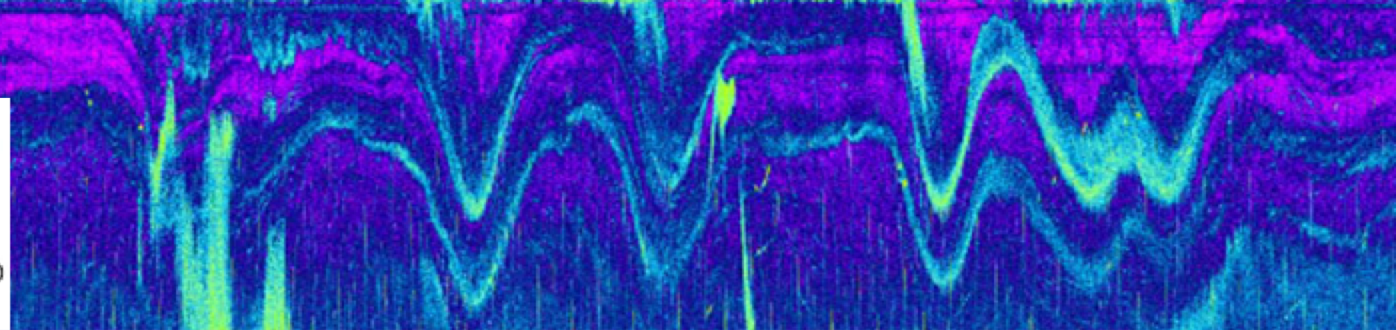

SAR mode altimetry observations of internal solitary waves in the tropical ocean

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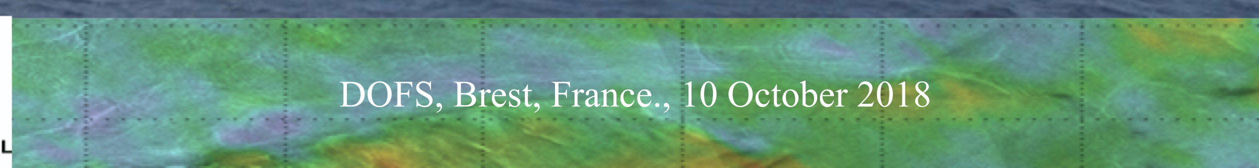


DOFS, Brest, France., 10 October 2018

Outline of this Talk

- Introduction
  - Internal solitary waves (ISWs)
  - Theoretical considerations about observability of ISWs with altimeters
    SAR imaging of internal waves at oblique incident angles and at nadir
  - Evidence of ISW signatures with SAR – Altimetry

- Method of detection
  - Mean Square Slope & Sea Level Anomaly
  - Statistics for the tropical Atlantic (off the Amazon shelf)

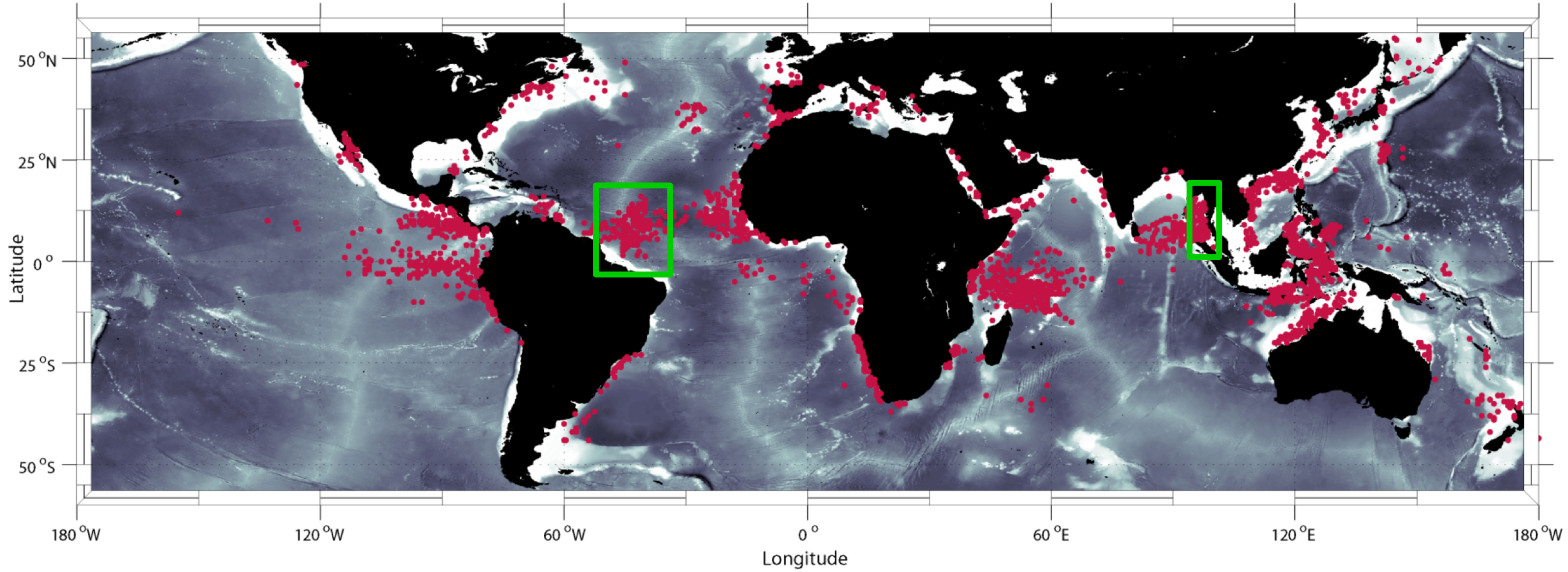
- Conclusions & prospects of future work

Aims:

- *Develop a synergetic approach that enables the identification of large-amplitude, short-period ISWs from SAR altimeters (Sentinel-3)*
- *Automatic detection based on mean square slope measurements*

Internal solitary waves (ISWs)

Global Map of ISWs

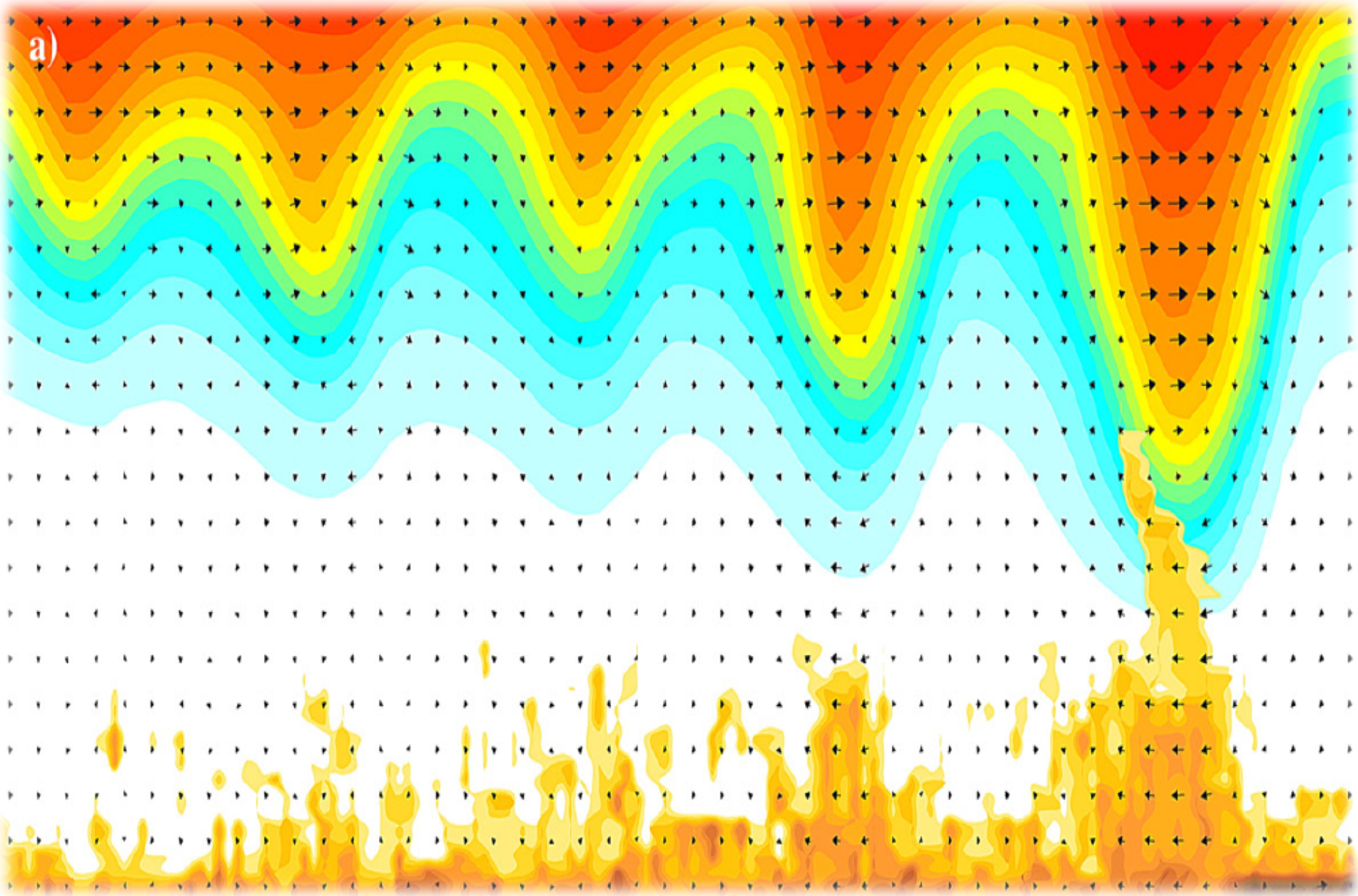


The location of nonlinear internal waves observed in 250 m resolution MODIS (Moderate-Resolution Imaging Spectroradiometer) satellite sunglint imagery acquired from August 2002 through May 2004.

