Comparison of data and model predictions of current, wave and radar cross-section modulation by seabed sand waves

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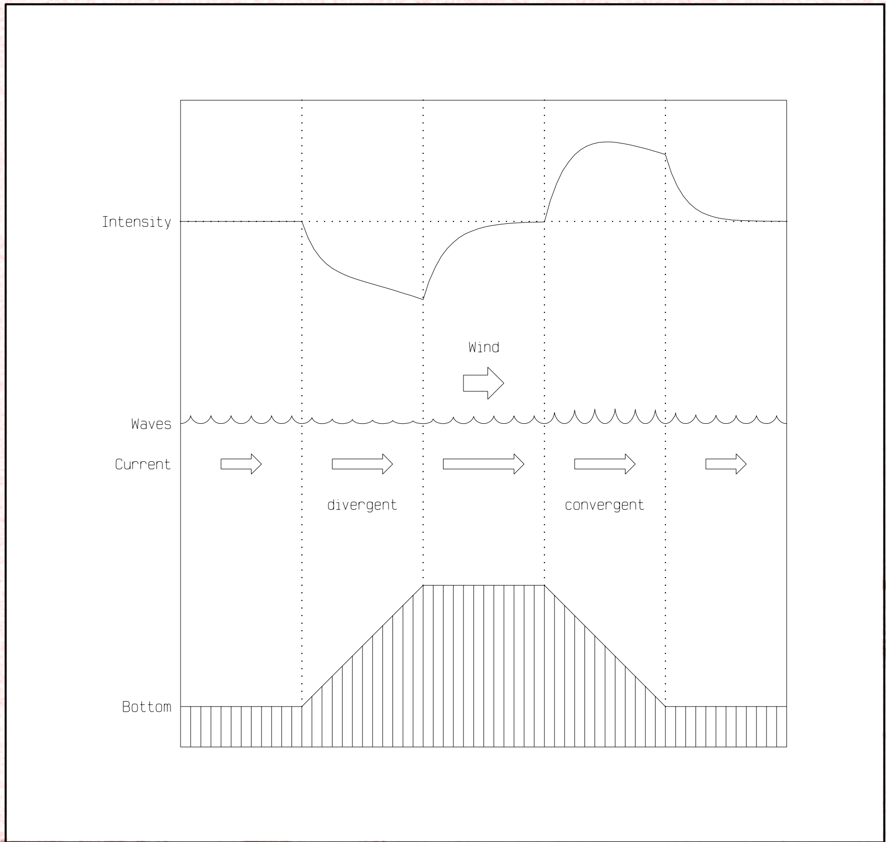
SeaSAR2008

22 January 2008

Summary

- **SAR Imaging of seabed features**
- **Seabed Sand waves**
- **Objectives**
- **Test site**
- **Images and bathymetry**
- **Modelling**
- **Model validation**
- **Retrieval**

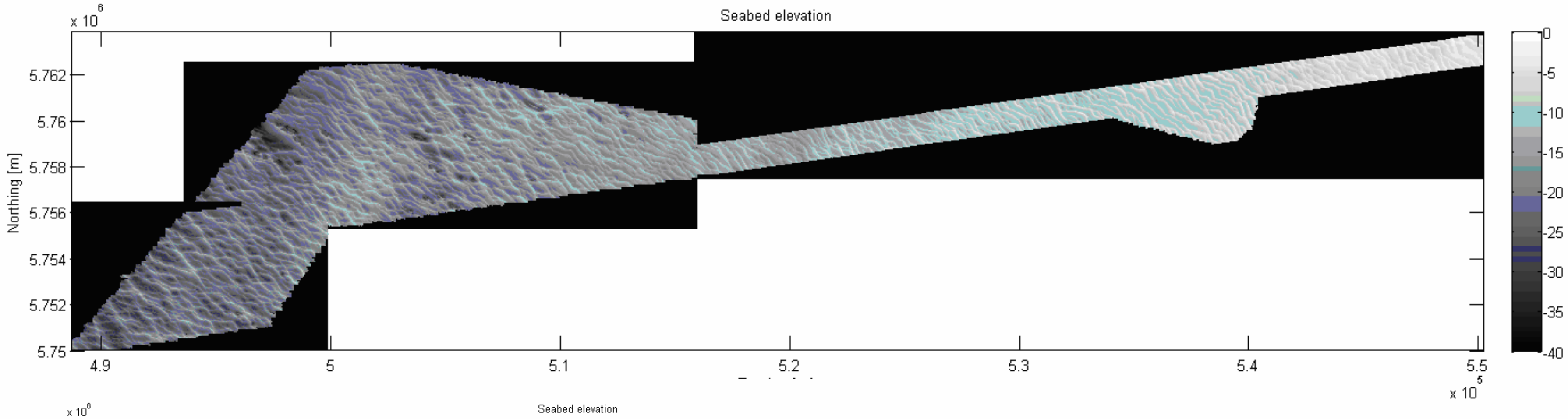
Radar imaging of seabed features in shallow tidal seas

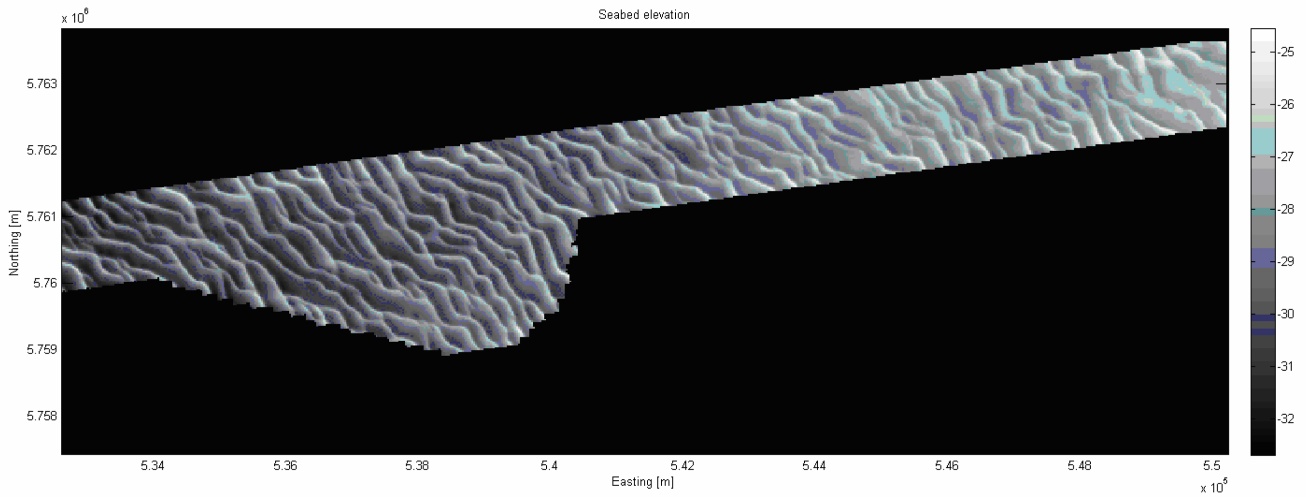


- **Imaging mechanism:**
  - **De Loor et al, 1978, Boundary Layer Meteorol., Vol. 13: observations explained**
  - **Romeiser and Alpers, 1997, J. Geophys. Res., 102: comprehensive two-scale model**

Variations in bathymetry (seabed elevation) modulate the tidal current, and by wave-current interaction also the sea surface waves and radar backscatter

Seabed sand waves





Sand waves (100-1000 m wavelength) are generated in sandy seabeds under the influence of the oscillating tidal current.

