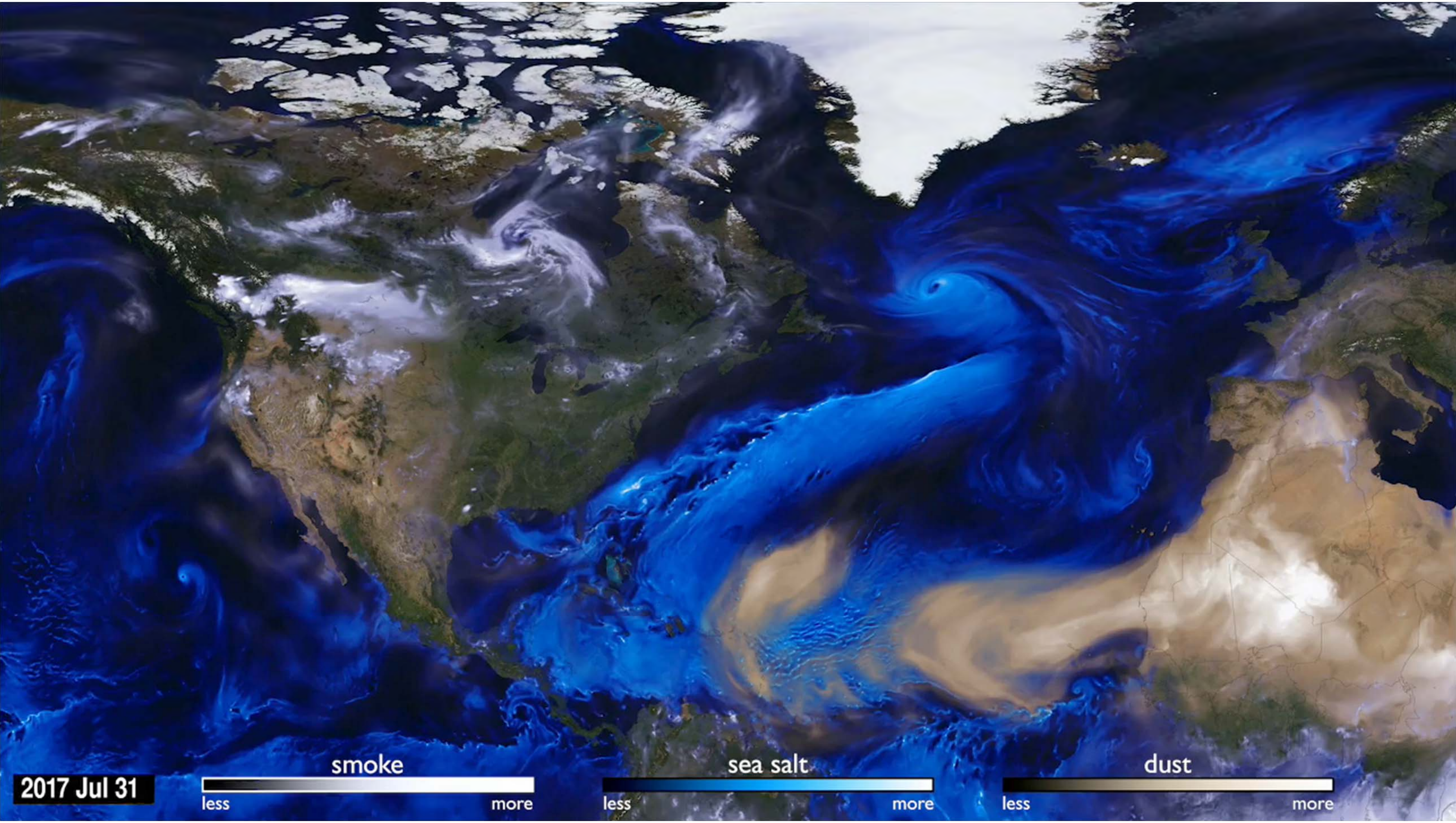
→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Satellite Oceanography: Ocean surface waves