Jackson et al. (2012)

Internal solitary waves (ISWs) and motivation to study them

Sediment re-suspension in the nepheloid layer measured in the Nazareth Canyon, Portugal



Sediment re-suspension

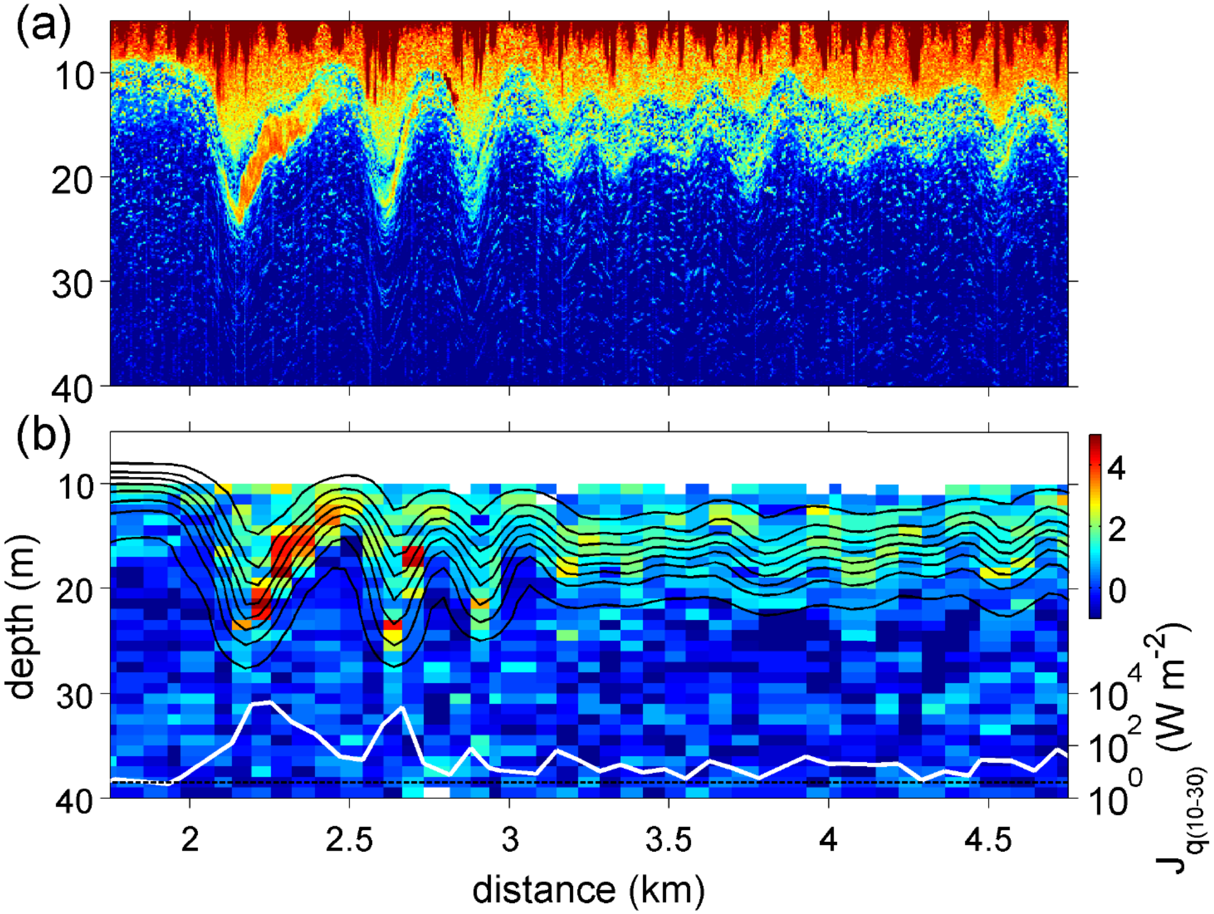
Adapted from Quaresma et al. (2007)

Internal solitary waves: why should we care?

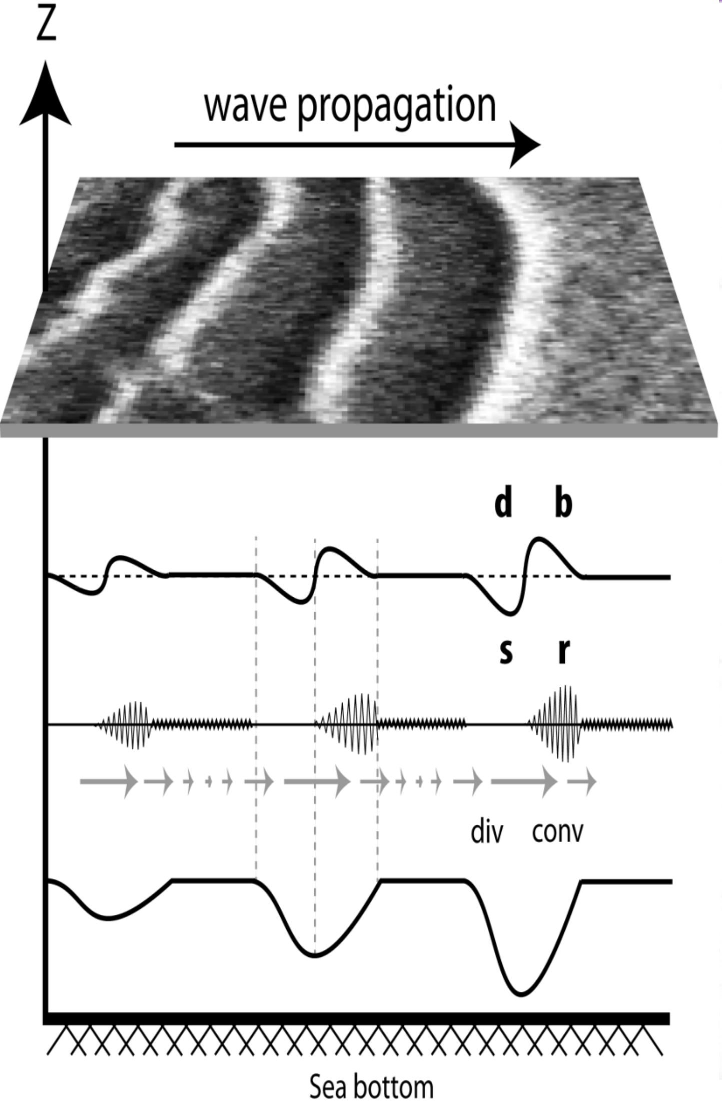
Vertical heat fluxes peaked at over **1000 times** greater in the leading wave than in the background shelf waters (E. Shroyer, 2009).

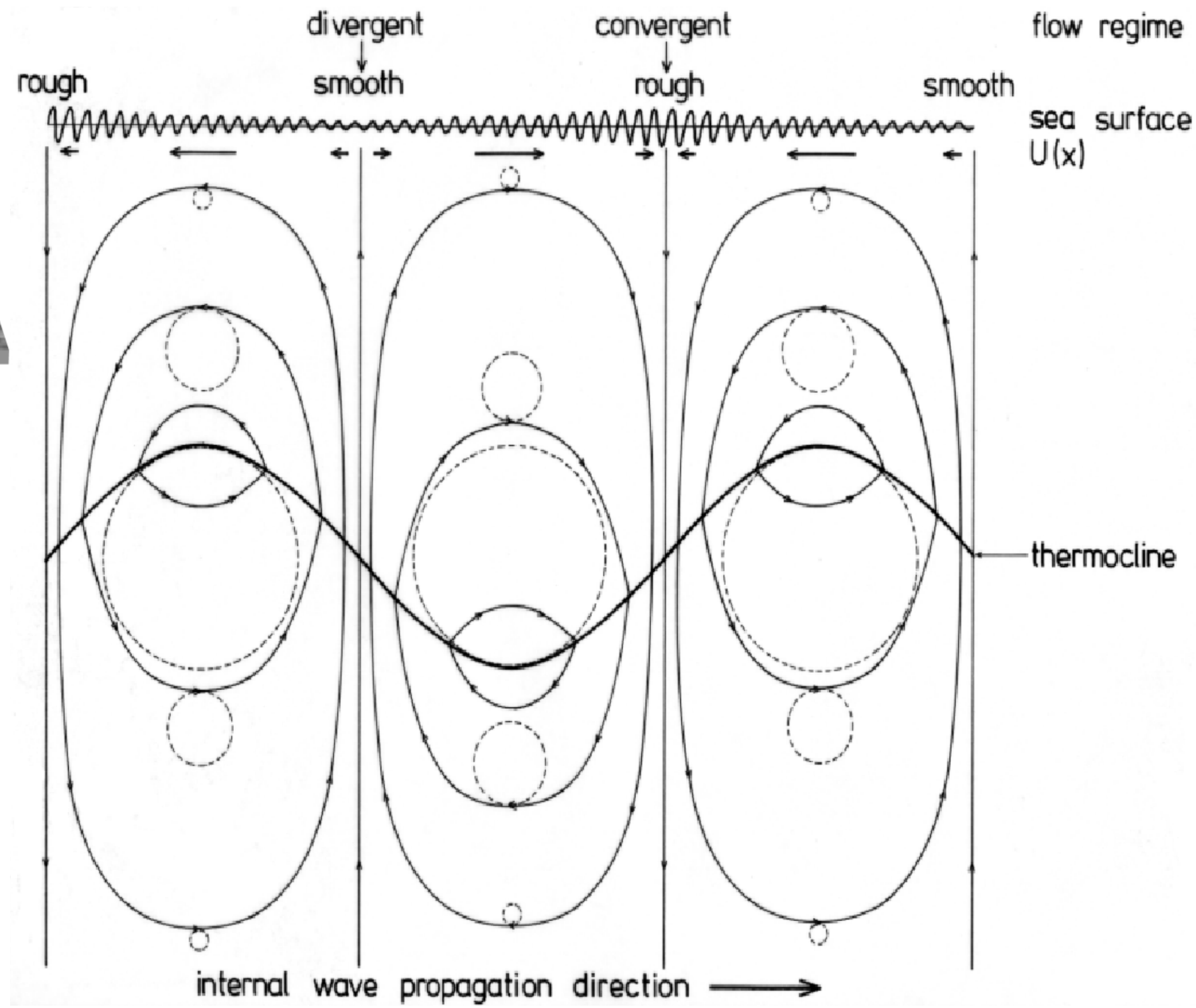
Acoustic backscatter

Vertical heat flux (log scale)