They are ideal for studying radar imaging of seabed features

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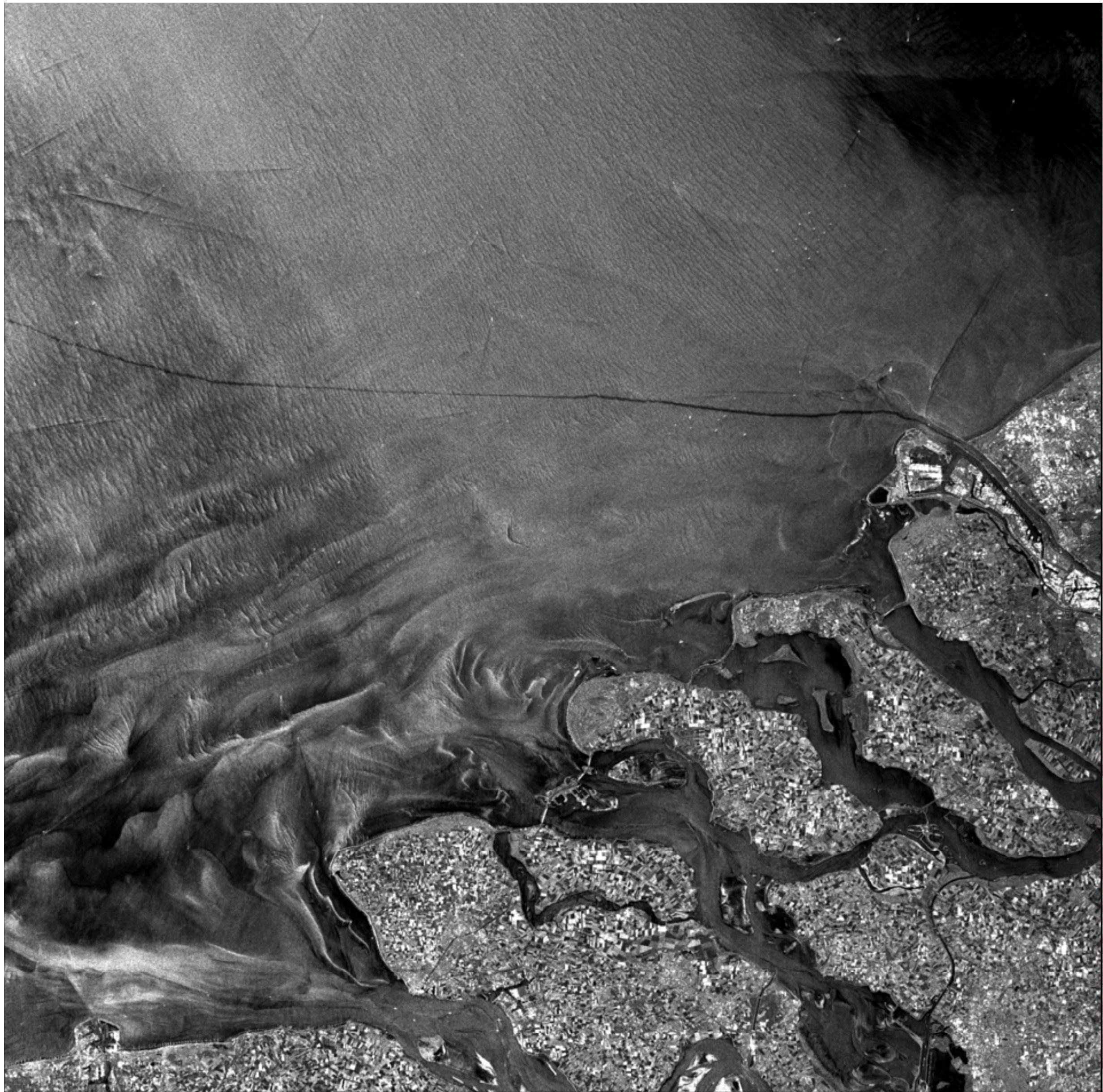
Objectives

Objectives: analyse a batch of SAR images of an accurately charted site to determine

- **How well can we predict the signatures of seabed sand waves in C-band SAR imagery? Is the imaging model (wave-current and wave-wave interaction, radar backscatter) valid/sufficiently accurate?**
- **What are favourable conditions for imaging of sand waves? How often do they occur?**
- **Can we reconstruct seabed sand waves from SAR images alone (without supporting soundings) by inverse modelling? How accurate is the reconstruction?**



Test site

Europoort (port of Rotterdam), near shipping channel:

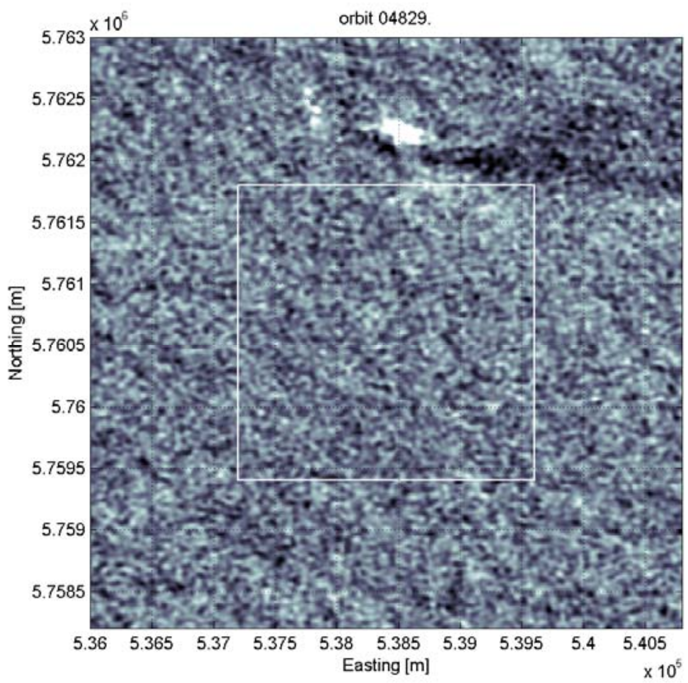
- **Sand wave area**
- **High-resolution area-covering multibeam bathymetric data**
- **Several hundreds of ERS/Envisat SAR images have been acquired here**

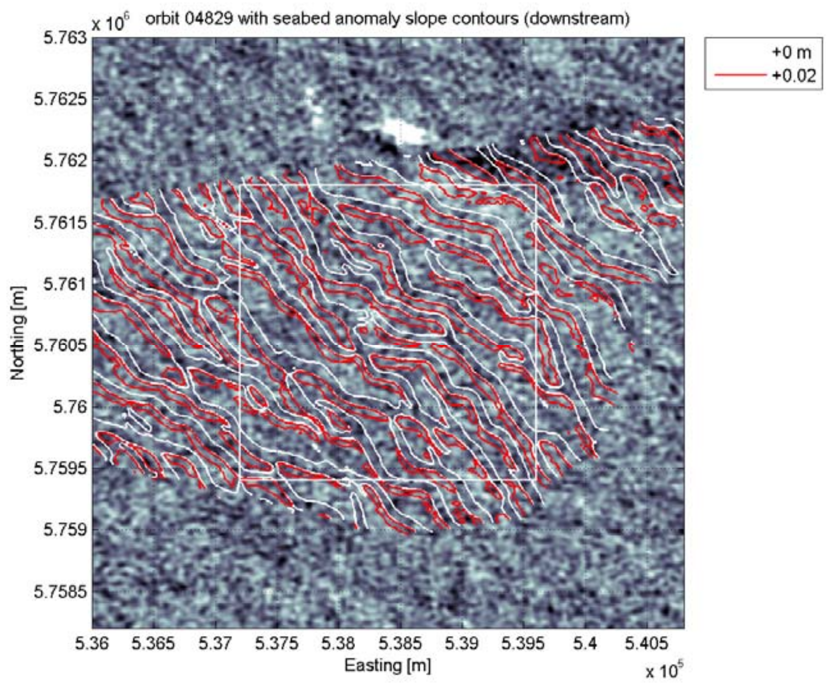
ERS-2 SAR image from orbit 16230 over Zeeland, the Netherlands, May 1998, source: European Space Agency

Data selection/evaluation

- Over >200 images of this area on EOLI (mostly ERS1/ERS2, some Envisat)
- Coincident tidal current and wind data collected
- Ordered: 25 ERS images (crude selection based on tidal current velocity, wind, and EOLI browse images)
- From these: 17 images were chosen based on visibility of sand-wave features
- Further analysis of 6 images over 2.5 km x 2.5 km subarea overlapping with depth survey
- Signal strength: S/N from coherence-spectrum of SAR image and depth chart (no. of wavenumber bins with S/N>1)