2017 Jul 31
smoke
less
more
sea salt
less
more
dust
less
more

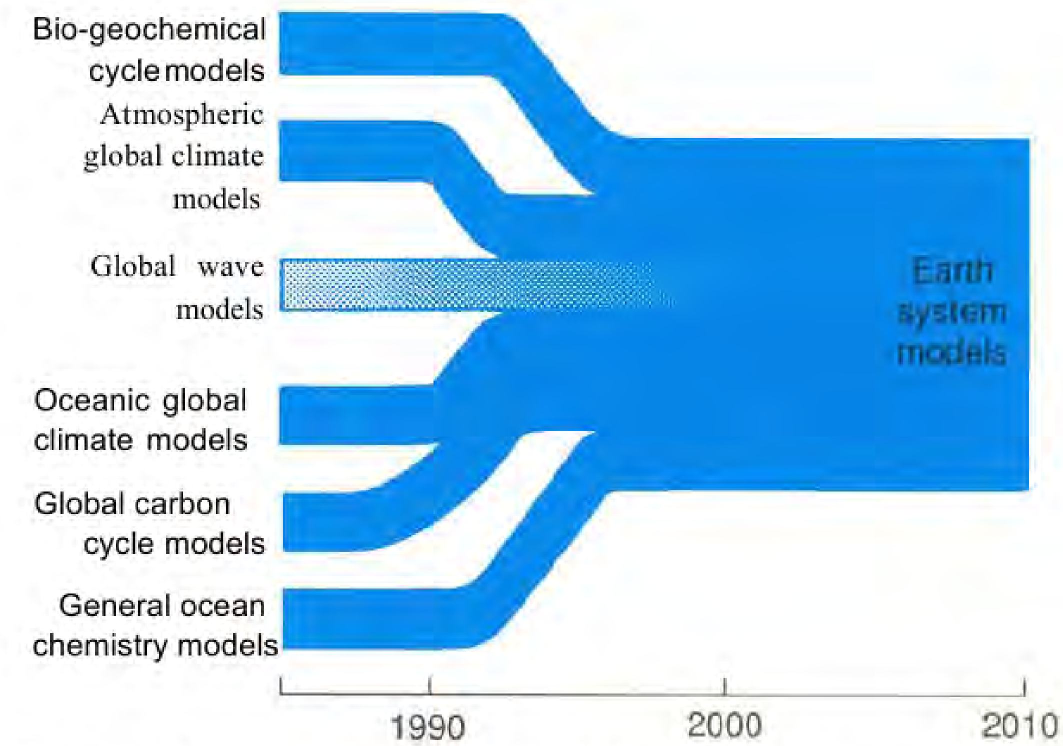
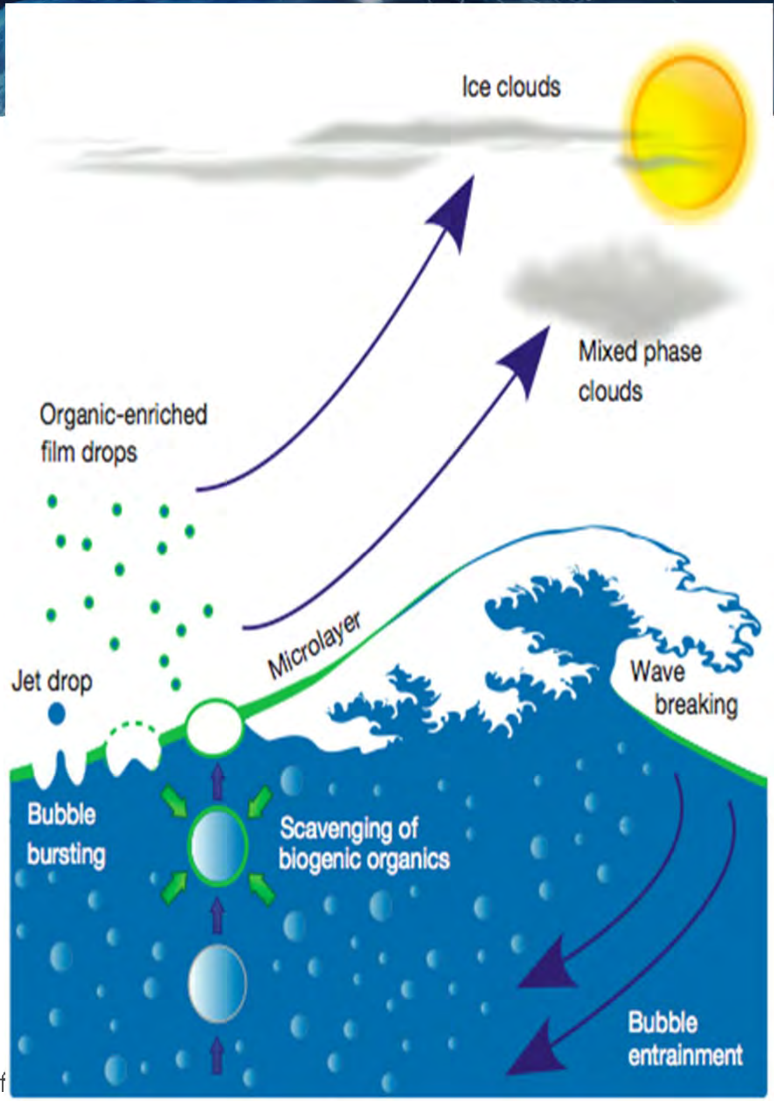
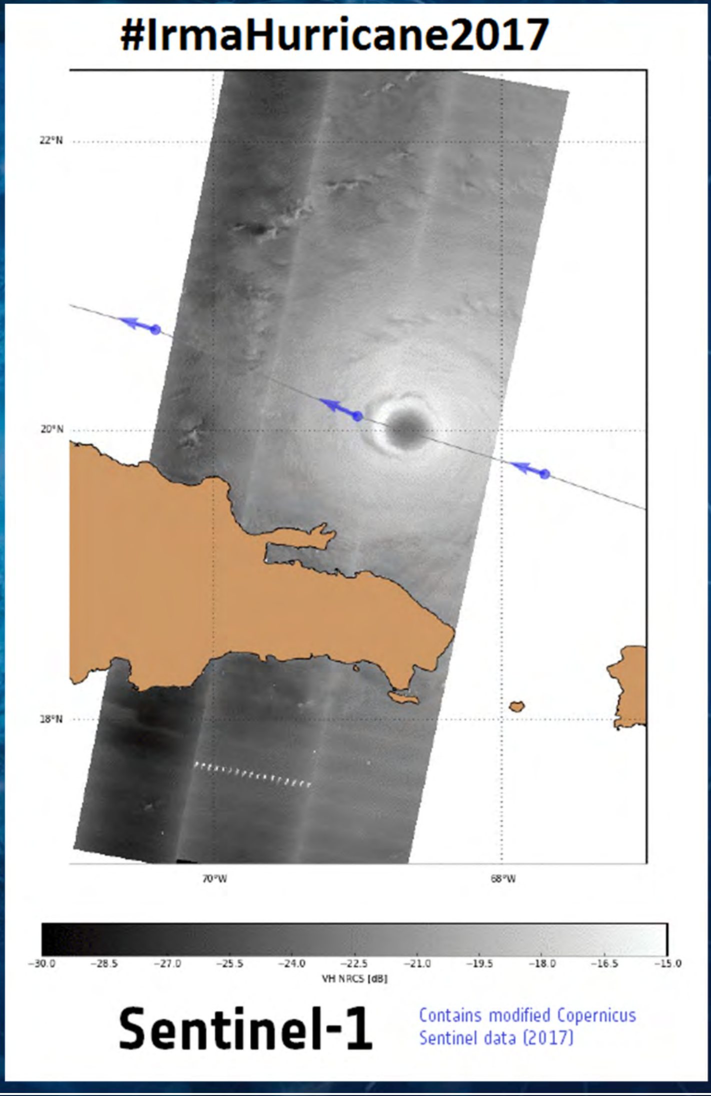


Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle models developed in the context ot the World Climate and Global Change programs.



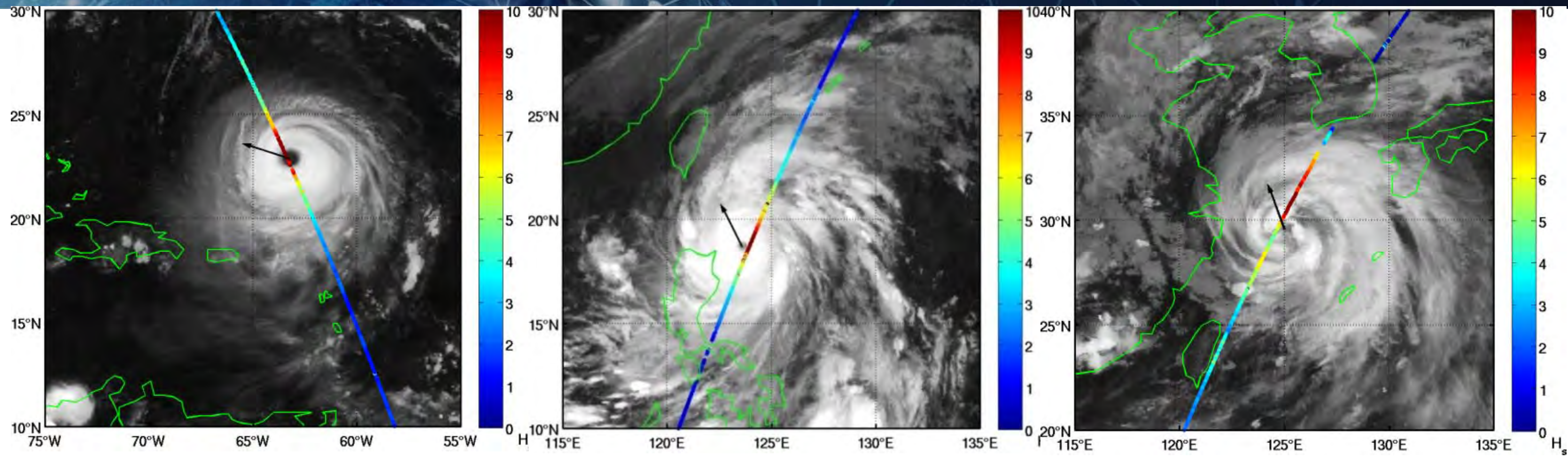
Sea-spray aerosol particles enriched in organic material are possibly generated when the air-sea interface is bursting