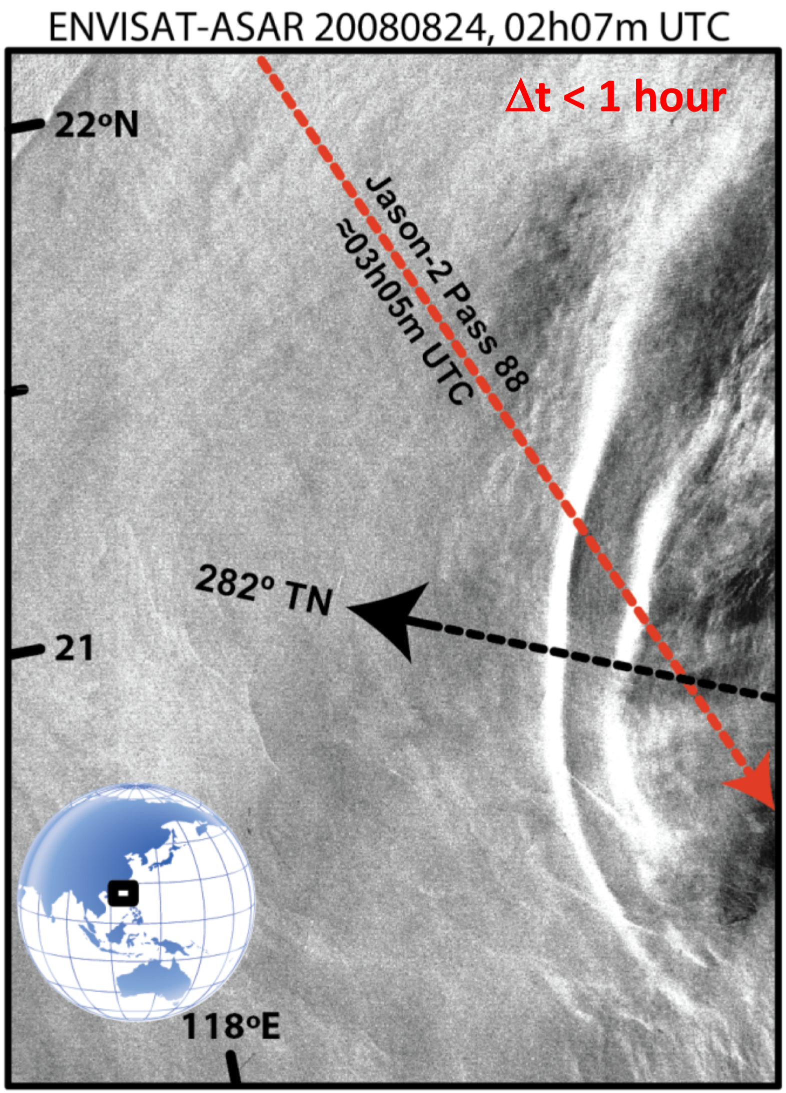
Introduction:
SAR imaging of internal waves at oblique incident angles

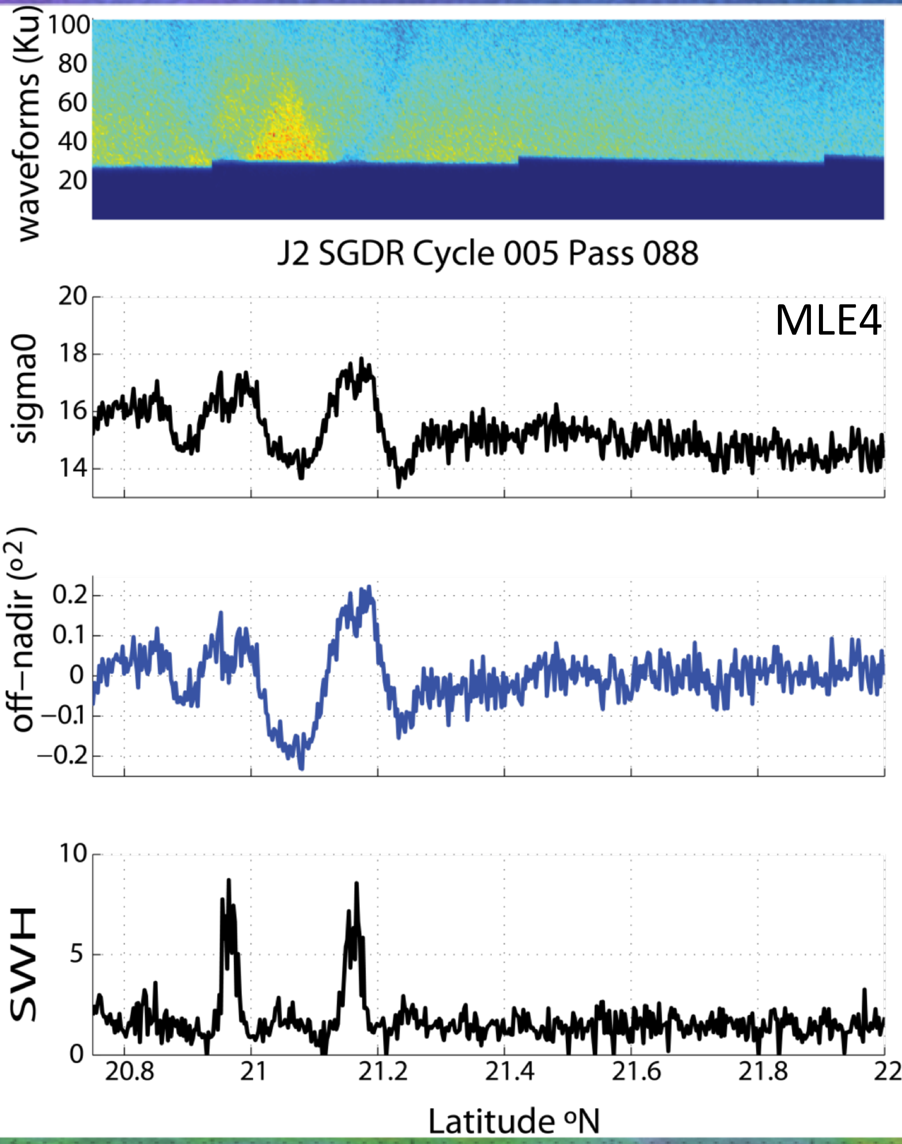




Sea surface roughness pattern generated by a linear internal wave

A case study with a pulse-limited altimeter: South China Sea





Theoretical considerations about observability of ISWs with altimeters

1) Roughness of the water surface with wind-driven waves may be “measured” with the mean square surface slope (mss), defined as,

$$\left\langle s^2 \right\rangle = \int_0^\infty S(\kappa)\ \kappa d\kappa$$

where S(κ) is the omnidirectional, one-sided wave number slope spectrum and κ is the wave number.

2) Apply the geometrical optics (Kirchhoff method) form of the integrated microwave backscatter cross section according to the expression,

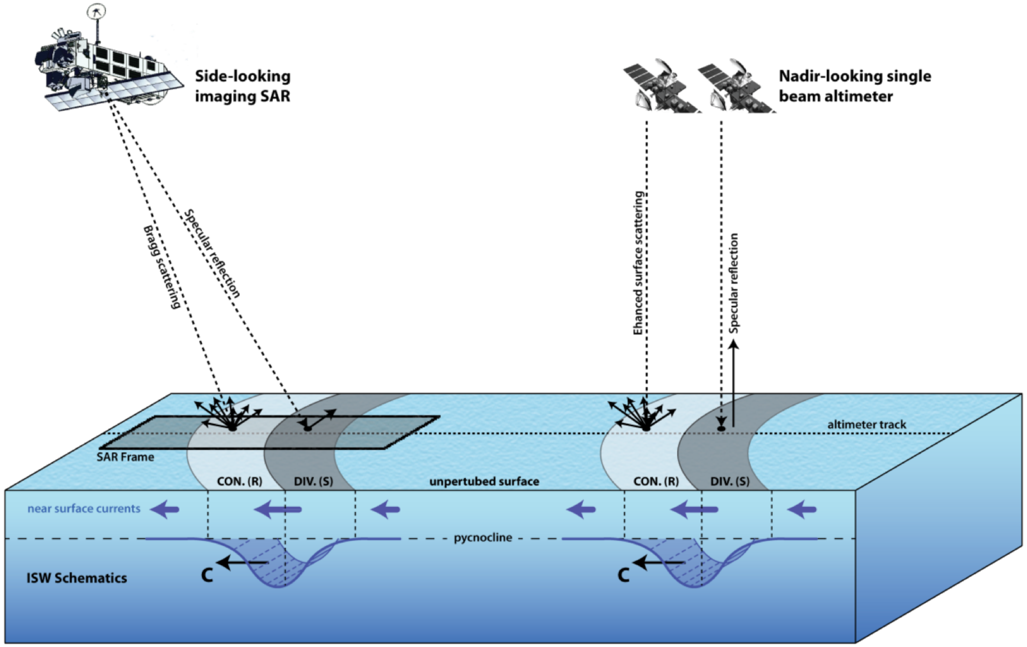
$$\sigma_0^{GO} = \left(\rho_g \sec^4\theta / \left\langle s_g^2 \right\rangle\right)\ e^{\left(-\tan^2\theta / \left\langle s_g^2 \right\rangle\right)}$$

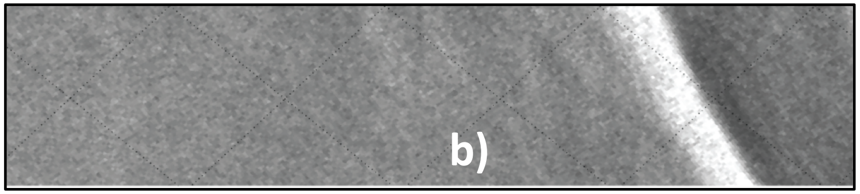
where ρ_g is an effective reflectivity, $<s_g^2>$ is an effective mean square slope estimate and θ is the pulse illumination incidence angle.

For near-nadir, (i.e. θ~0) satellite altimeter observations the mss is given by,

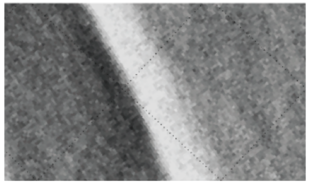
$$\left\langle s_n^2 \right\rangle = \frac{\rho_n^{'}}{\sigma_0}$$

Introduction:
How does an Altimeter and a SAR see internal waves in the ocean?