Images & bathymetry





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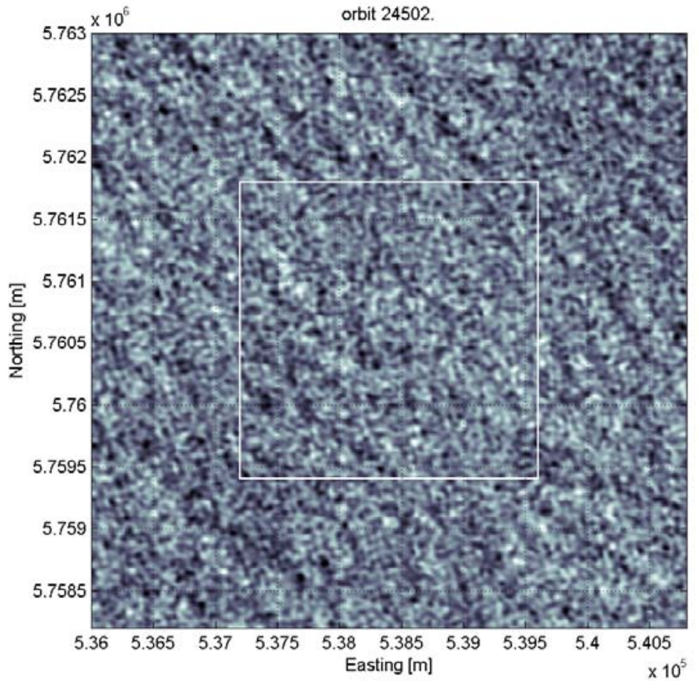
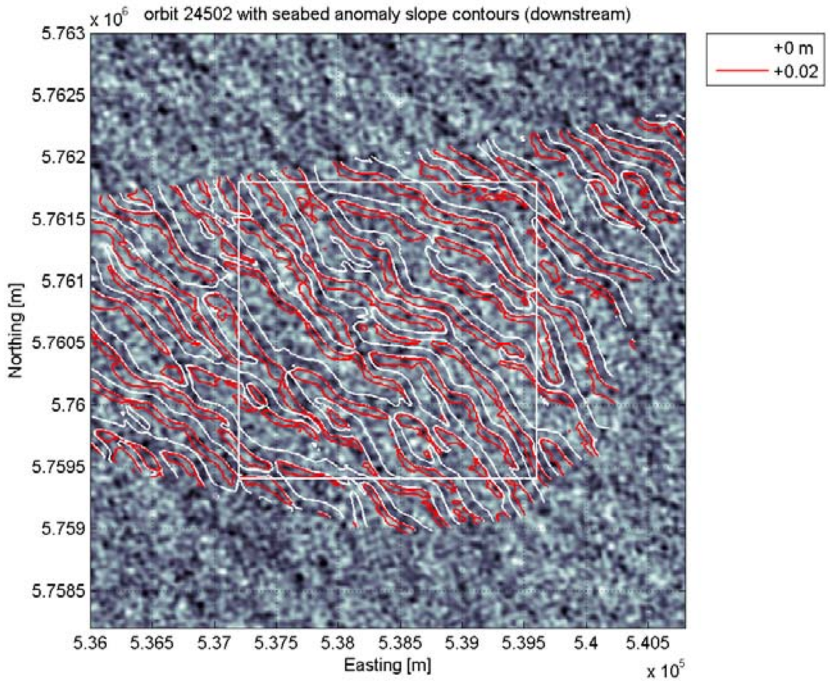
left: Image orbit 04829 (filtered) and area analysed

right: seabed slope contours superimposed on image

Images & bathymetry





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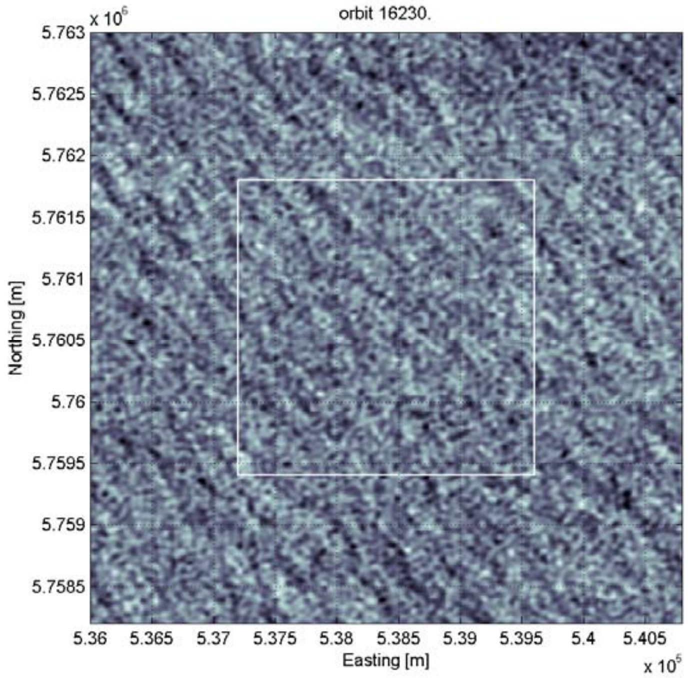
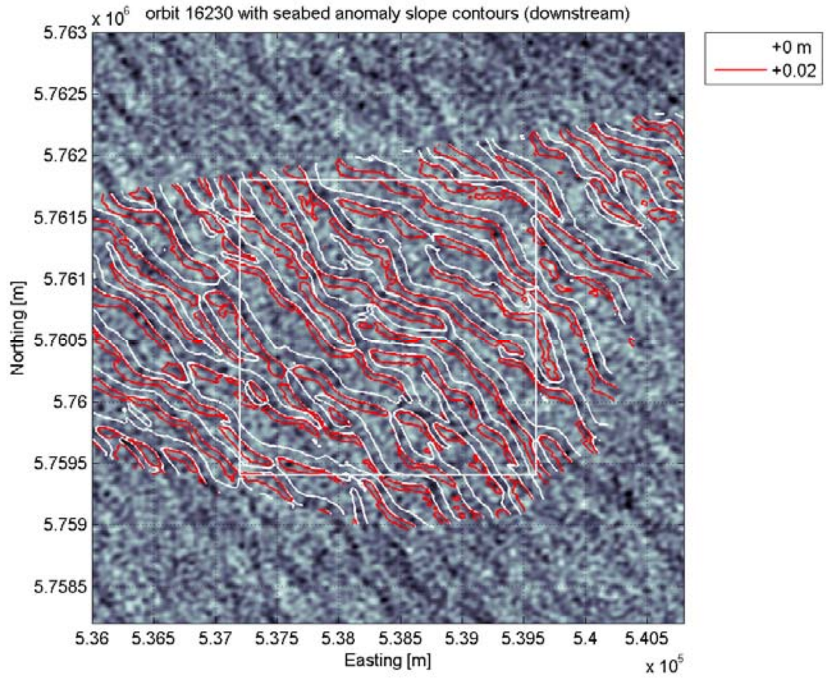
left: Image orbit 24502 (filtered) and area analysed