esa

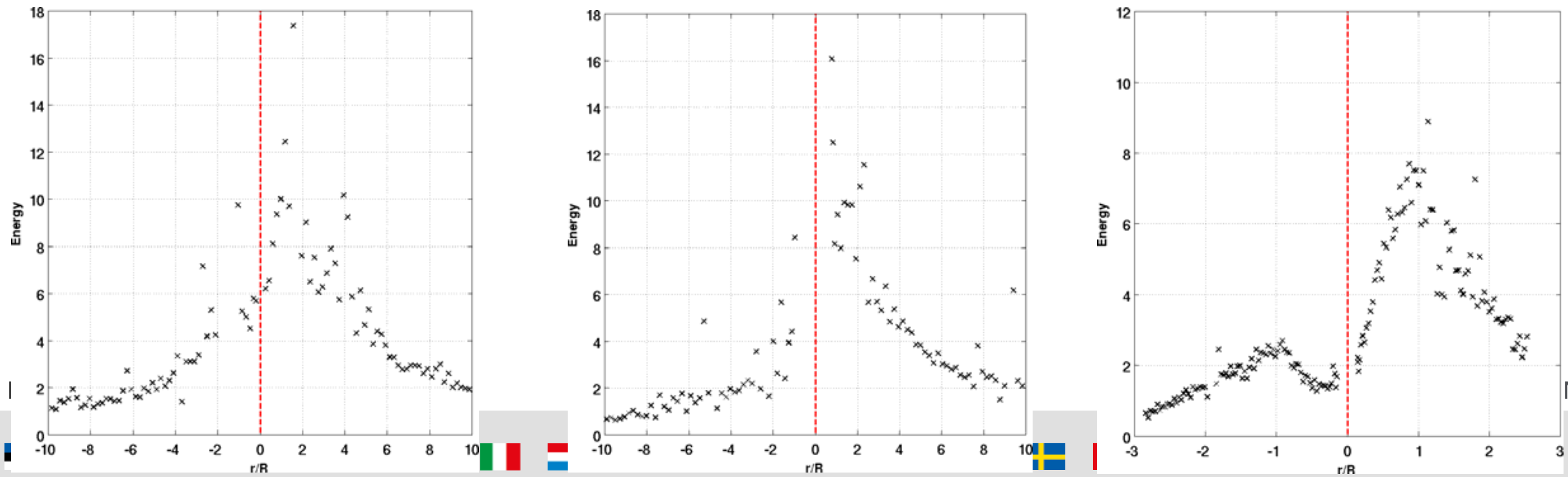

#IrmaHurricane2017
22°N
20°N
18°N
70°W
68°W
-30.0
-28.5
-27.0
-25.5
-24.0
-22.5
-21.0
-19.5
-18.0
-16.5
-15.0
VH NRCS [dB]
Sentinel-1
Contains modified Copernicus
Sentinel data (2017)

Examples: IR images with overlapped altimeter tracks

Isabel (2003) Songda (2011) Muifa (2011)



Altimeter Significant Wave heights



Model approach: based on self-similarity of wave generation (Kudryavtsev et al., 2015)

Self-similarity:

$$\tilde{e} = c_e \tilde{x}^p;$$
$$\tilde{\omega}_p \equiv \alpha = c_\alpha \tilde{x}^q,$$
$$g^{-2}\omega^5 E(\omega) = B(\omega/\omega_p, \alpha),$$

$\tilde{x} = Xg/u_{10}^2$ is dimensionless fetch;

$\tilde{e} = eg^2/u_{10}^4$ is dimensionless energy;

$\tilde{\omega}_p = \omega_p u_{10}/g$ is dimensionless spectral peak frequency.

c_e, p and c_α, q are "constants",

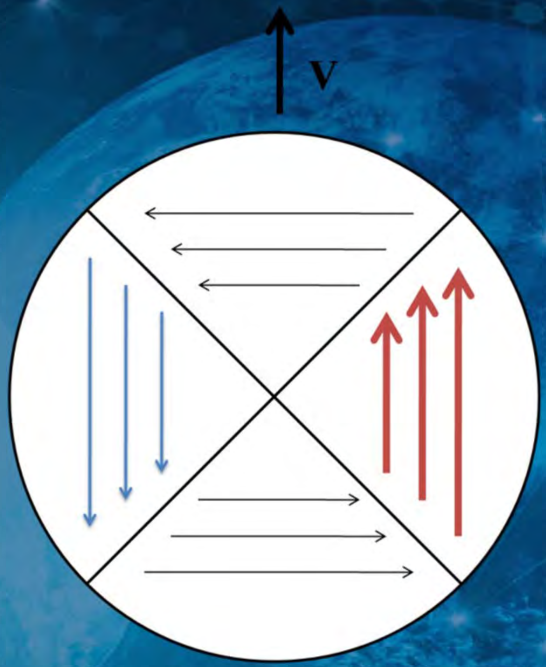
$B(\omega/\omega_p, \alpha)$ is universal function.

Wave spectrum and energy source obey the energy balance equation:

$$\partial E/\partial t + c_g \partial E/\partial x = S \equiv S_W + S_D + S_N.$$

Using growth rate laws, this energy balance helps consistently define the energy source:

$$S/c_g = \partial E/\partial x$$
$$= qc_\alpha^{1/q}\alpha^{1-1/q}(gu_{10}^{-2})E'_\alpha,$$
$$(S/c_g)'_\omega = (\partial\omega_p/\partial x)E''_\omega$$
$$= qc_\alpha^{1/q}\alpha^{1-1/q}(g^2u^{-3})E''_\omega$$



Right sector (wave enhancement):

$$(\alpha_L/\alpha_0)^{1/q}\left[1-(1+q)^{-1}\alpha_L/\alpha_T\right]=1-\tilde{L}_{cr}/\tilde{L}$$

$$\tilde{e}_L/\tilde{e}_0=(\alpha_L/\alpha_0)^{p/q}$$

Left sector (wave diminution):

$$(\alpha_L/\alpha_0)^{1/q}\left[1-(1+q)^{-1}\alpha_L/\alpha_T\right]=1$$

$$\tilde{e}_L/\tilde{e}_0=(\alpha_L/\alpha_0)^{p/q}$$

where α_L, $\tilde{e}_L$ - inverse wave age and energy, respectively;

$\alpha_0=c_\alpha\tilde{L}^q$; $\tilde{e}_0=c_e(\alpha_0/c_\alpha)^{p/q}$ - expected wave parameters (not accounting for TC movement);

c_α, c_e, p, q - "standard" coefficients in JONSWAP parameterizations;

$\alpha_T=u/2V$ - wave age of trapped waves, u - wind speed, V - translation speed;

$\tilde{L}_{cr}=-c_\alpha^{-1/q}\dfrac{q}{1+q}\alpha_T^{1/q}$ - critical fetch;

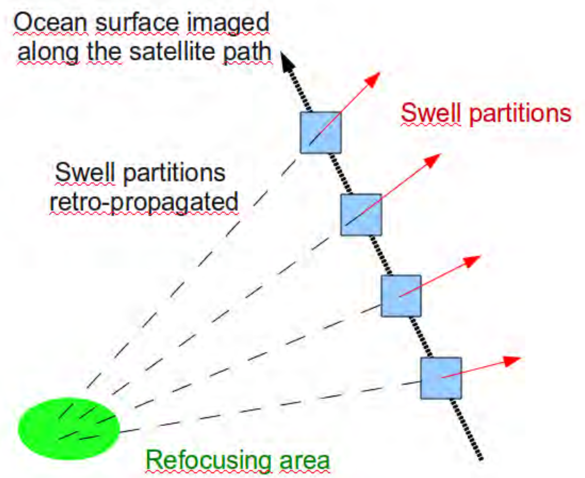
$\tilde{L}$ - dimensionless fetch.