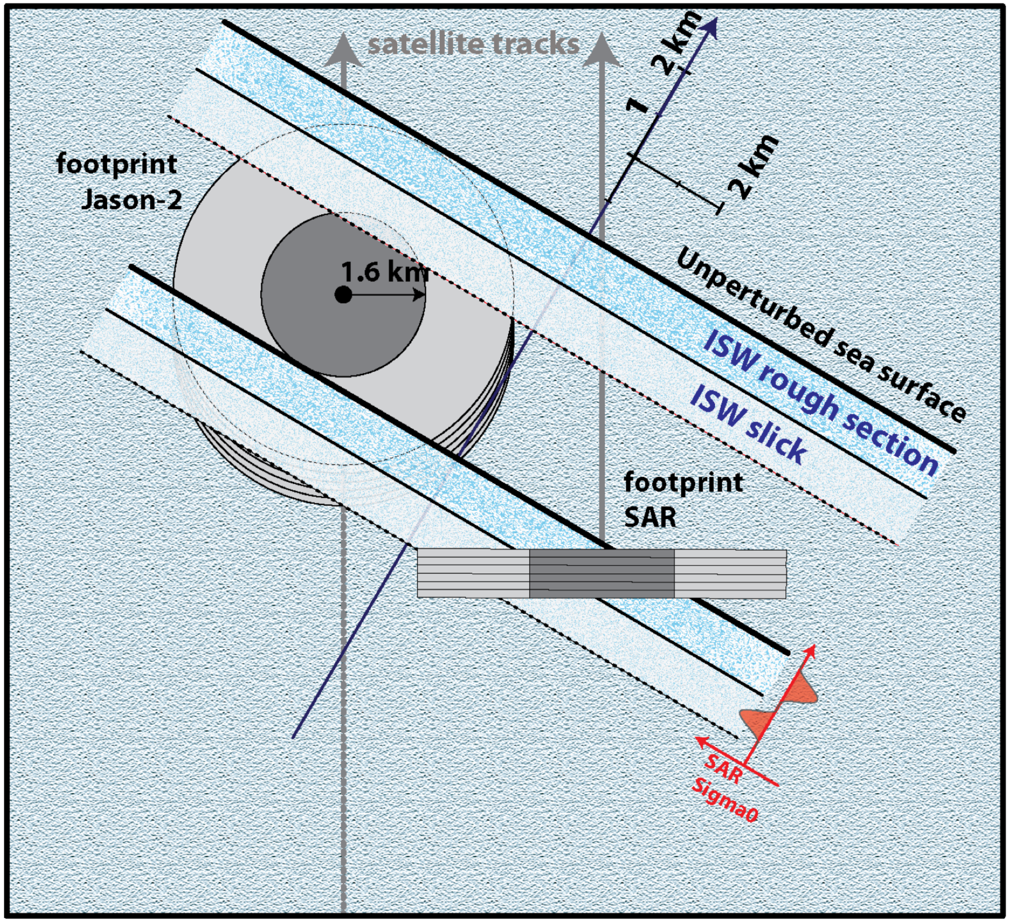


altimeter?



Altimeter
dark/bright

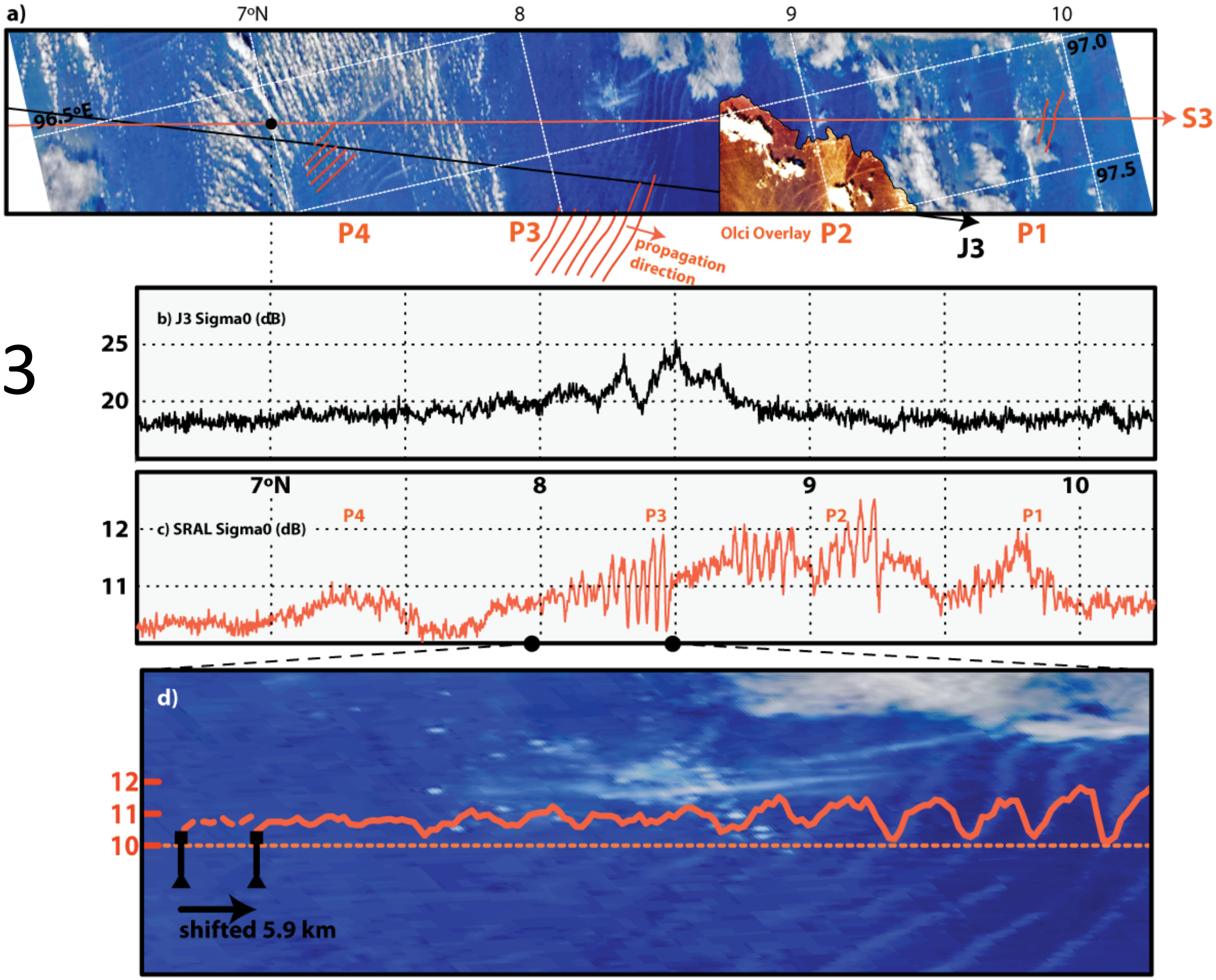
SAR Mode Versus Pulse-limited High Rate Mode