right: seabed slope contours superimposed on image

Images & bathymetry

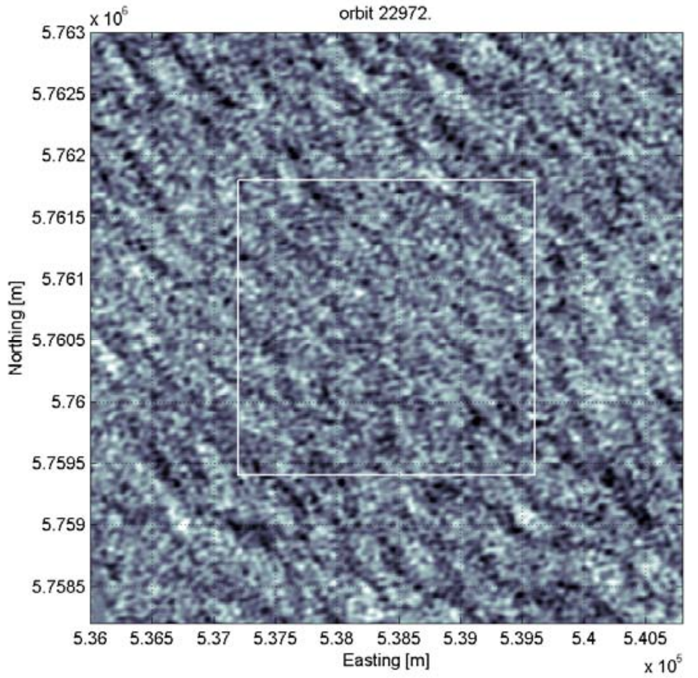


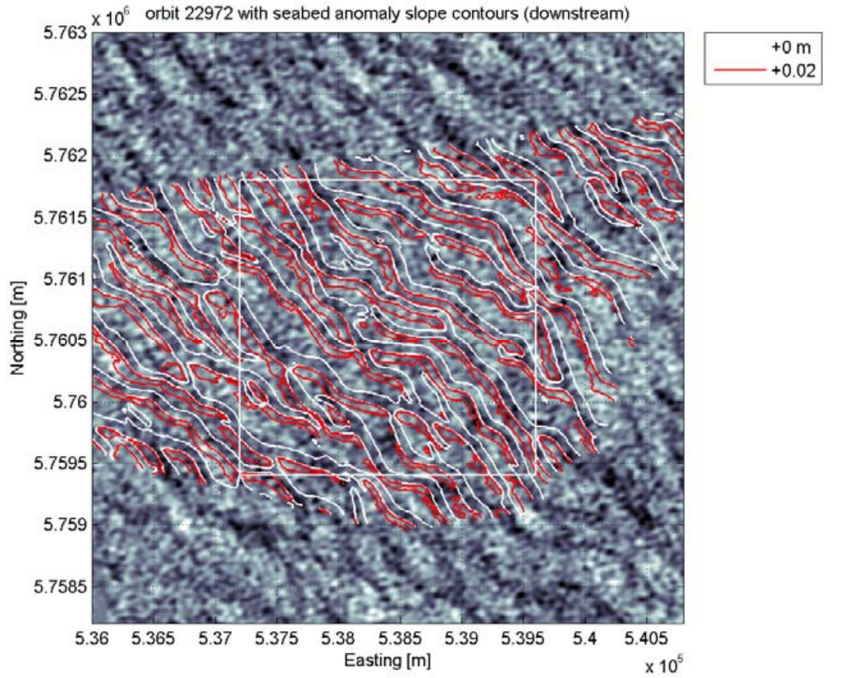


left: Image orbit 16230 (filtered) and area analysed

right: seabed slope contours superimposed on image

Images & bathymetry





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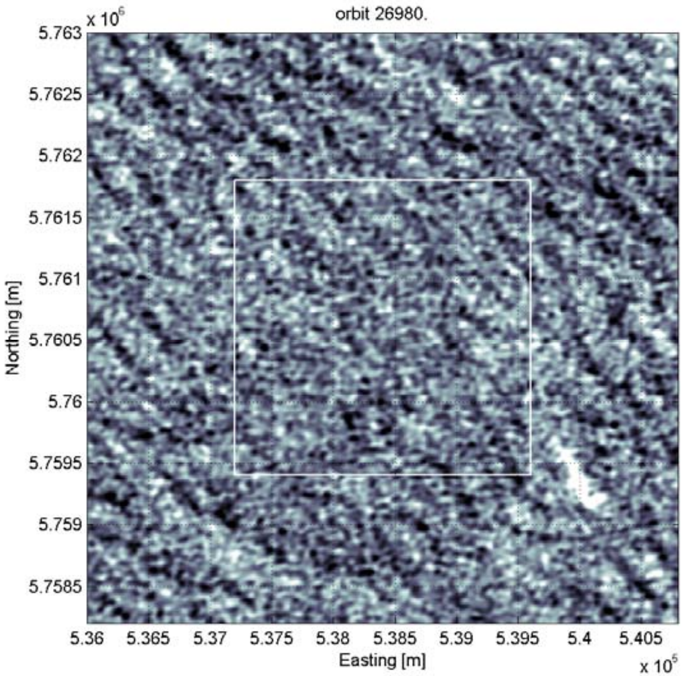
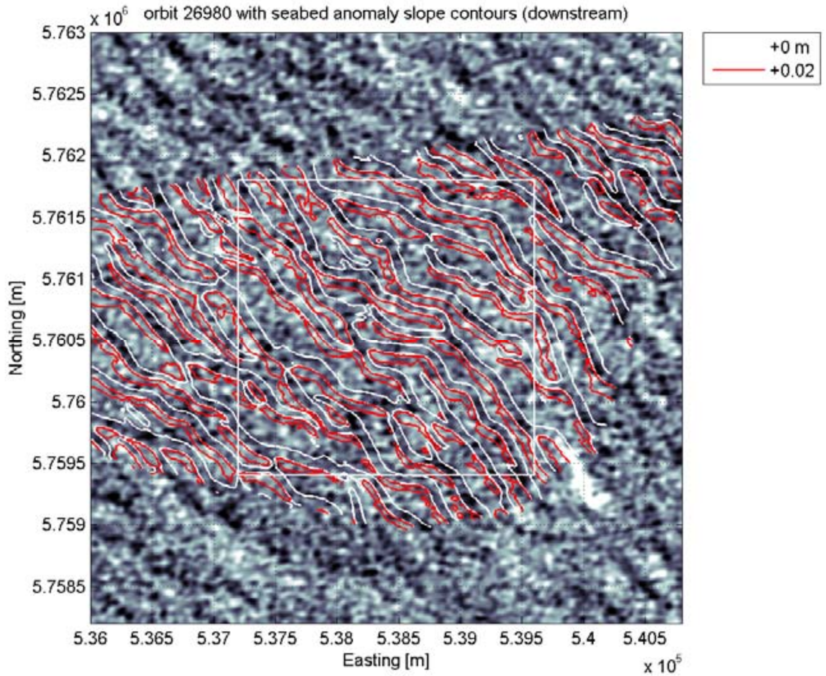
left: Image orbit 22972 (filtered) and area analysed

right: seabed slope contours superimposed on image

Images & bathymetry





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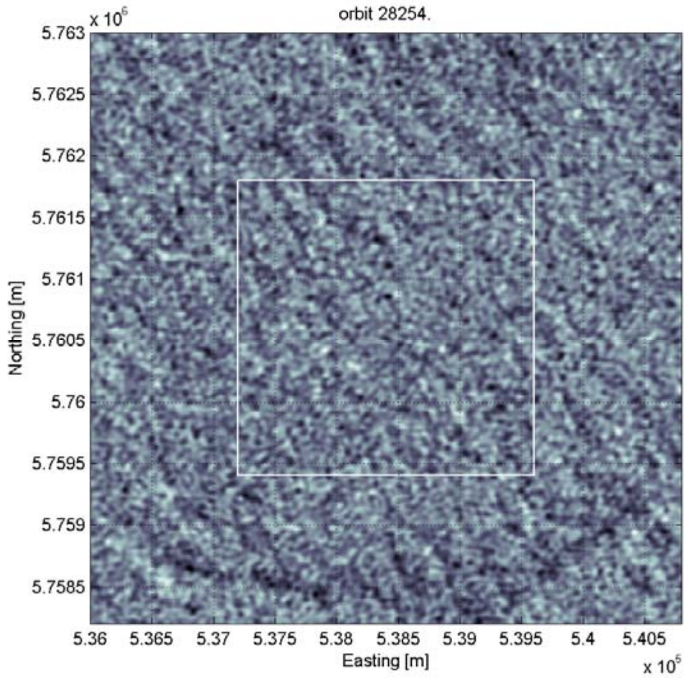
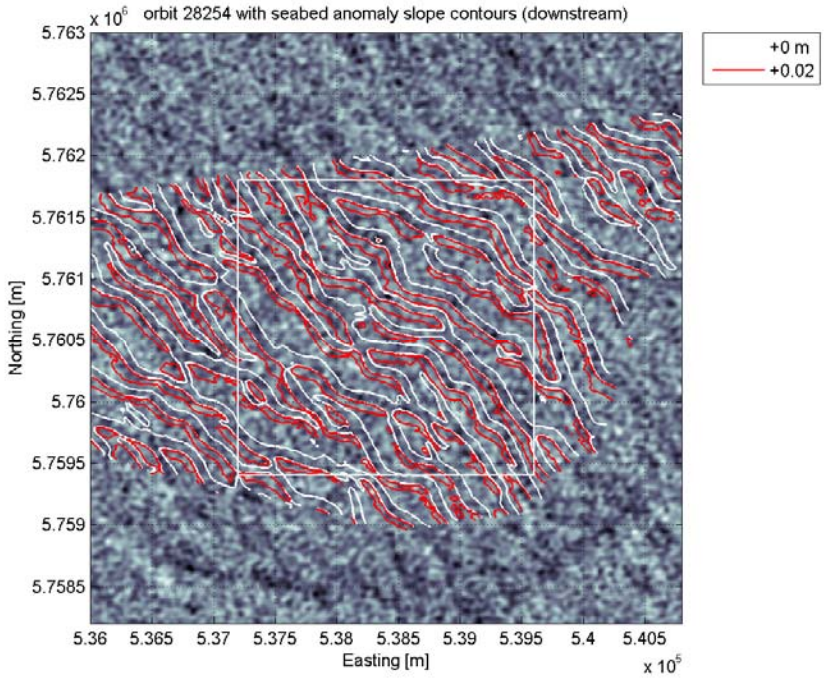
left: Image orbit 26980 (filtered) and area analysed