Identifying swell field source

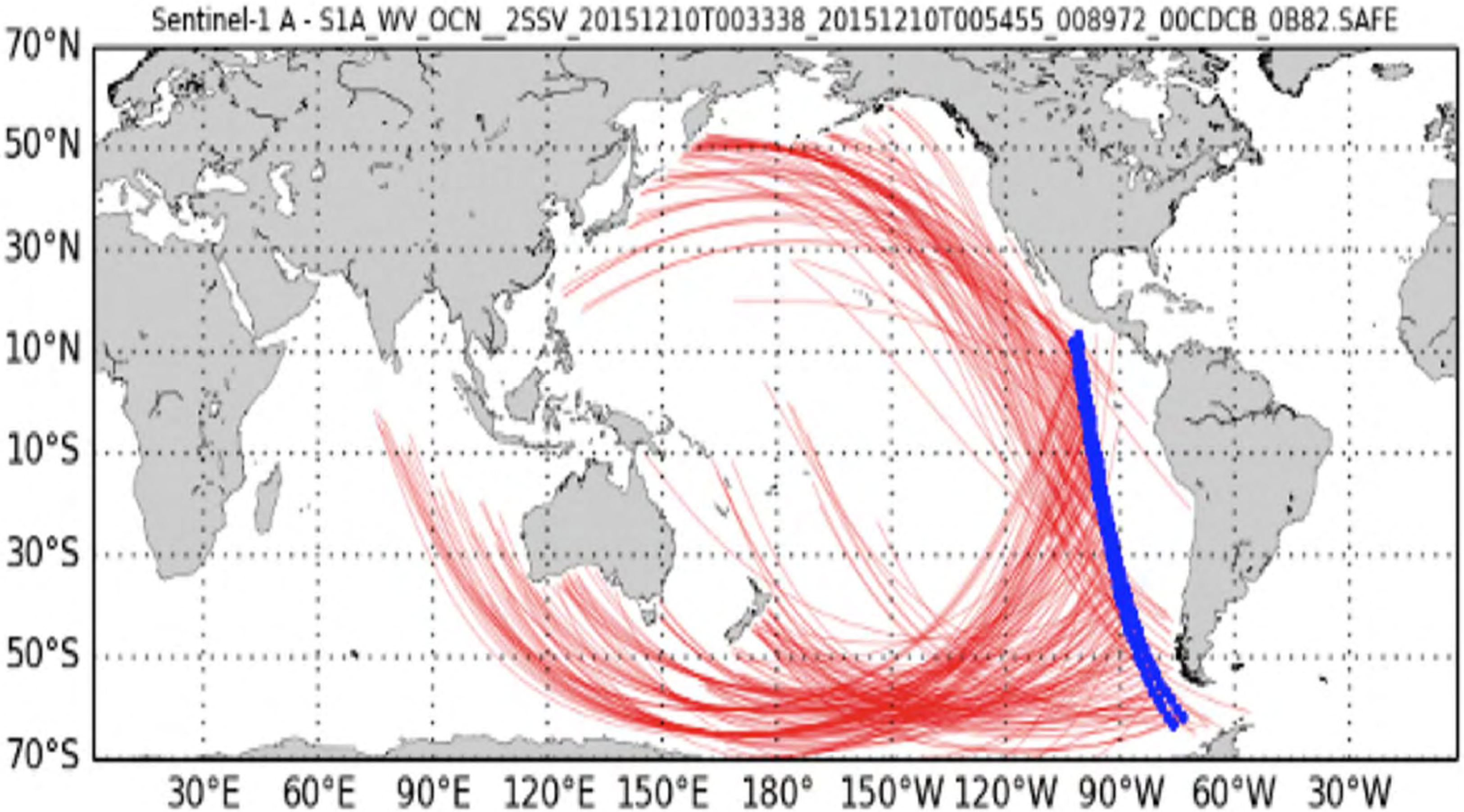
- Linear theory of swell propagation:
  - in open ocean, far from islands
  - swell propagates at group speed, $Cg=gT_p/4\pi$
  - along great circles of direction θ_p

→ compensate for sparse and track-based sampling of the swell partitions.

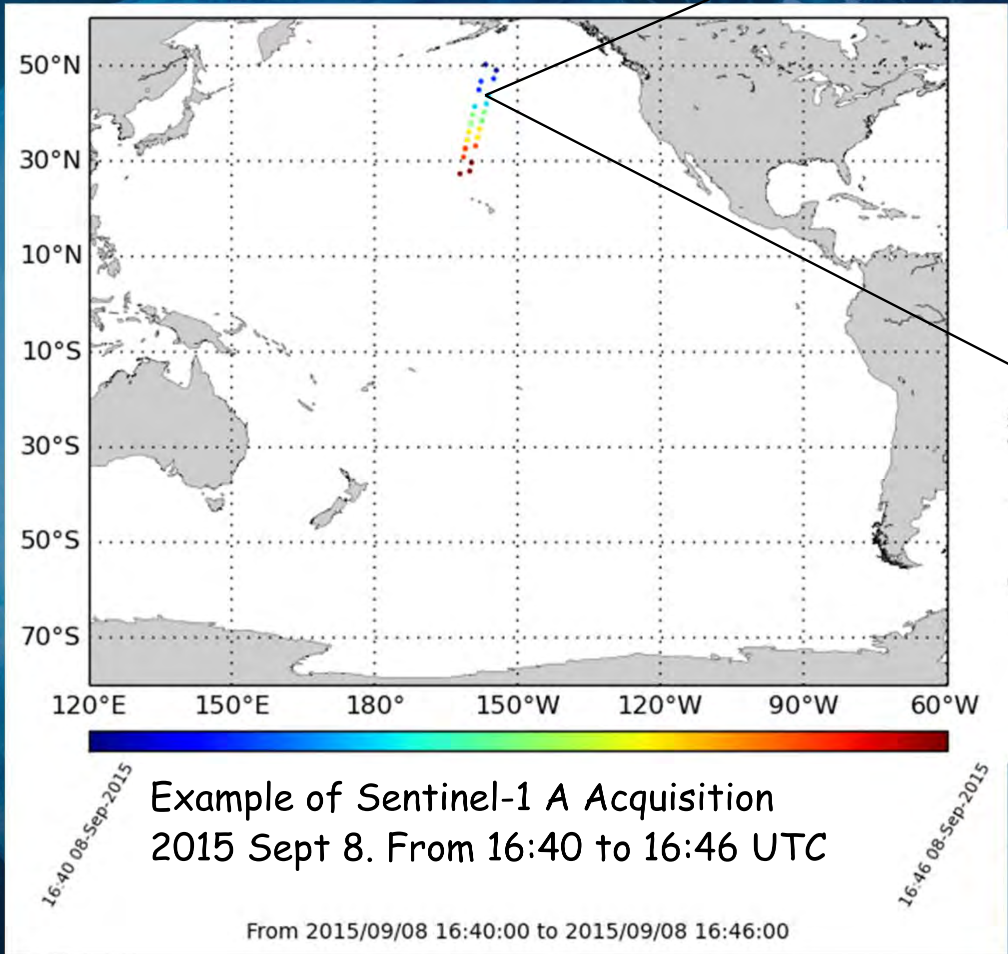
- Refocusing of the swell partitions
  → converge in space and time to regions systematically (96% collocations) **coinciding with Storms events**