Pulse-limited versus SAR altimetry

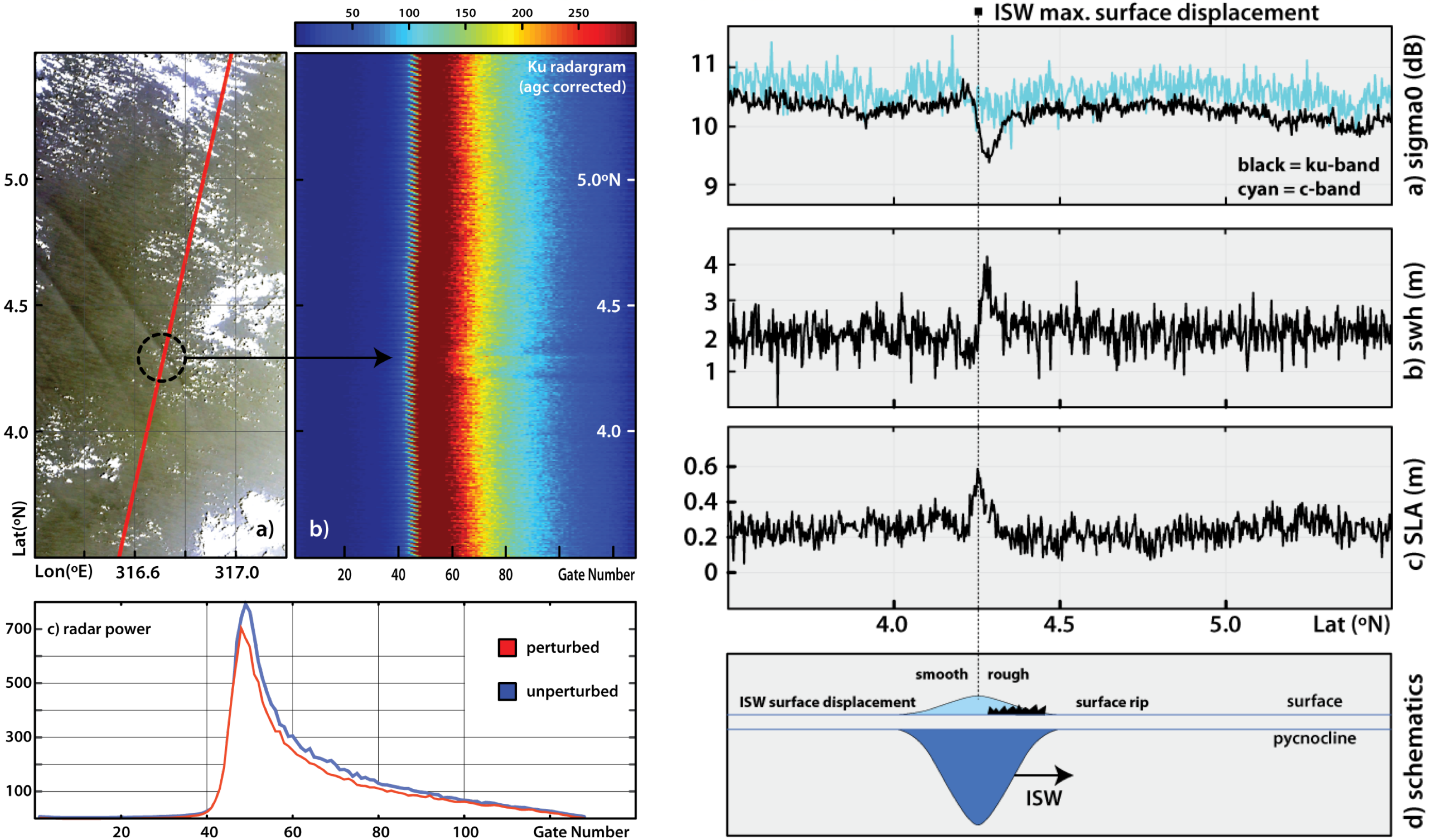
Jason-3

SAR



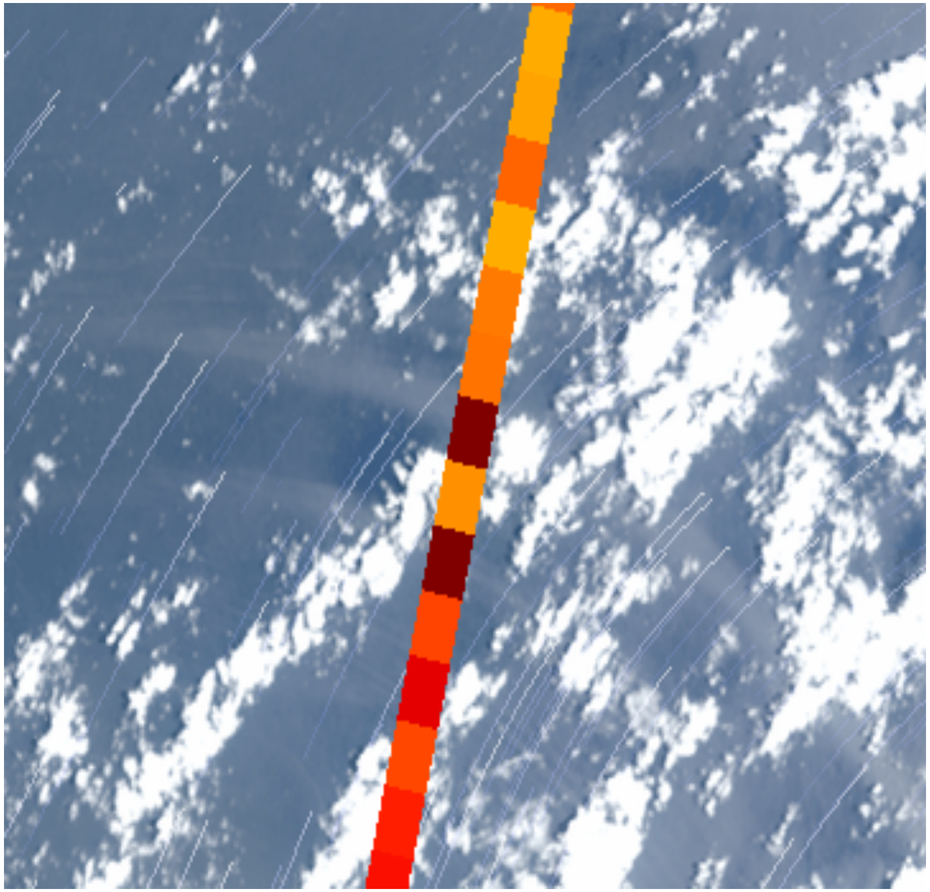
2017.02.12 03:16 UTC Andaman Sea

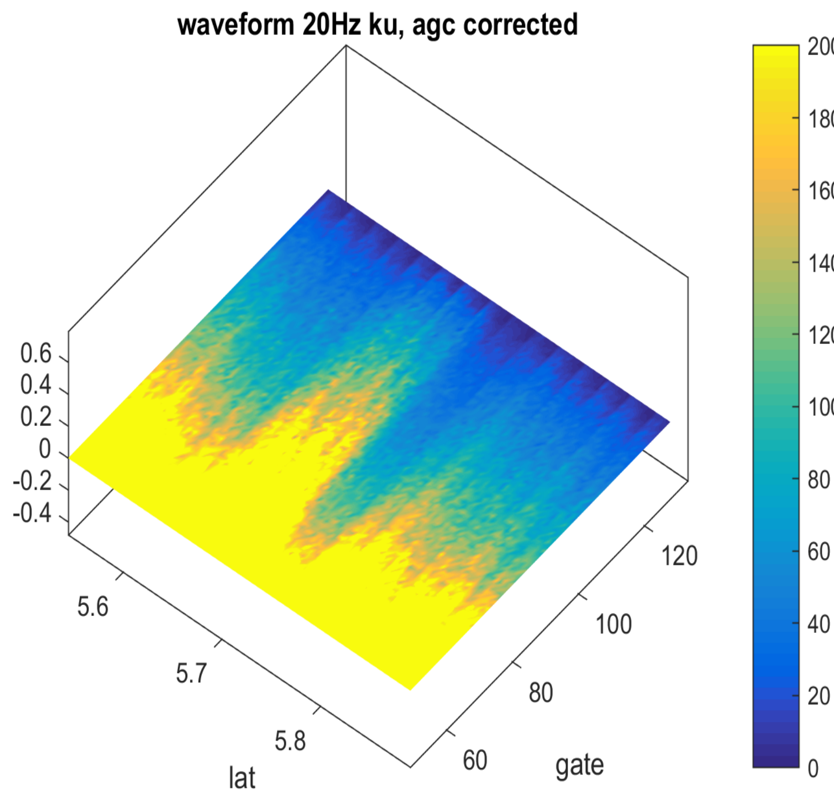
2017.09.14 12:54 UTC Amazon Seas



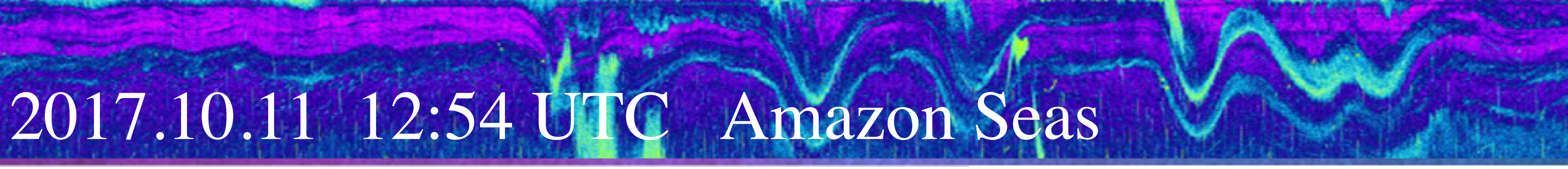
2017.10.11 12:54 UTC Amazon Seas

Quasi-true Color OLCI image



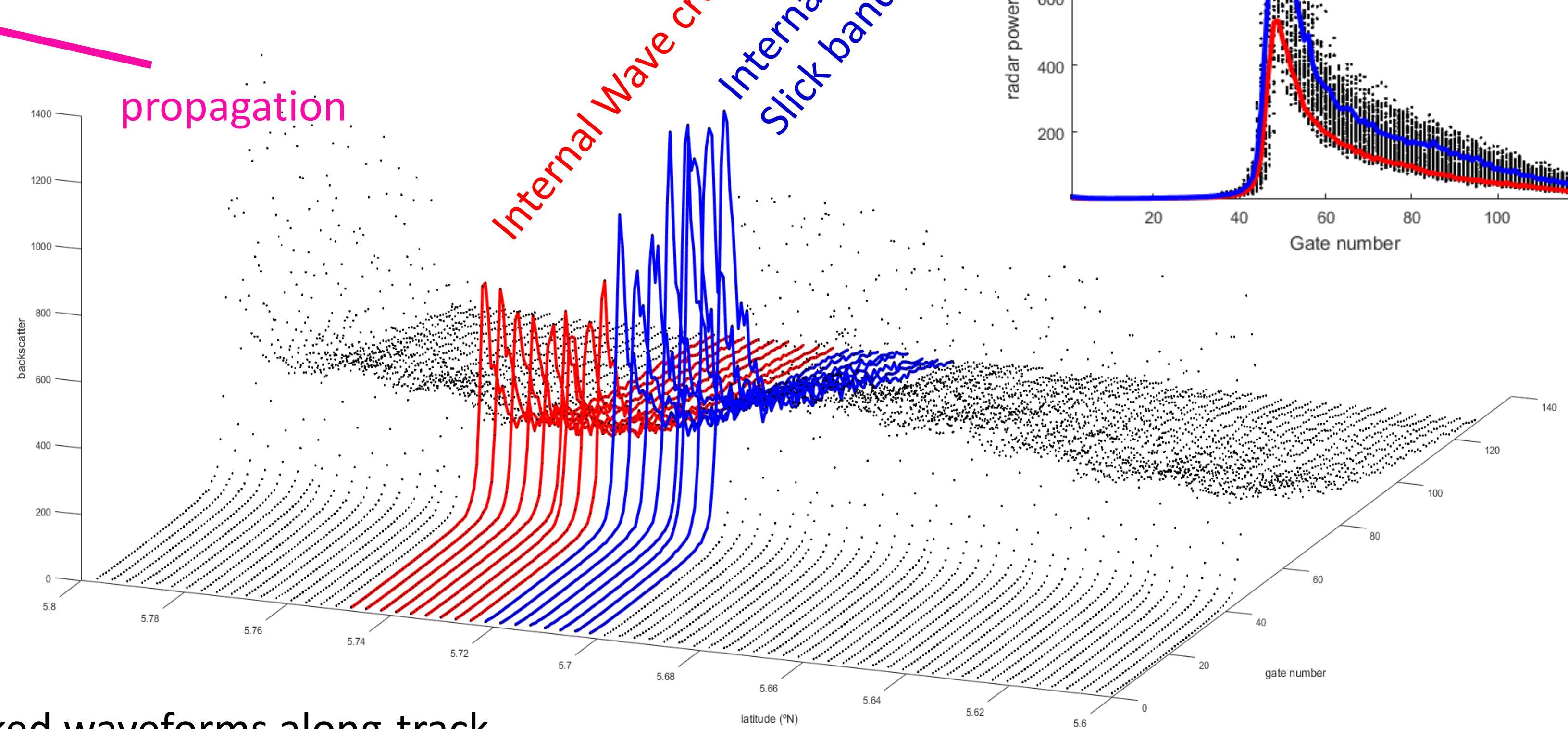


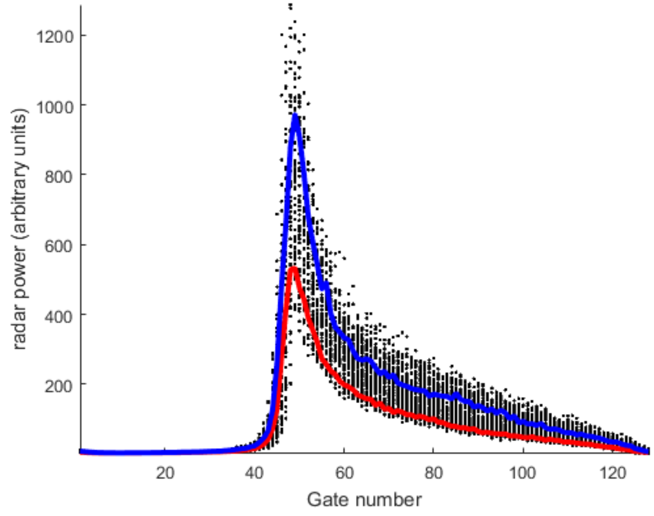
Obtained from Ocean Virtual Lab.
Color code is SLA at 1 Hz.



