Average

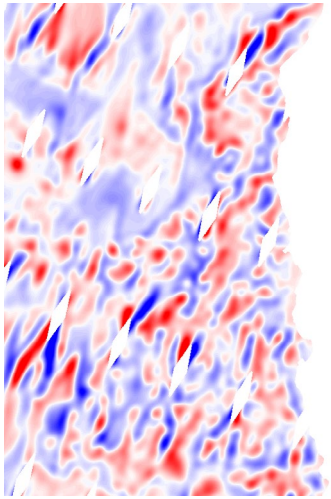
Error Free
Full CCS Domain



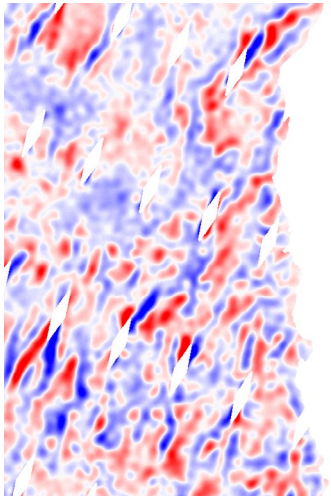
2.74 cm Measurement Errors
Full CCS Domain

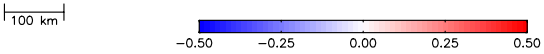


Error Free
SWOT Sampled



2.74 cm Measurement Errors
SWOT Sampled





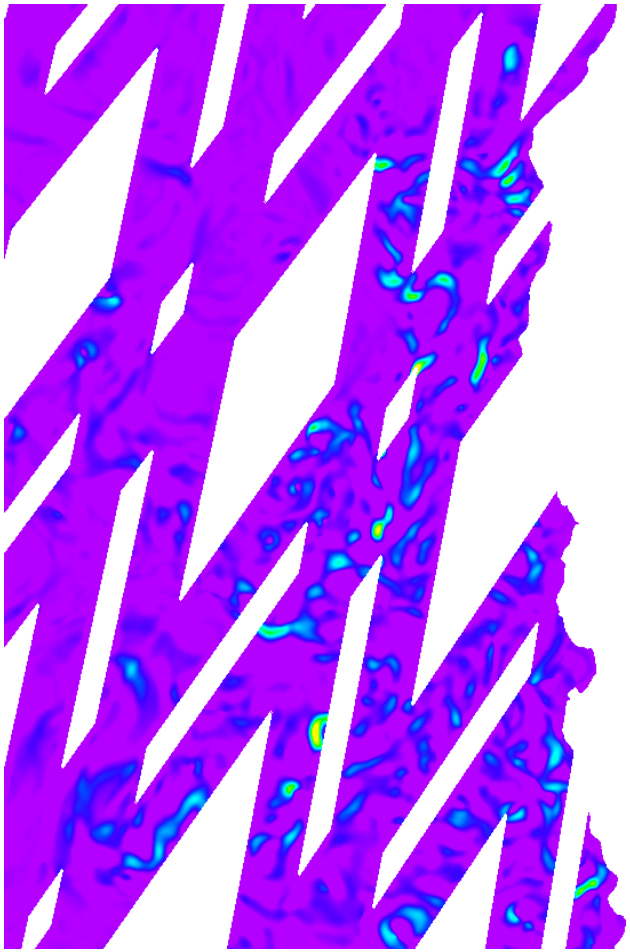
# The Effects of Sampling Errors Alone on SWOT Estimates of Current Speed and Vorticity

Normalized errors of smoothed maps constructed from a snapshot of constant error-free SSH within just the SWOT measurement swaths over periods of 4 and 14 days.

Consideration of constant SSH eliminates sampling errors associated with the rapid evolution of submesoscale variability.

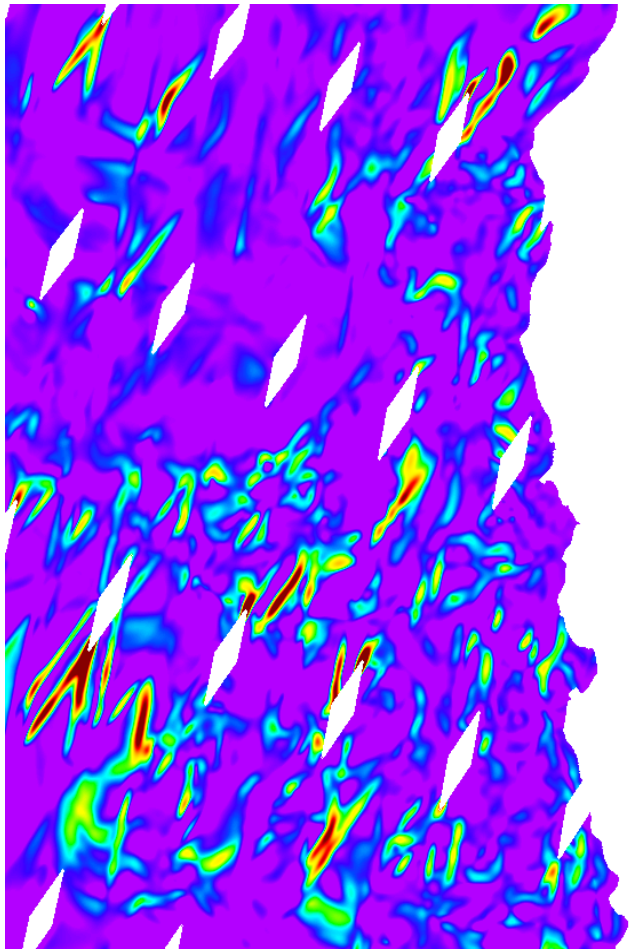
# SWOT Speed Errors from Sampling Errors Alone for Constant SSH After Smoothing with a Filter Cutoff Wavelength of 25 km