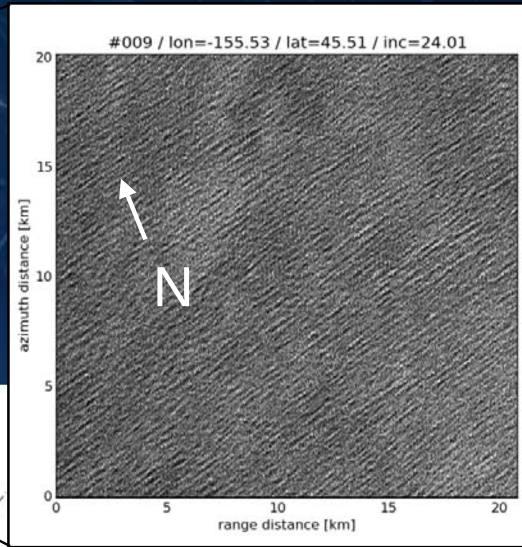
Great-Circle propagation determined by the detected wavelength direction and related group velocity

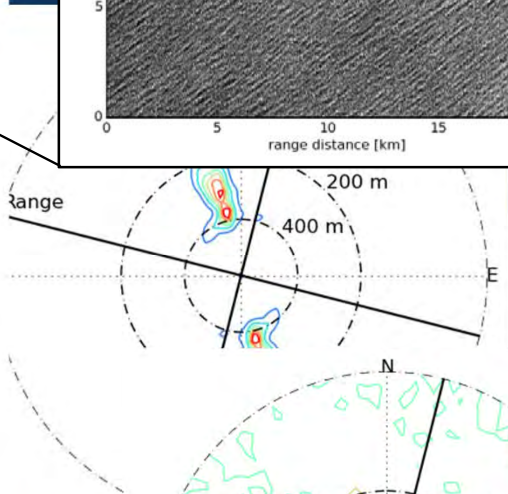


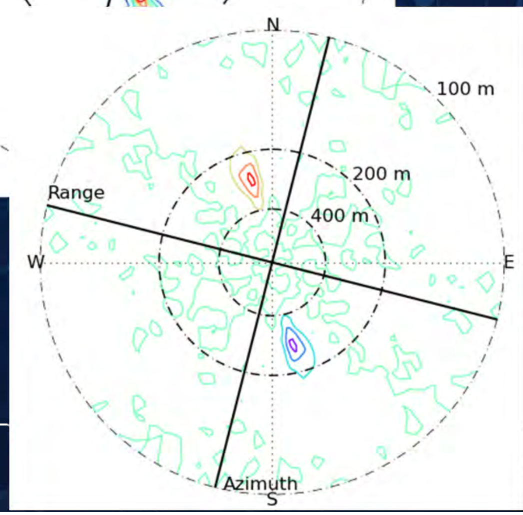
Jimena : wave generation



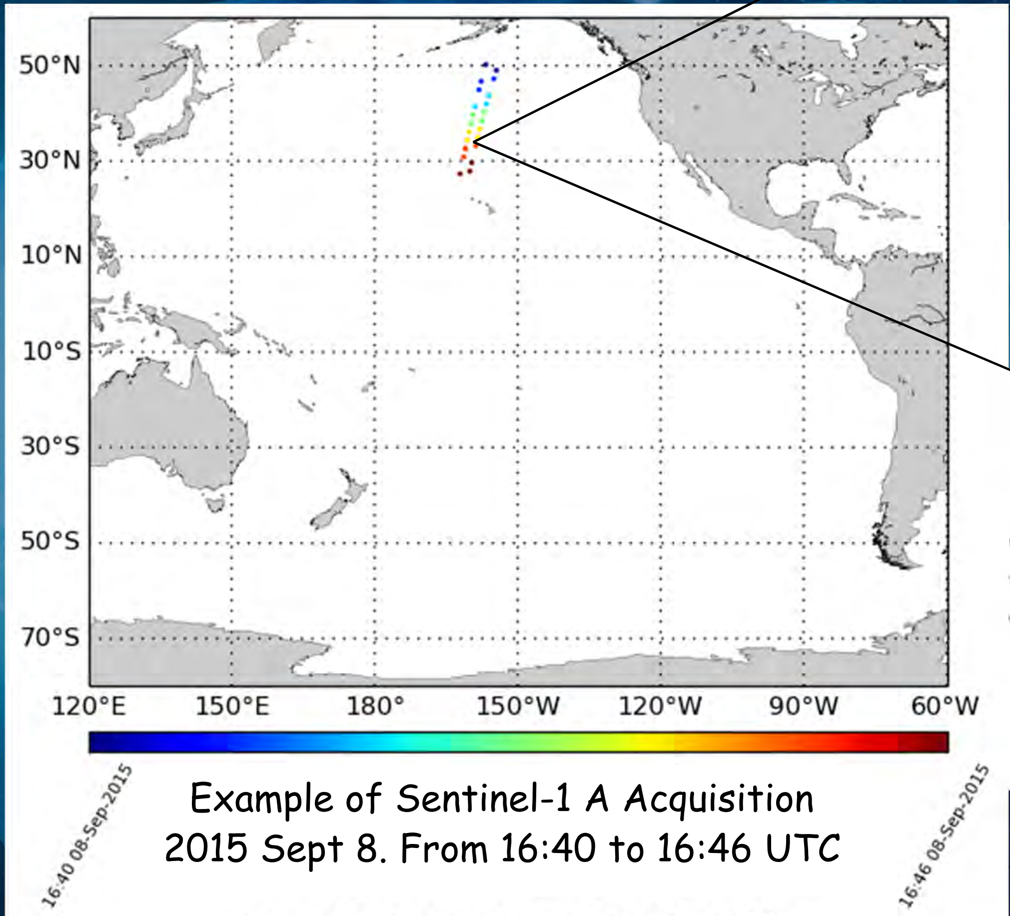
Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC