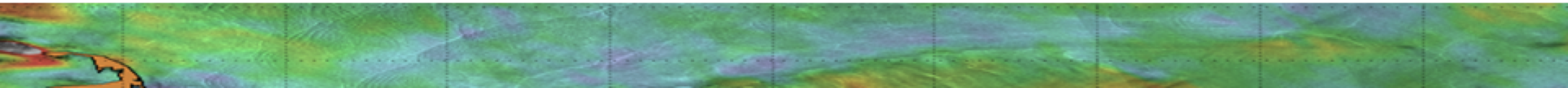
2017.10.11 12:54 UTC Amazon Seas

Ku, agc corrected





Stacked waveforms along-track (L2)



Method of detection: Mean Square Slope

Isolation of the mean square slope contribution of the small-scale waves between 6.3 cm and 16.5 cm is possible by differencing the estimates from the two frequency bands of Sentinel-3 altimeter (Ku and C bands).

$$\langle s^2 \rangle = \int_{k1}^{k2} S(\kappa)\, \kappa d\kappa$$

[k1, k2] = [40, 100] rad/m
[6.3, 16.5] cm

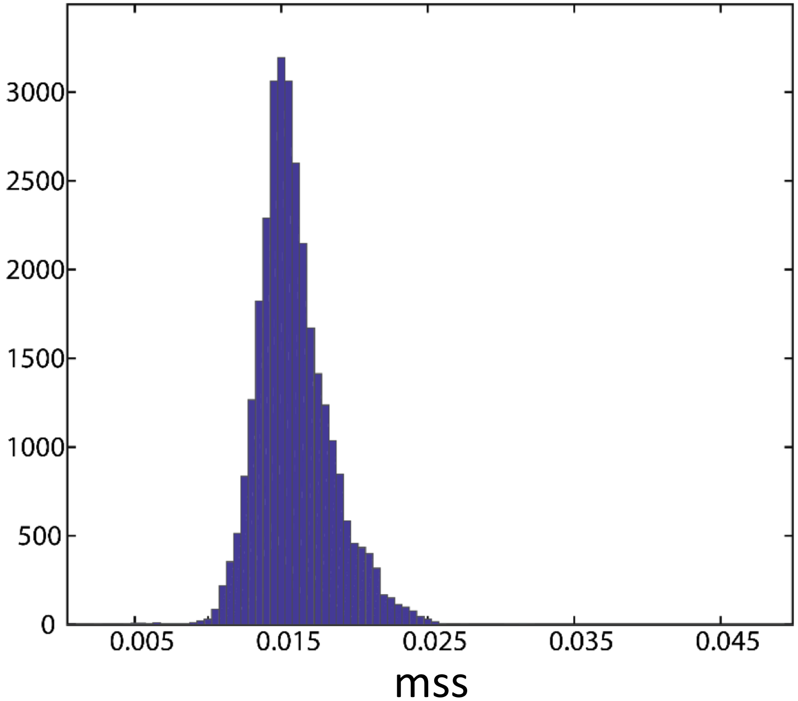
Differenced mean square slope:

$$\Delta\langle s_n^2\rangle = \langle s_n^2\rangle^{ku} - \langle s_n^2\rangle^{c} = \frac{\rho_n'^{ku}}{\sigma_0^{ku}} - \frac{\rho_n'^{c}}{(\sigma_0^{c} + \alpha)}$$

where α is a calibration constant (Chapron et al., 1995)

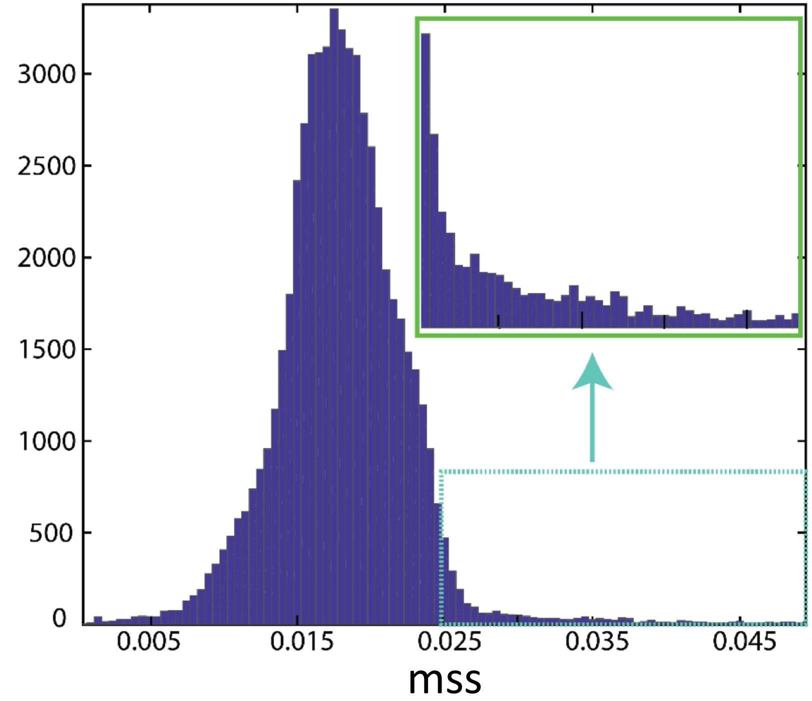
Method of detection: Mean Square Slope

Unperturbed by ISWs



PDF of mss for South Pacific

Region includes ISWs



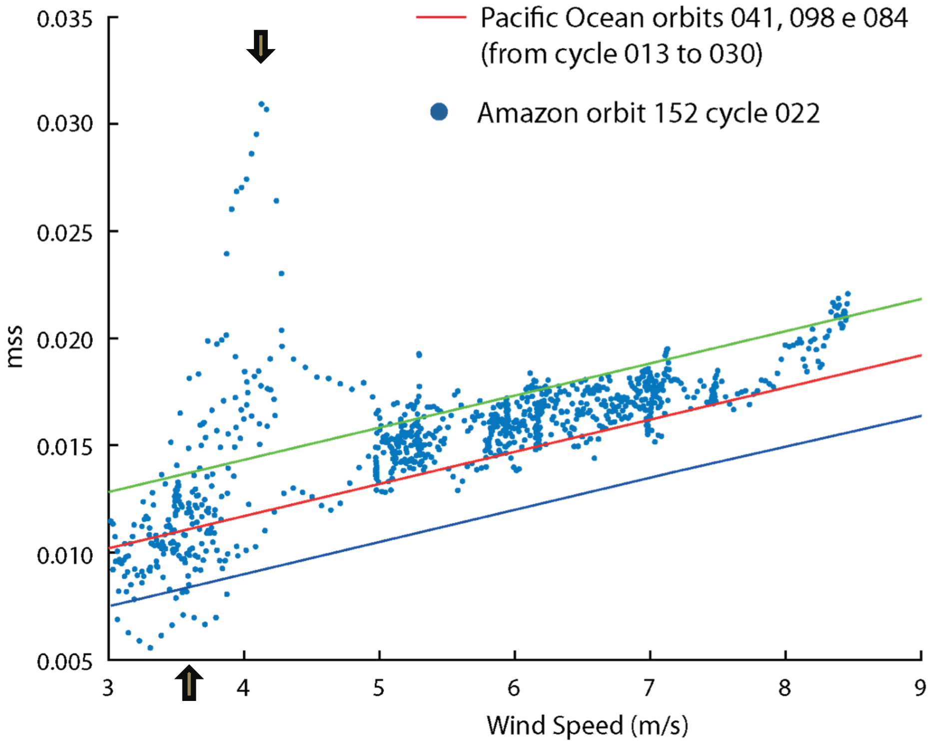
PDF of mss for Amazon

Method of detection: Mean Square Slope

$mss^{S3}(U_{10}) \geq mss^{S3}(U_{10} + 2\ \mathbf{m/s})$	**(1)**

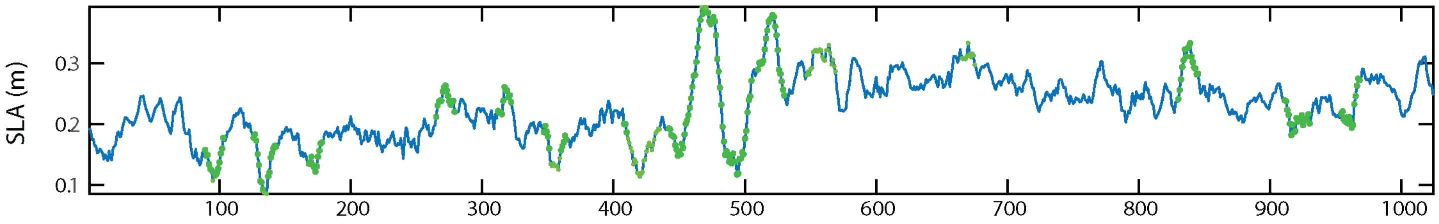
&

$mss^{S3}(U_{10}) \leq mss^{S3}(U_{10} - 2\ \mathbf{m/s})$	**(2)**



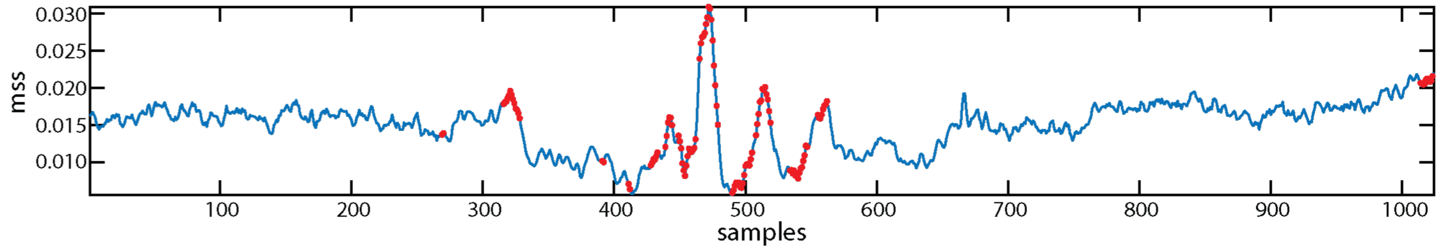
Method of detection: Mean Square Slope & SLA