4-Day Average




Speed Errors Normalized by the
Standard Deviation of 25-km Smoothed Speed

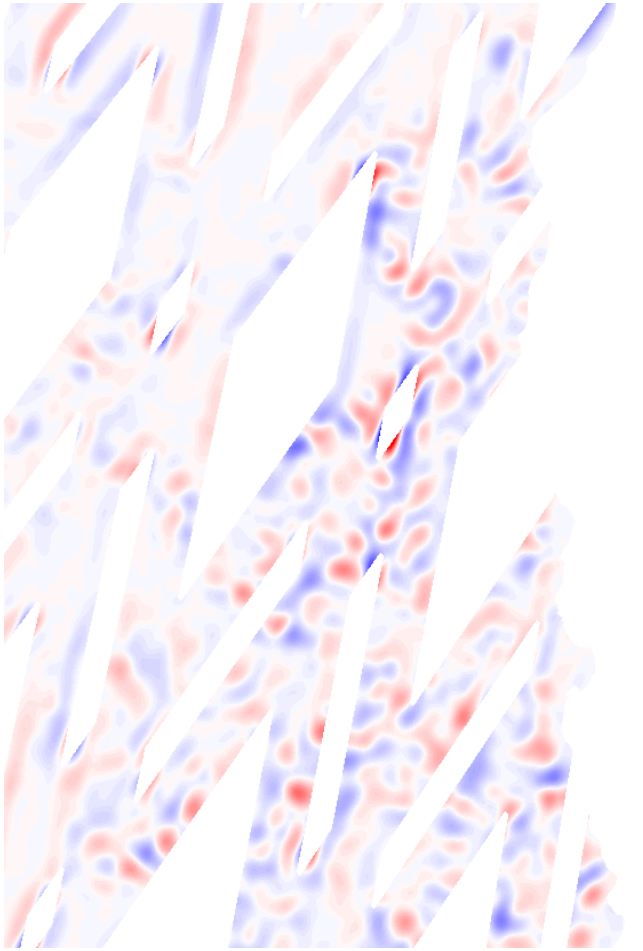
14-Day Average

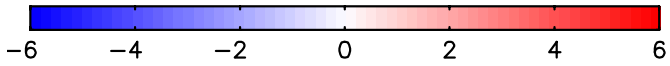



Speed Errors Normalized by the
Standard Deviation of 25-km Smoothed Speed

# SWOT Vorticity/f Errors from Sampling Errors Alone for Constant SSH After Smoothing with a Filter Cutoff Wavelength of 50 km

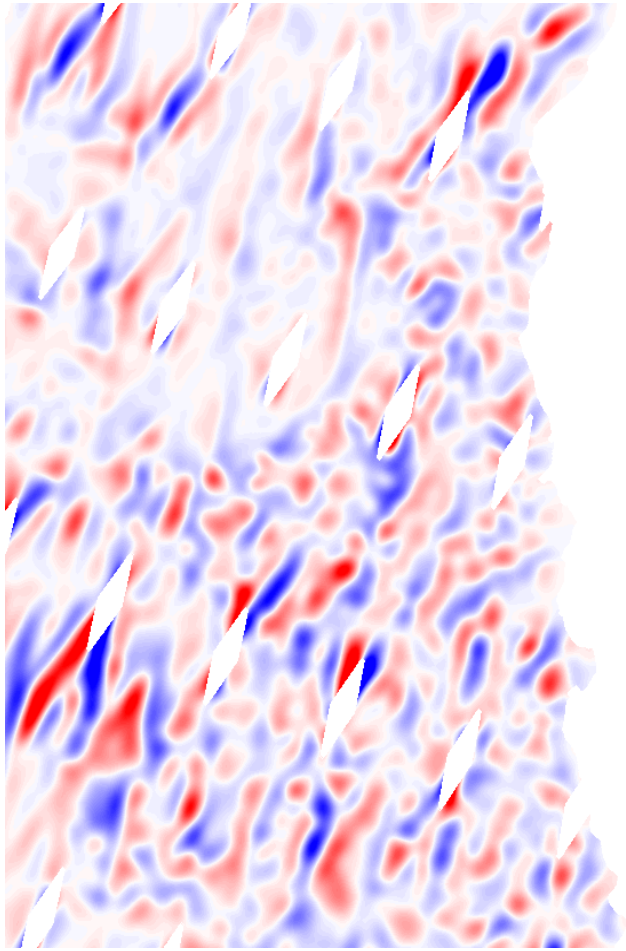
4-Day Average

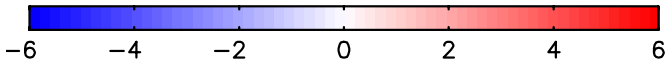





Vorticity/f Errors Normalized by the Standard Deviation of 25-km Smoothed Vorticity/f

14-Day Average






Vorticity/f Errors Normalized by the Standard Deviation of 25-km Smoothed Vorticity/f