right: seabed slope contours superimposed on image

Images & bathymetry

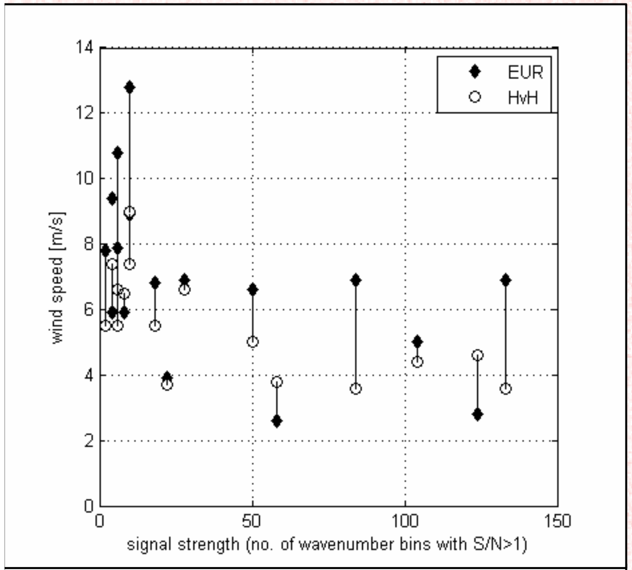


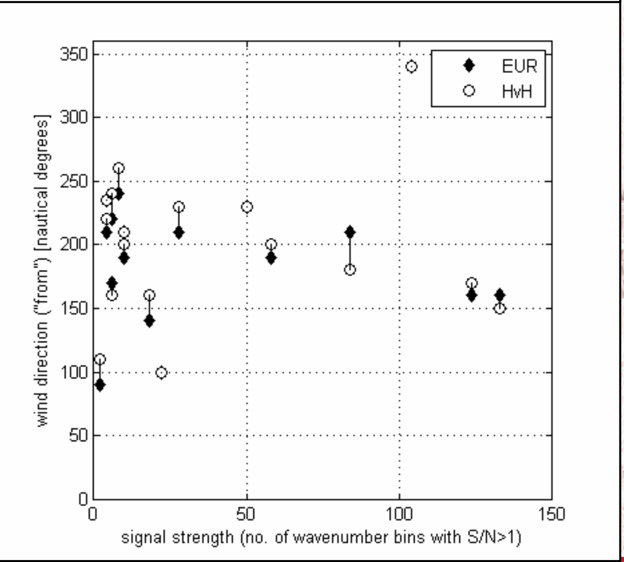


left: Image orbit 28254 (filtered) and area analysed

right: seabed slope contours superimposed on image

Suitability of images





- **The images with the strongest signal all have low wind speeds**
- **Fetch-limited wave conditions appear to be favourable. Exceptional wind direction for orbit 16230: low wind speed further offshore so also limited fetch**
- **All 17 selected images coincide with a current direction from NE. Most likely explanation: the asymmetry of sand wave profile with steep slopes facing NE**

These and other restrictions (current velocity etc.) left only a small fraction of images suitable for further analysis of sand wave signatures.

Imaging mechanism long-wave scale

First-order perturbation:

) and then express the linearised equations in the spatial wave number domain.

In this domain, a single wave component of the depth field can be interpreted as a monochromatic sand wave.

Similarly, a single wave component of the current field can be seen as the response of the current to a sand wave, etc.

$$K = (K_1, K_2)$$

is wavenumber of depth/current perturbation

$$K^* = (-K_2, K_1)$$

$$\bar{d}(K \cdot \tilde{u}) + \tilde{d}(K \cdot \bar{u}) = 0$$

$$cK^* \cdot \tilde{u} + \frac{\partial c}{\partial d}(K^* \cdot \bar{u})\,\tilde{d} = 0$$

$$c = \frac{|\bar{u}|}{\bar{d}C^2}$$

$$C = \kappa^{-1} \log(12\bar{d} / k)$$

Modulation of tidal current by depth variations

Imaging mechanism
long-wave scale

Influence of depth and current variations on long wave

Perturbation of the action balance equation gives

$$[K^T(\mathbf{u}+\mathbf{c}_g)-i\mu]\frac{\tilde{A}}{\bar{A}}=\left[\frac{\partial\log\bar{A}}{\partial\log k}(\mathbf{e}^T K)+\frac{\partial\log\bar{A}}{\partial\theta}(\mathbf{e}^{*T}K)\right](\tilde{\mathbf{u}}^T\mathbf{e}+\tilde{d}\,\frac{\sigma'}{k})$$

in which

$$\frac{\sigma'}{k}=\frac{\partial\sigma}{k\partial d}=\tfrac{1}{2}\sigma[\coth(kd)-\tanh(kd)]$$

Relaxation rate μ from Plant.

Direct modulation of surface wave action density by current and depth variations

Imaging mechanism short-wave scale

Influence of long wave orbital velocity on short wave

perturbation of the action balance equation gives

$$\frac{\tilde{A}}{\bar{A}} = \frac{-\left[\frac{\partial \log \bar{A}}{\partial \log k}\mathbf{e}^T K + \frac{\partial \log \bar{A}}{\partial \theta}\mathbf{e}^{*T} K\right] |K|^{-1} (K^T \mathbf{e})}{(i\mu - K^T(\mathbf{u}+\mathbf{c}_g))/\Omega + 1}\tilde{\varsigma}$$

Modulation of short surface wave action density by orbital velocity of longer waves

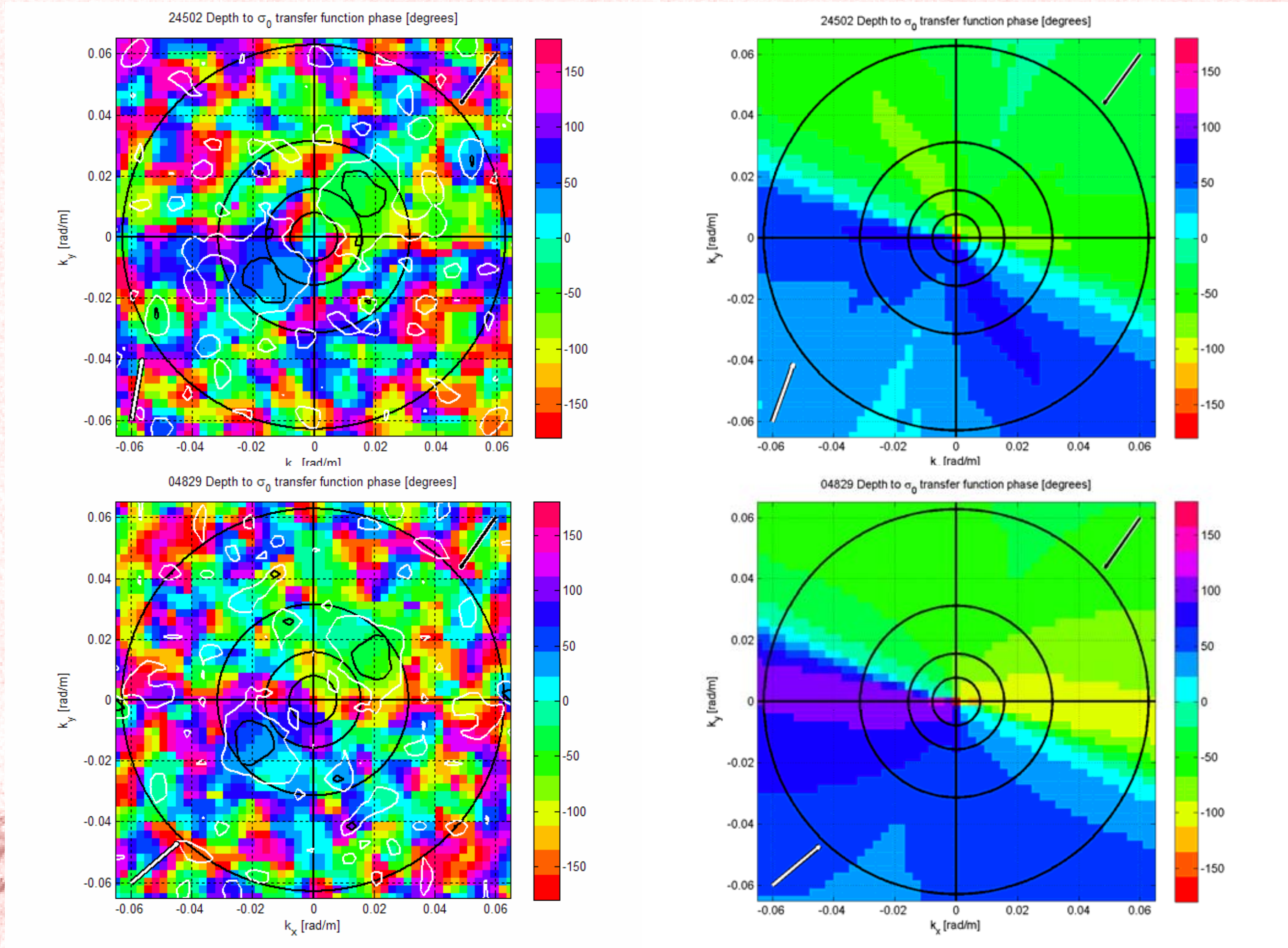
Imaging mechanism
backscatter modulation (VV, HH)