abs(SLA) ≥ 6 cm

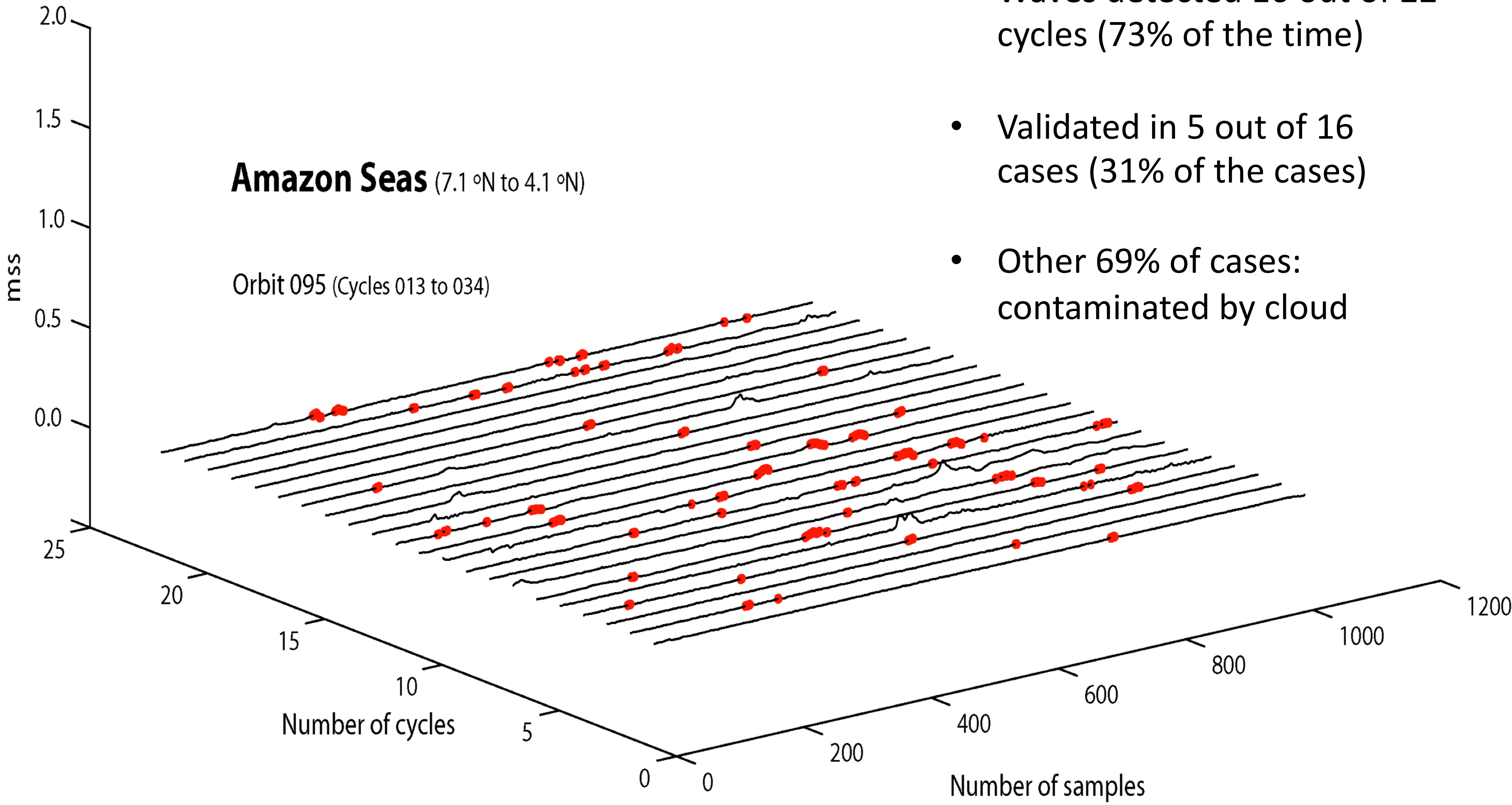


Wavelet analysis algorithm to detect high frequency signals

Combined automatic detection



Statistics for the tropical Atlantic (off the Amazon shelf)

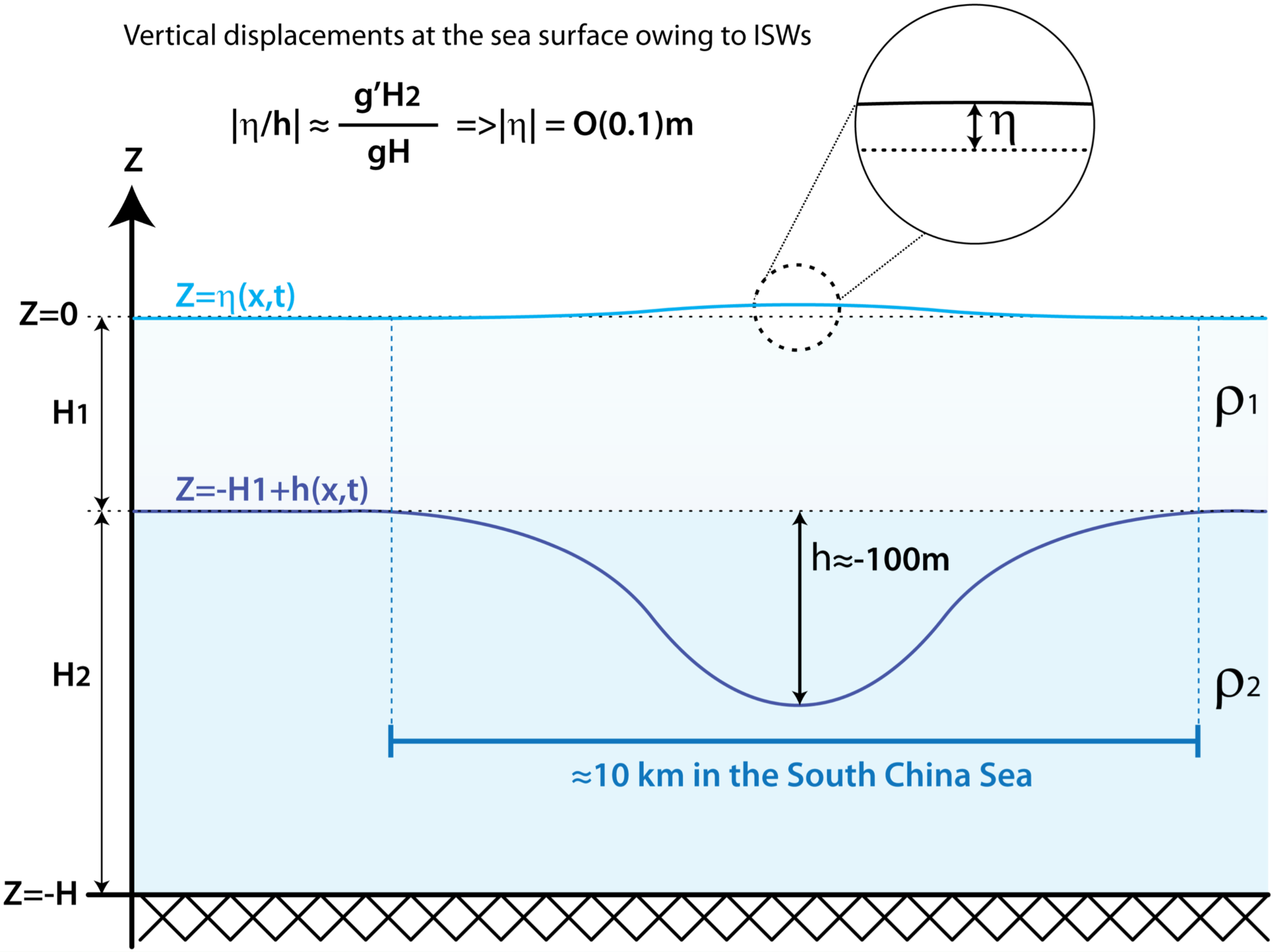


- Waves detected 16 out of 22 cycles (73% of the time)
- Validated in 5 out of 16 cases (31% of the cases)
- Other 69% of cases: contaminated by cloud

Prospects of future work

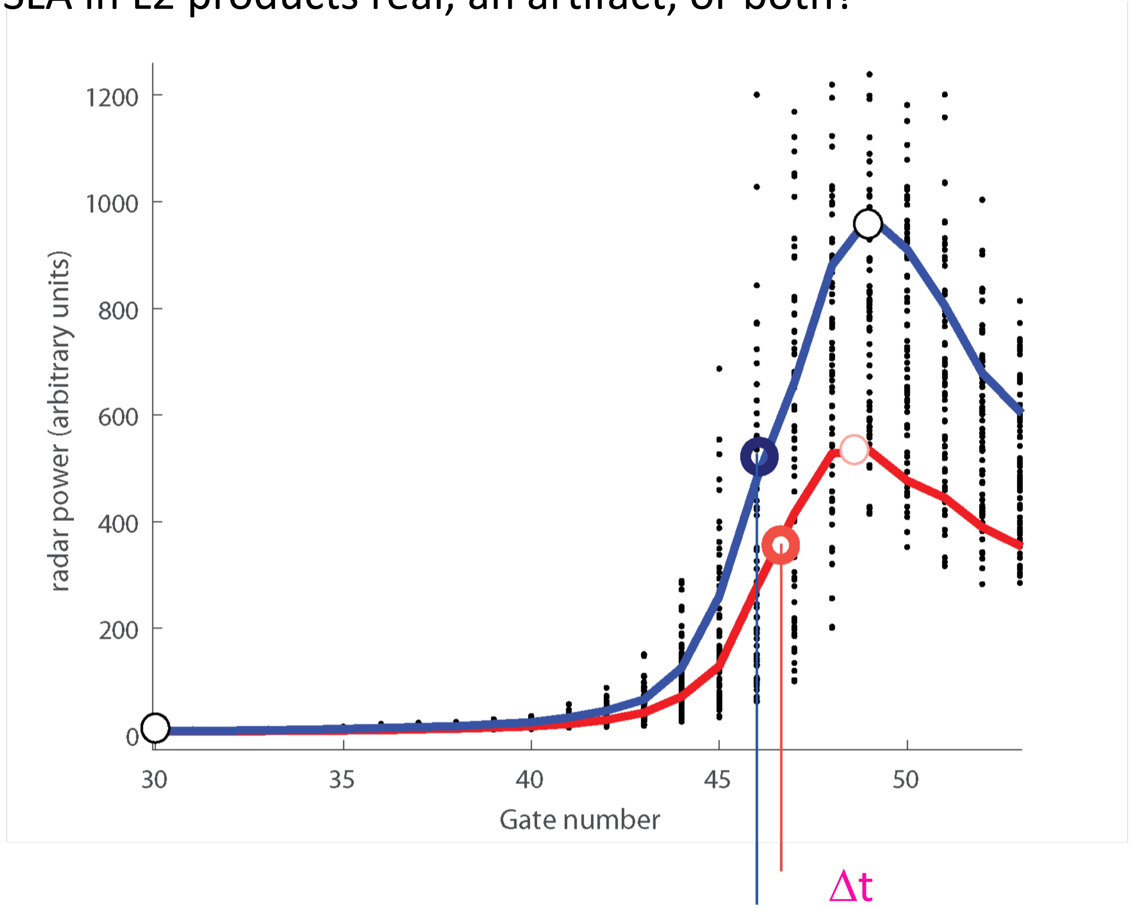
Vertical displacements at the sea surface owing to ISWs