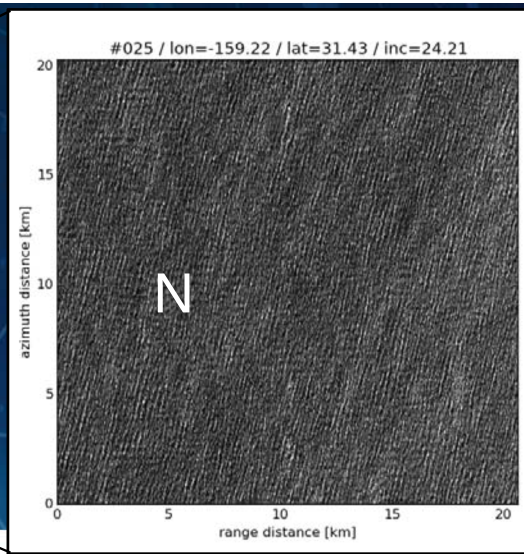


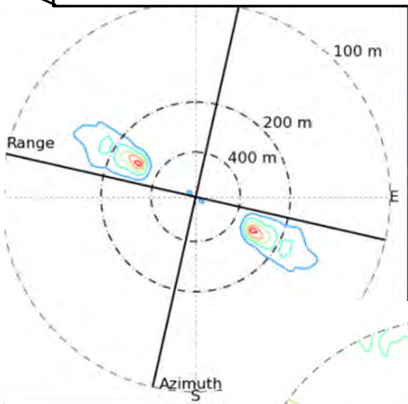
Jimena : wave generation

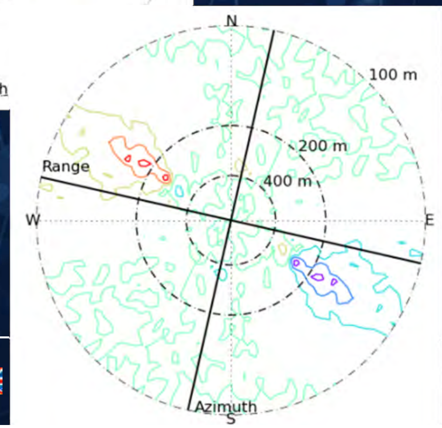


Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC

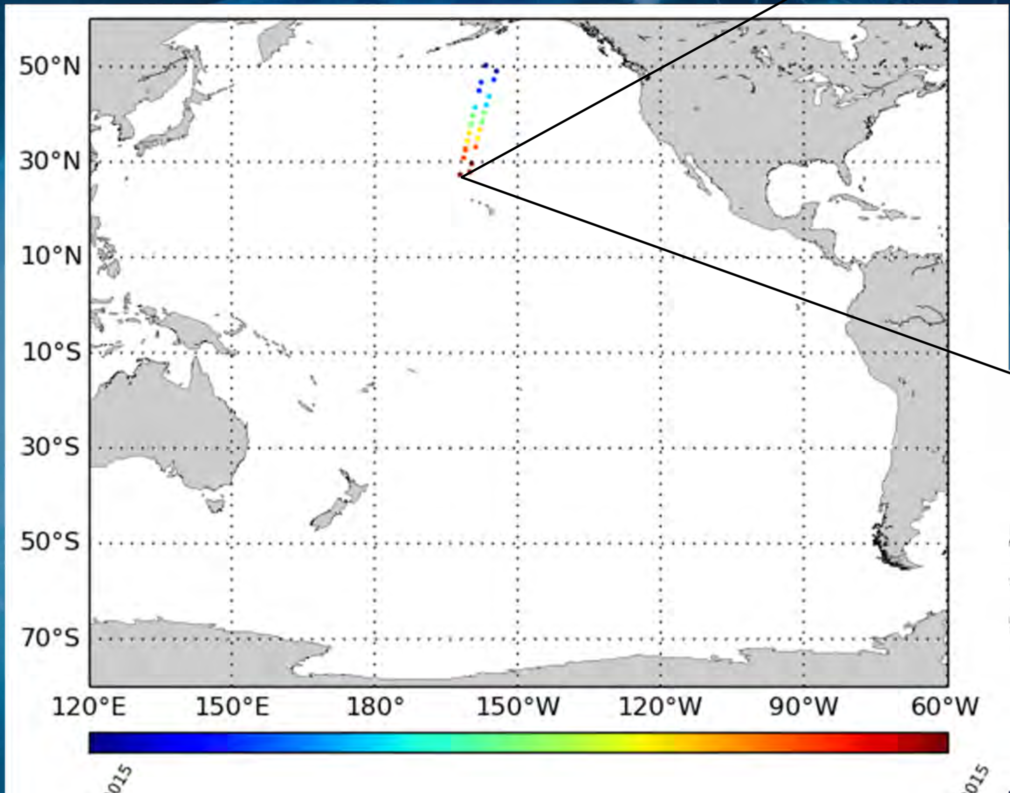
From 2015/09/08 16:40:00 to 2015/09/08 16:46:00