1. Simplified model for HH or VV: log of normalised radar cross-section (NRCS) is very nearly linear in sea surface slope; same for hydrodyn. modulation (does not work for HV)
2. Sea surface elevation Gaussian to first approximation
3. Mean of NRSC (over long waves) can therefore be approximated as the mean of the exponent of a Gaussian random variable
4. Much simpler model than 2nd order expansion

Imaging mechanism
Combining the models to MTF

1. **MTF: transfer function from perturbation of depth to perturbation of the log of the mean normalised radar cross-section**
2. **Combines component models for tidal current, long wave-current/depth interaction, short wave-long wave interaction, and backscatter**
3. **Can also be estimated empirically from SAR image and high-resolution bathymetric sounding data**

Modulation Transfer Functions



- black contour: area of S/N>1
- black arrow: current direction
- white arrow: wind direction

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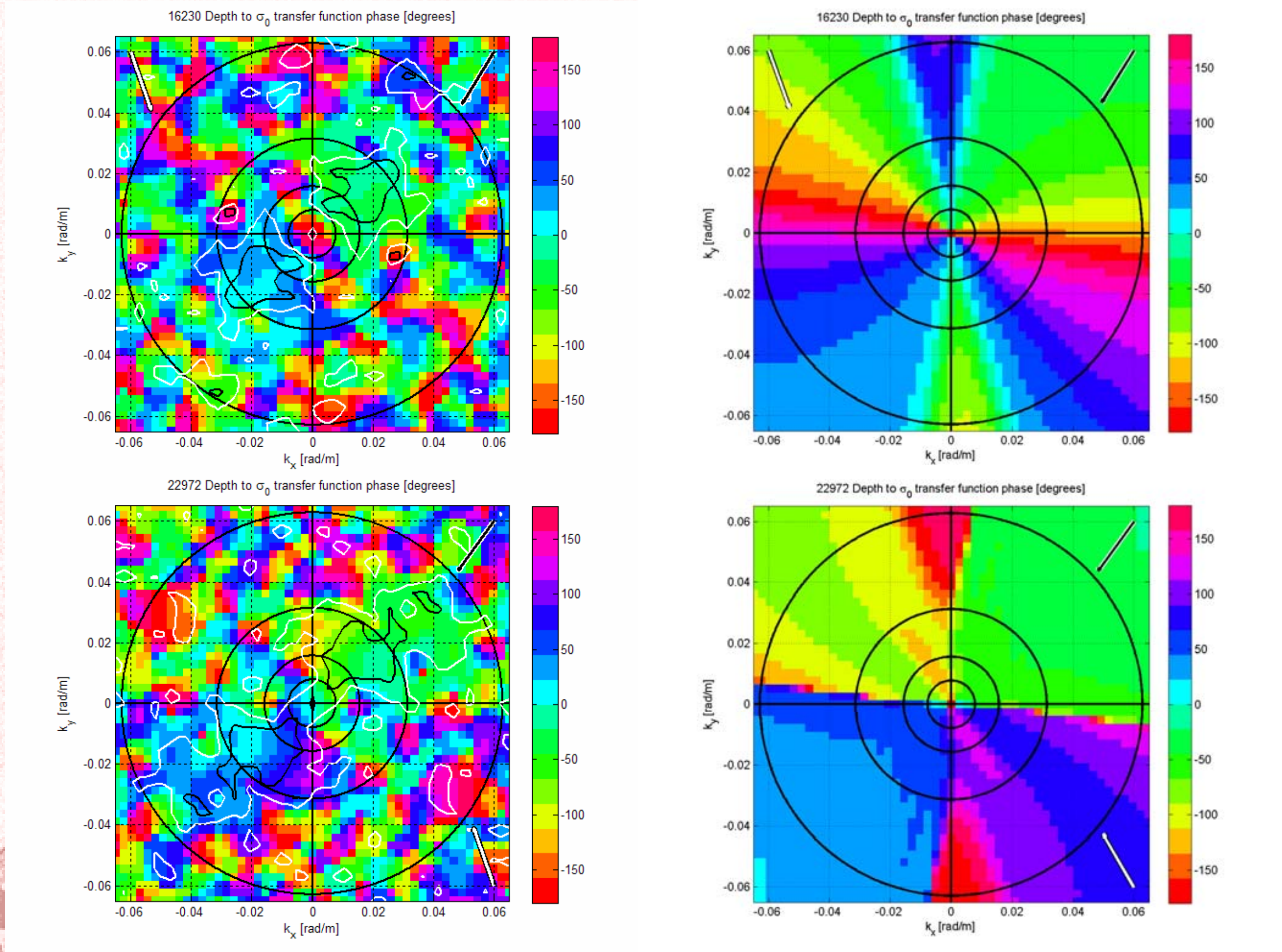
Measured and simulated transfer function phases for the images in orbit 24502 (upper) and orbit 04829 (lower)