$$|\eta/h| \approx \frac{g' H_2}{g H} \Rightarrow |\eta| = O(0.1)\text{m}$$



Prospects of future work

Is the measured SLA in L2 products real, an artifact, or both?



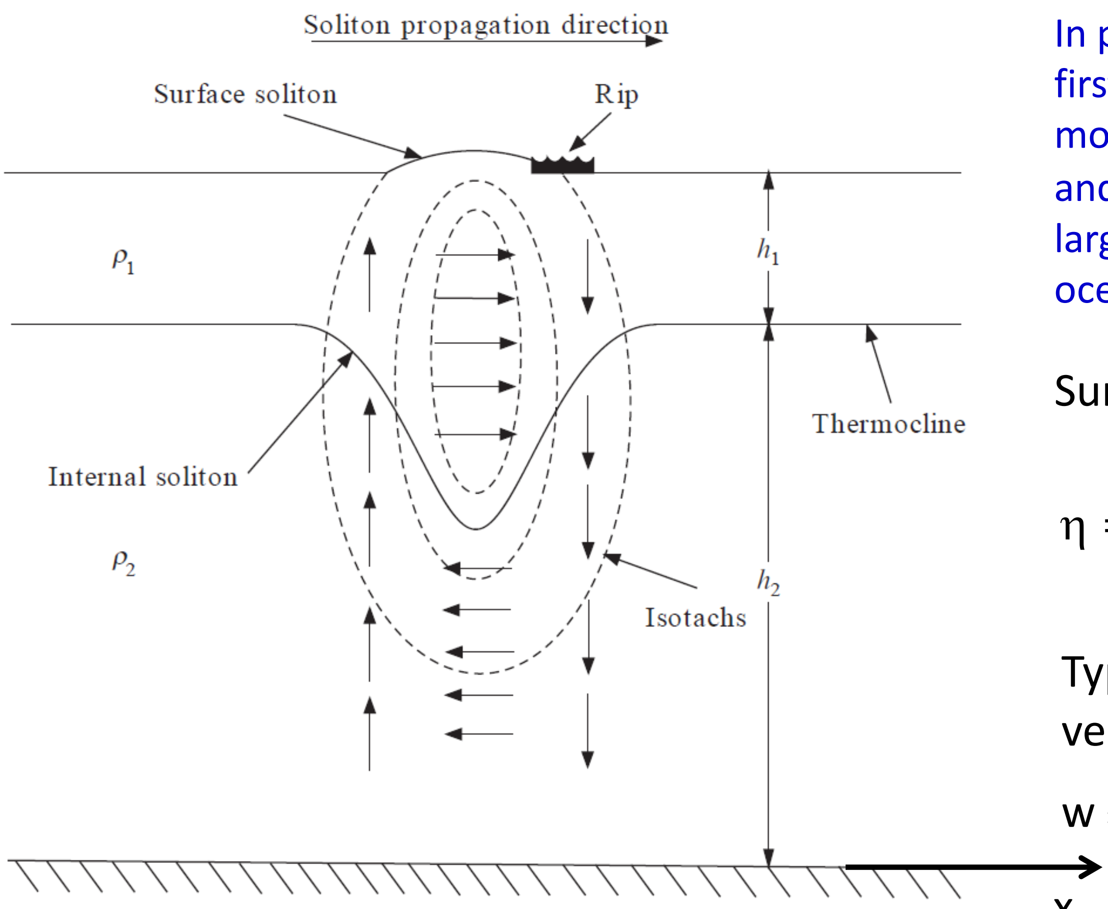
Δt

➔ Is this the origin of SLA in ISWs ?

Can we do something about this ambiguity ?

Conclusions & prospects of future work

Powerfull vertical and horizontal currents: strong vertical heat flux & transport of momentum



Osborne & Burch, 1980

In principle, it is possible (for the first time), to develop a robust model to infer wave amplitudes and vertical velocities due to large-amplitude ISWs in deep ocean.

Surface displacement η

$$\eta = -\frac{1}{g}\int_{-\infty}^{x}(u-c)\frac{\partial u}{\partial x}dx'$$

Typical horizontal velocities $u \approx 2$m/s

$w \approx 0.2$ m/s

Conclusions & prospects of future work

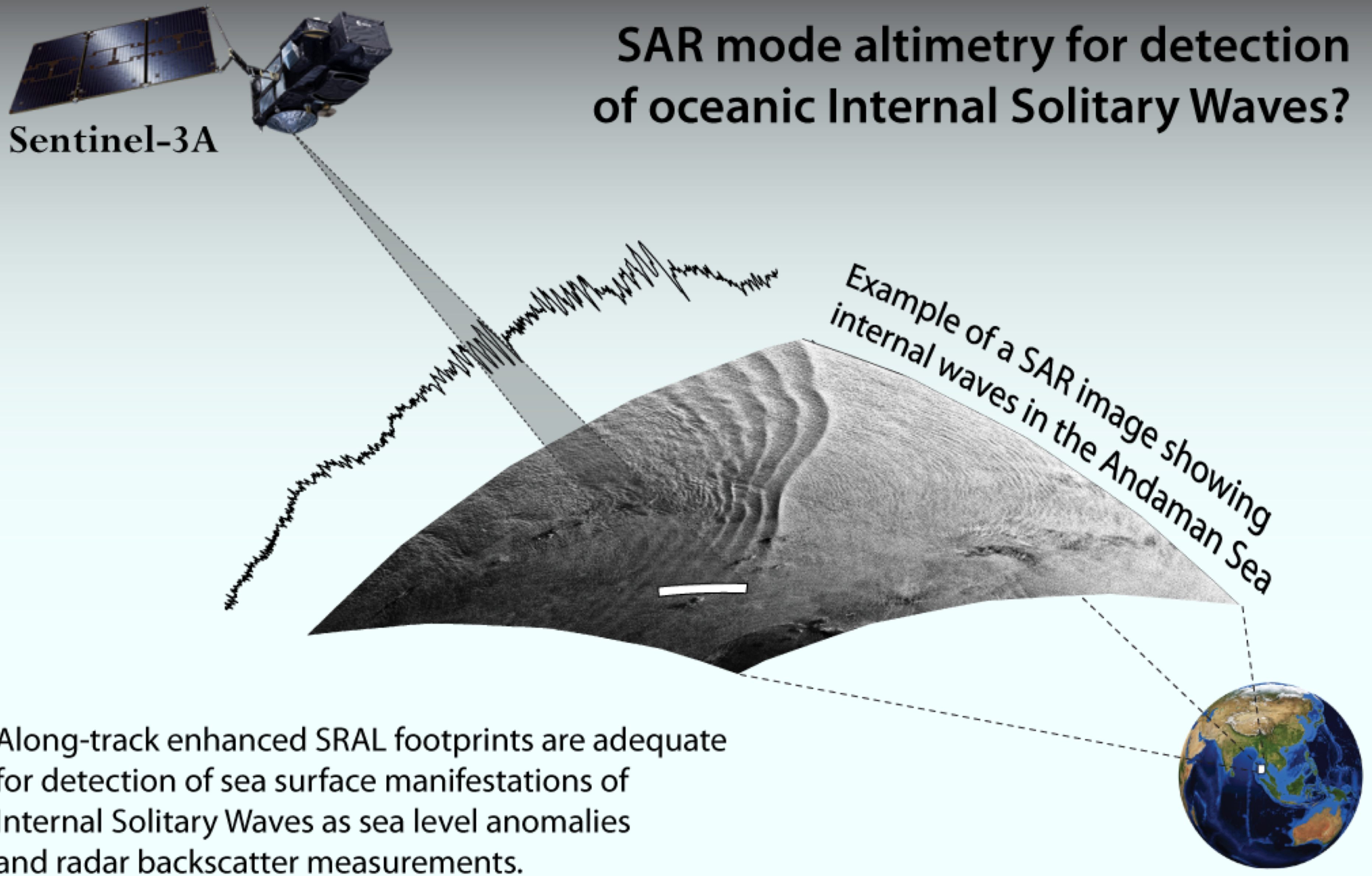
Conclusions:

- SAR altimeter on board Sentinel-3 is sensitive to surface roughness modulations originated by large-scale ISWs in the tropical ocean.
- ISW signatures apparent in radargram, radar power (sigma0), and in SLA.
- Algorithm for automatic detection of internal solitary waves validated with OLCI
- There appears to be a signature in sea surface height anomaly, as predicted by internal wave theory. This may enable us to retrieve ISW amplitudes and (vertical) currents.

Doppler Oceanography from Space

From science to technology and applications

SAR mode altimetry for detection of oceanic Internal Solitary Waves?



Along-track enhanced SRAL footprints are adequate for detection of sea surface manifestations of Internal Solitary Waves as sea level anomalies and radar backscatter measurements.

Thank you!