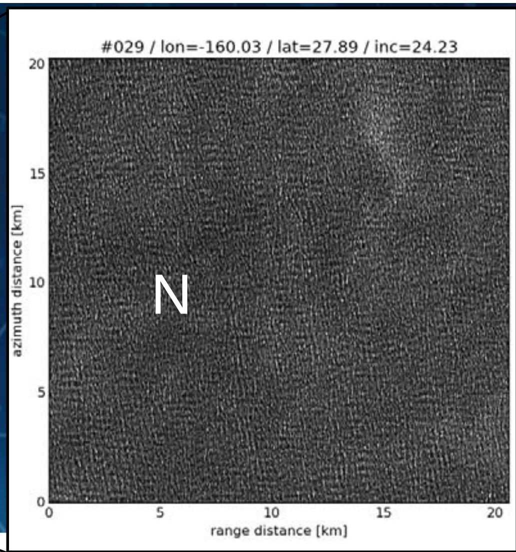


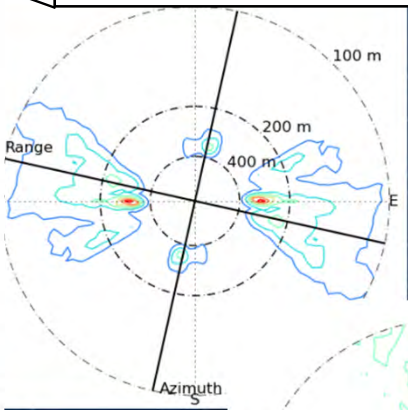


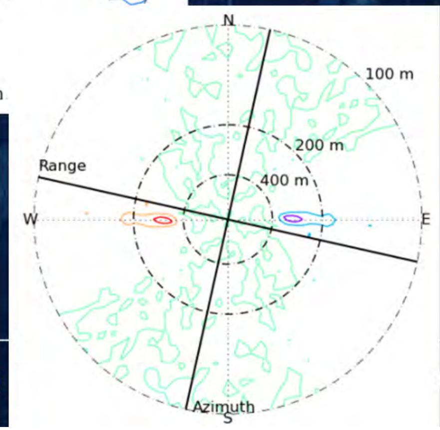
Jimena : wave generation



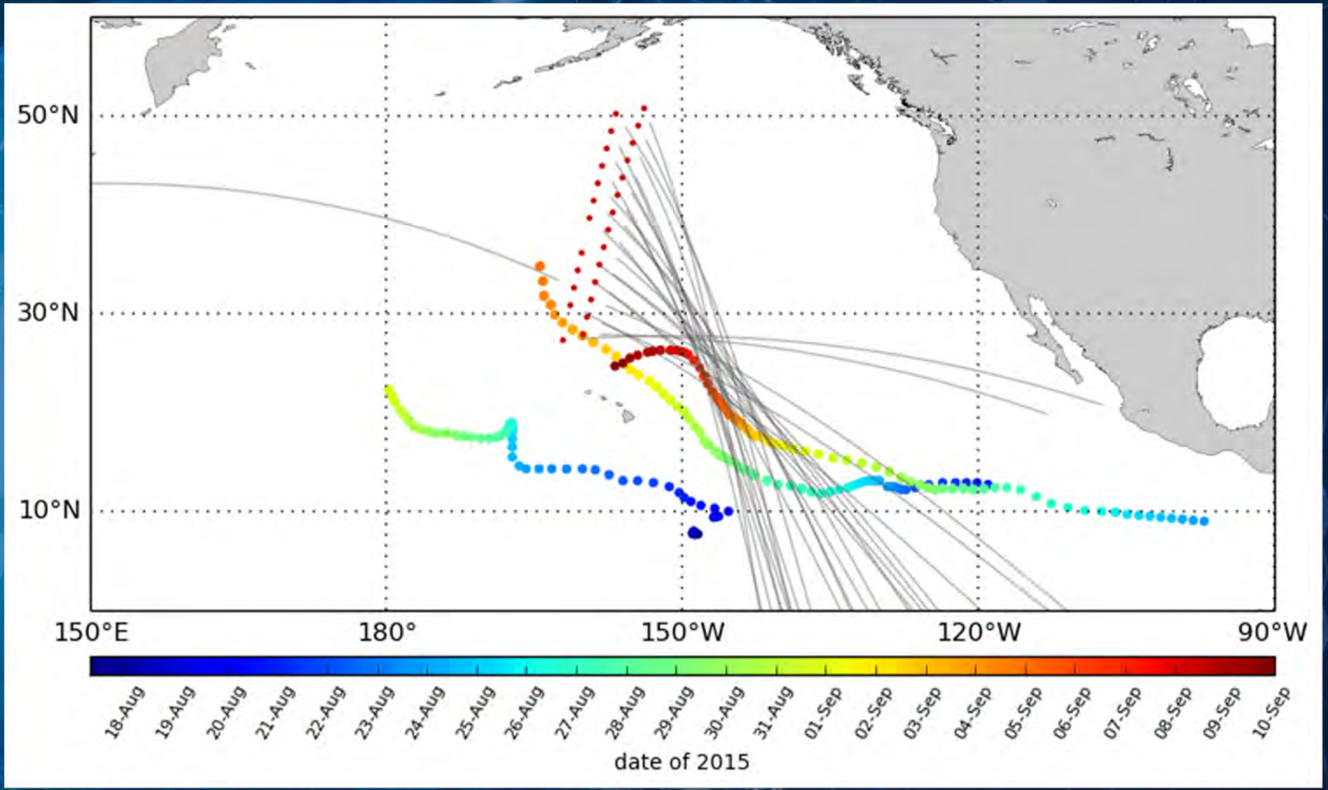
Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC





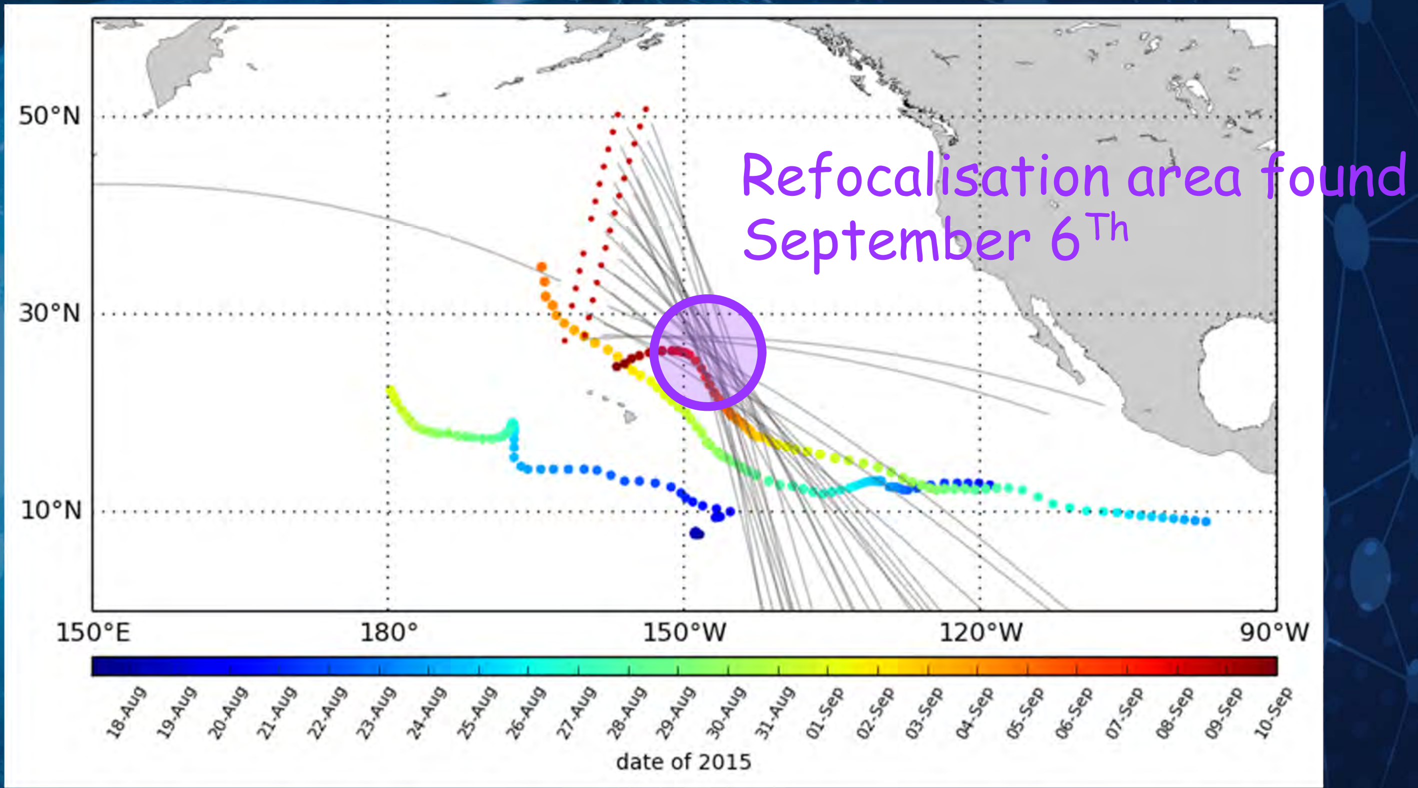


Jimena : wave generation



- Example of retro-propagated Sentinel-1 A Swell Measurements. Data acquired the 2015 Sept 8 16:40 to 16:46 UTC
- 3 tracks corresponding to the 3 hurricanes Kilo, Ignacio and Jimena (from left to right) are overplotted. Color code is time.