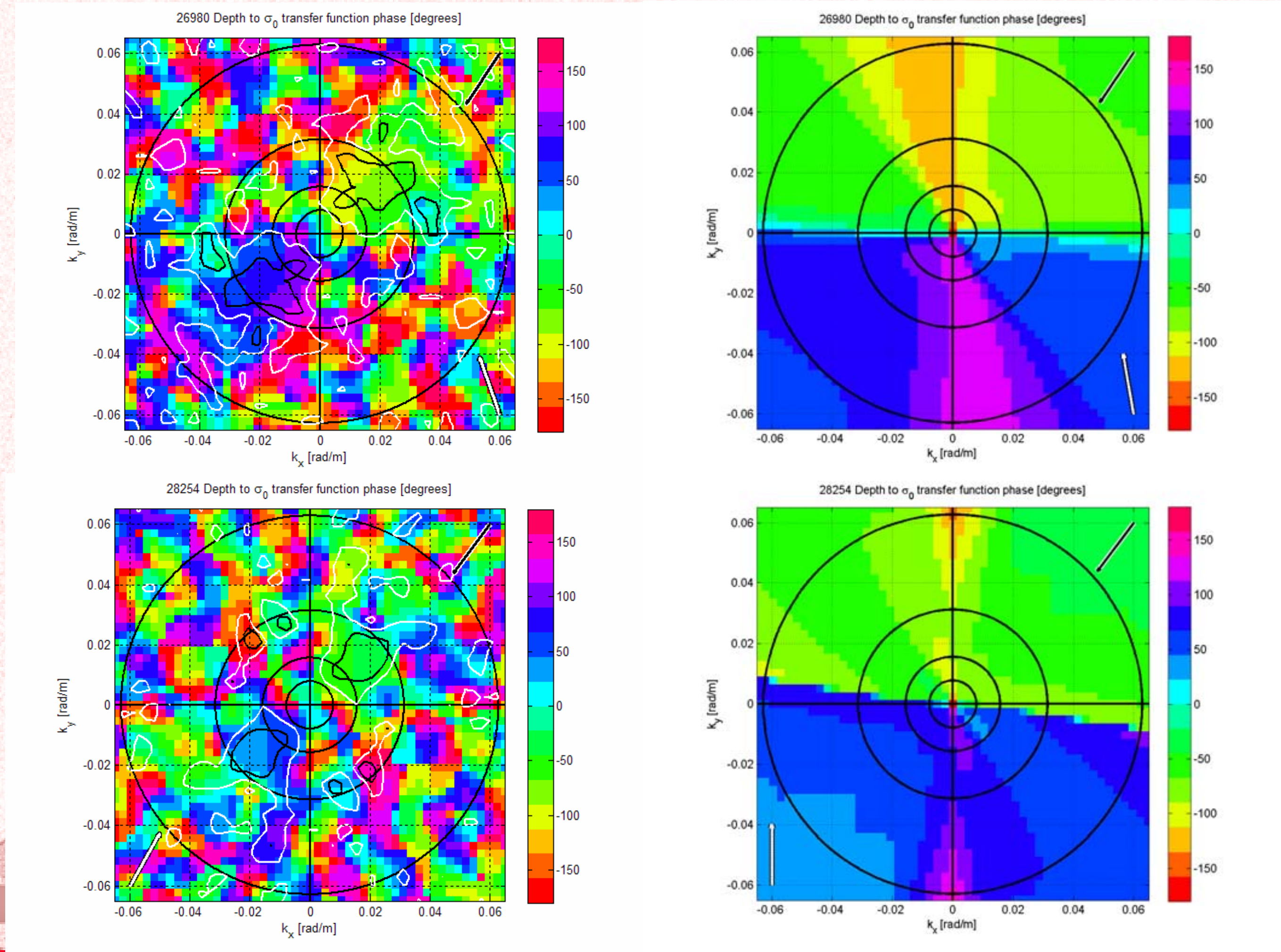
Modulation Transfer Functions



- black contour: area of S/N>1
- black arrow: current direction
- white arrow: wind direction

Measured and simulated transfer function phases for the images in orbit 16230 (upper) and orbit 22972 (lower)

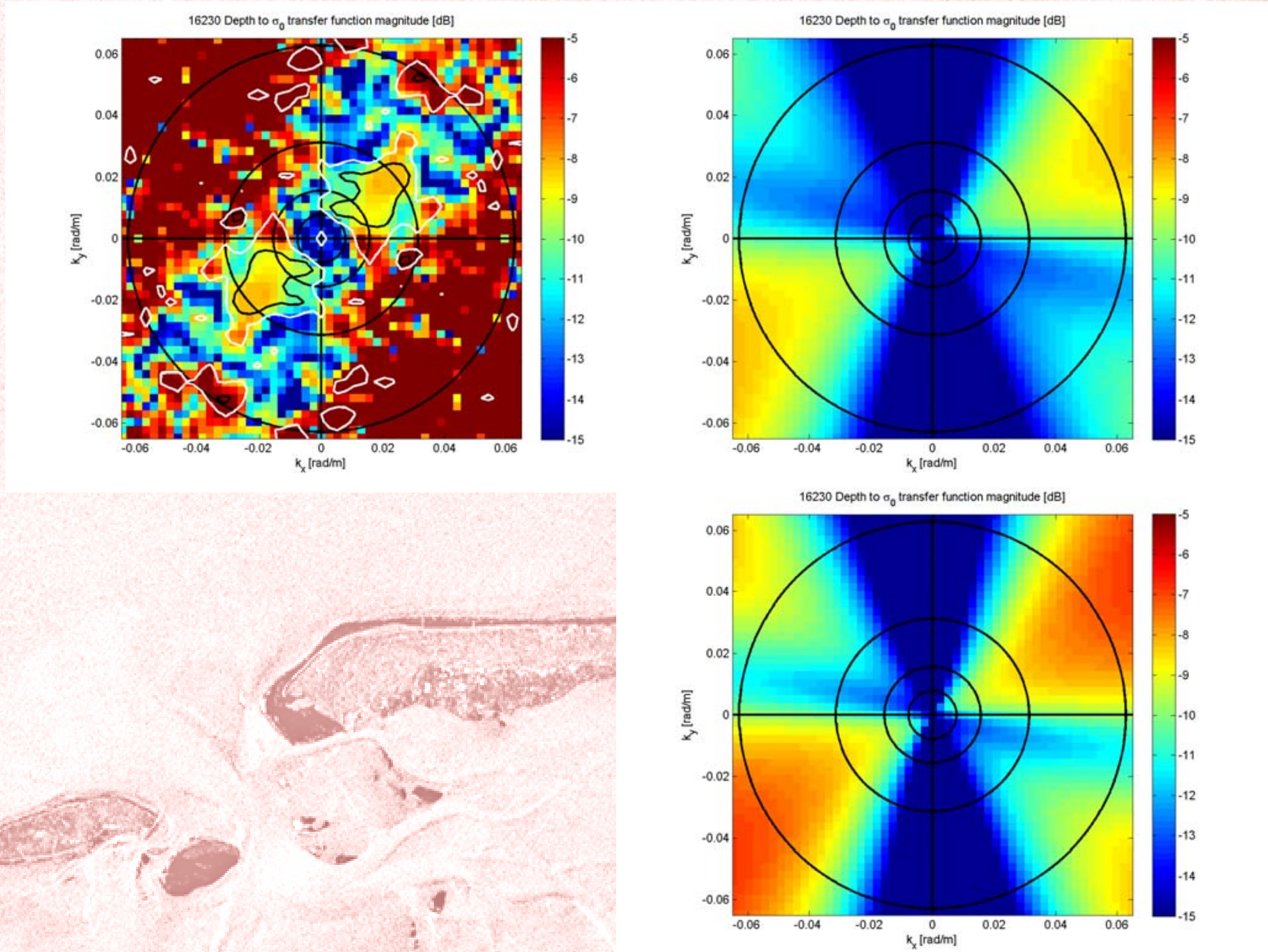
Modulation Transfer Functions



- black contour: area of S/N>1
- black arrow: current direction
- white arrow: wind direction

Measured and simulated transfer function phases for the images in orbit 26980 (upper) and orbit 28254 (lower)

Modulation Transfer Functions



Measured and simulated transfer function amplitudes (sB) for the image 16230

Conclusions about the 2-scale forward model:

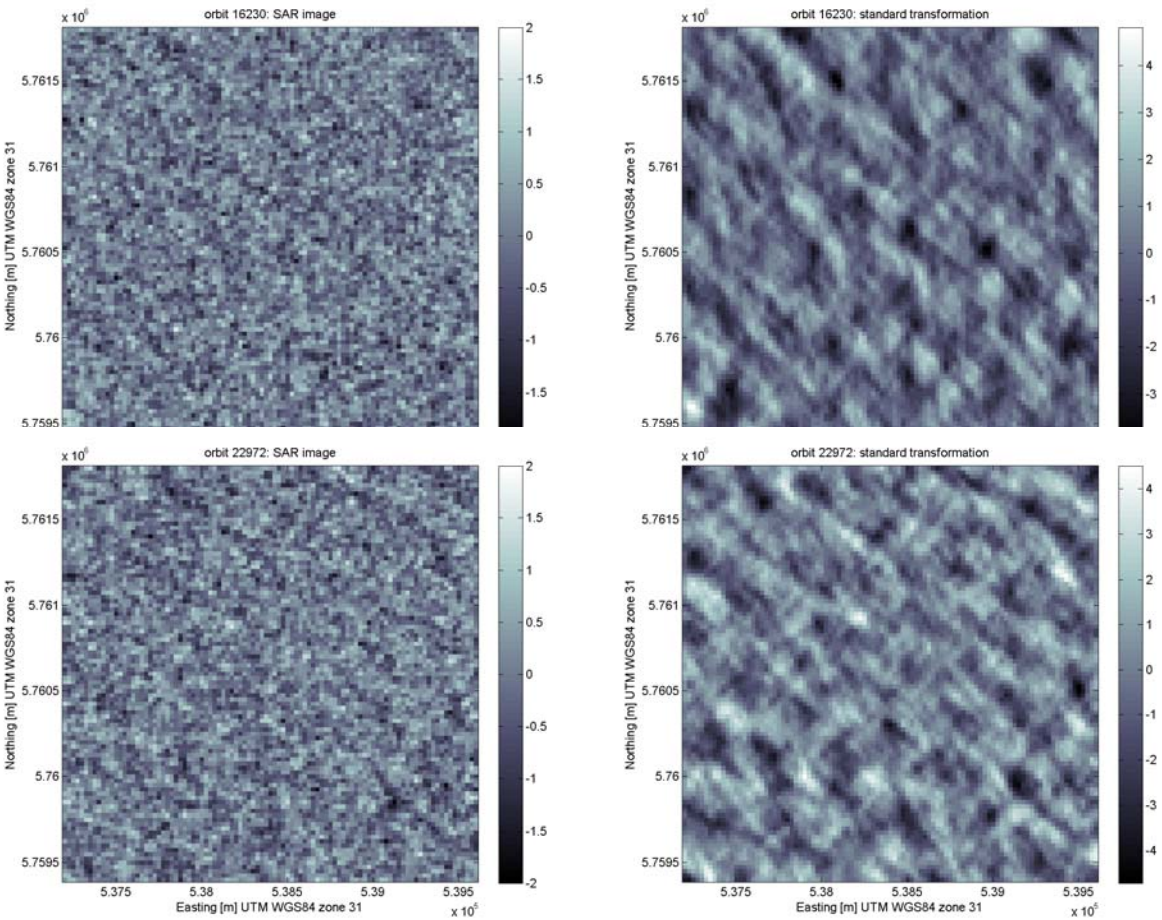
- **The two-scale model performs well in reproducing measured phase shifts in the wavenumber range where S/N>1.**
- **Phase shifts are near + or – 90º, while the two-scale mechanism (through tilting of Bragg waves by the long waves interacting with the current) is dominant: also these long waves are not far from local equilibrium with straining and refraction by the current**
- **Predicted Transfer Function magnitudes are somewhat lower than empirical values: some overestimation of relaxation rates of long waves**

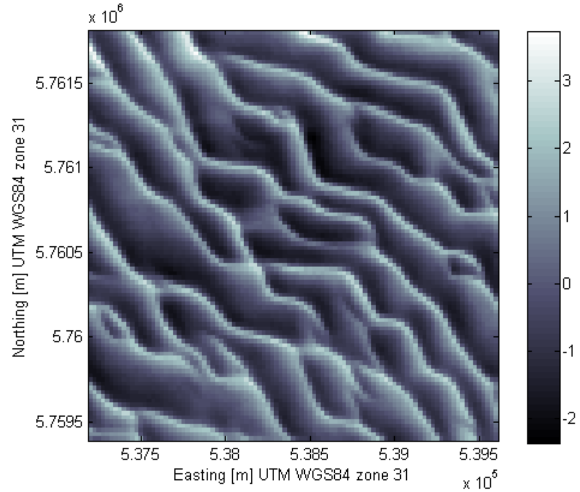
Simulated and measured transfer function phases for the images with high coherence (continued on next pages),.)

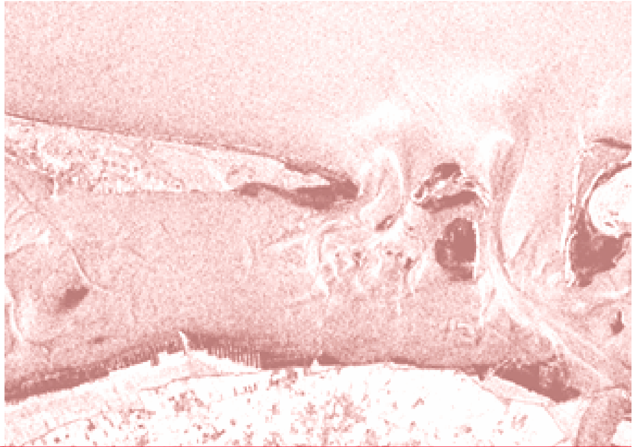
Retrieval of sand waves

- **Forward model (MTF) very easy to invert**
- **Needs regularisation to avoid blowing up noise in inversion (forward model is very insensitive to sand waves outside a narrow directional sector)**
- **Mean-square of seabed slope penalised**
- **Scale of retrieved depth variation needs to be tuned**

Retrieval of sand waves







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upper: image orbit 16230 and retrieval, and seabed soundings

lower: image orbit 22972 and retrieval

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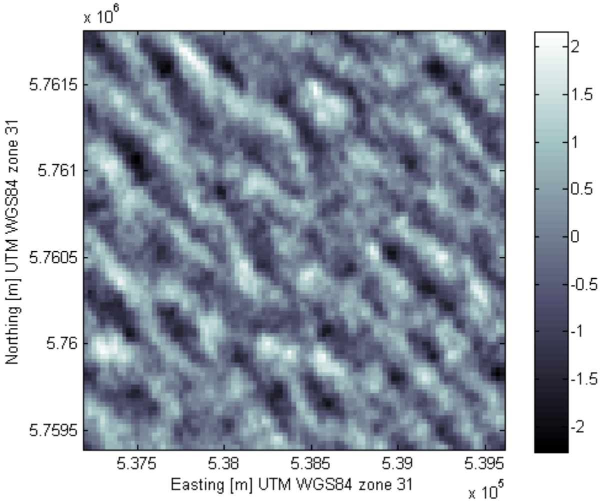
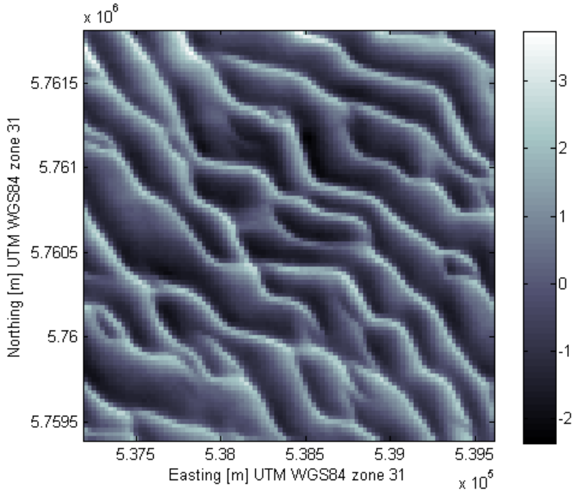
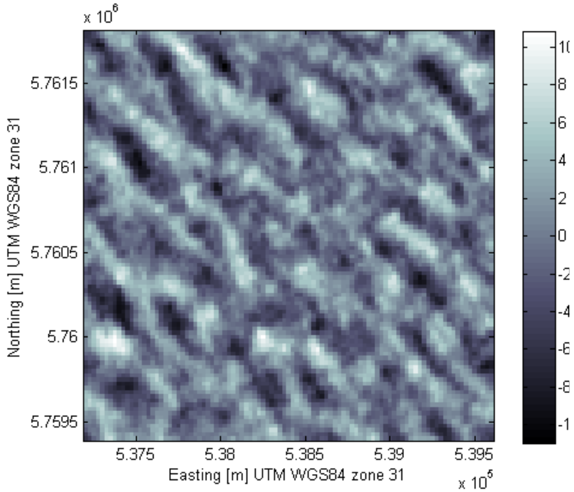
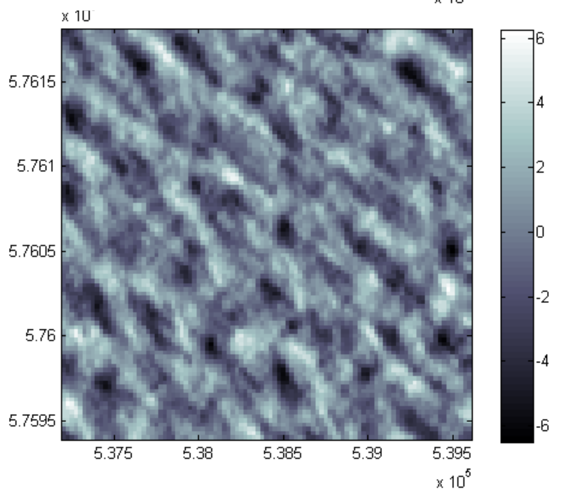
Retrieval of sand waves









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upper: retrieval from 6 images, and seabed soundings

lower: retrieval from 4, and 2 images (orbits 16230, 22972)

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Retrieval of sand waves

- Most of the sand wave crests are found back in retrieval
- Resolution loss (blurring)
- Cause: 2-scale mechanism rather than speckle
- Sand waves are short! In test area, 200-300 m.
- Example of engineering requirement: measure migration of sand wave crest, order 1-10 m per year. Clearly not feasible.
- Long radar wavelength (P band) appears able to localise sand wave crests more accurately (2-scale mechanism not important)

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