Jimena : wave generationx

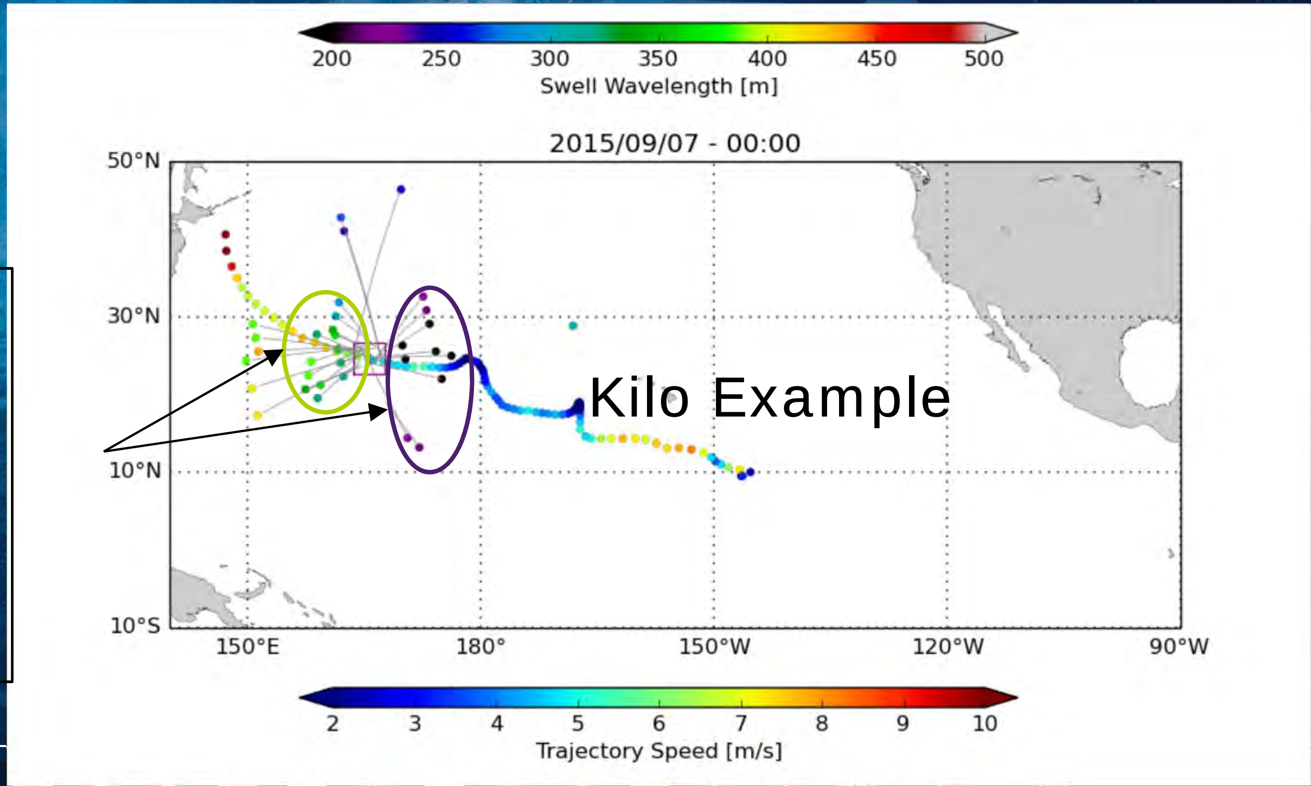


- Example of retro-propagated Sentinel-1 A Swell Measurements. Data acquired the 2015 Sept 8 16:40 to 16:46 UTC
- Refocalisation area is found along the Jimena track the 6th of September. On the right hand side of the track.

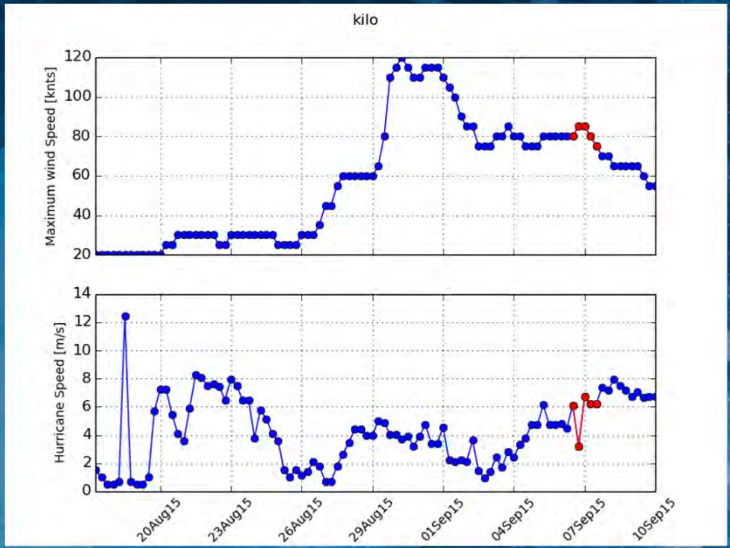
Back-propagation coupled with hurricane track should allow us to analyse the swell properties during the cyclones lifetime with respect to

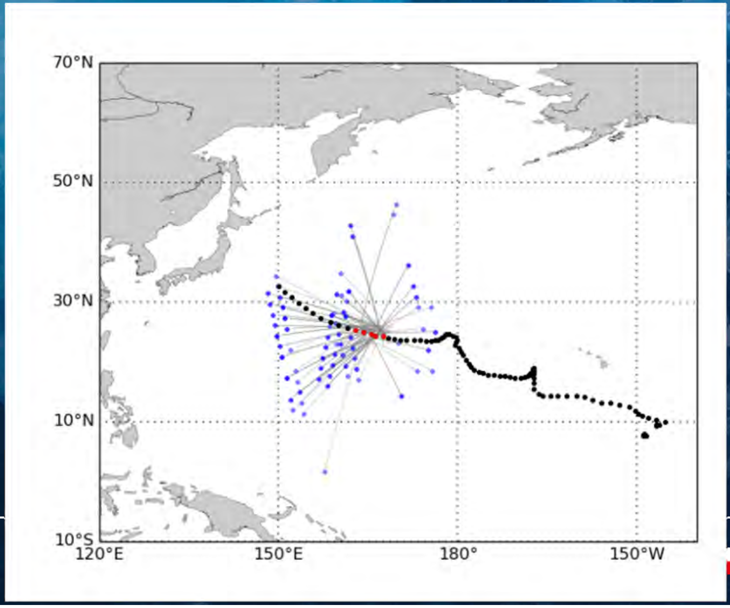
- Hurricanes speed
- Hurricanes wind speed
- Hurricanes radius of maximum wind speed
- Hurricanes phases (decay/increase)

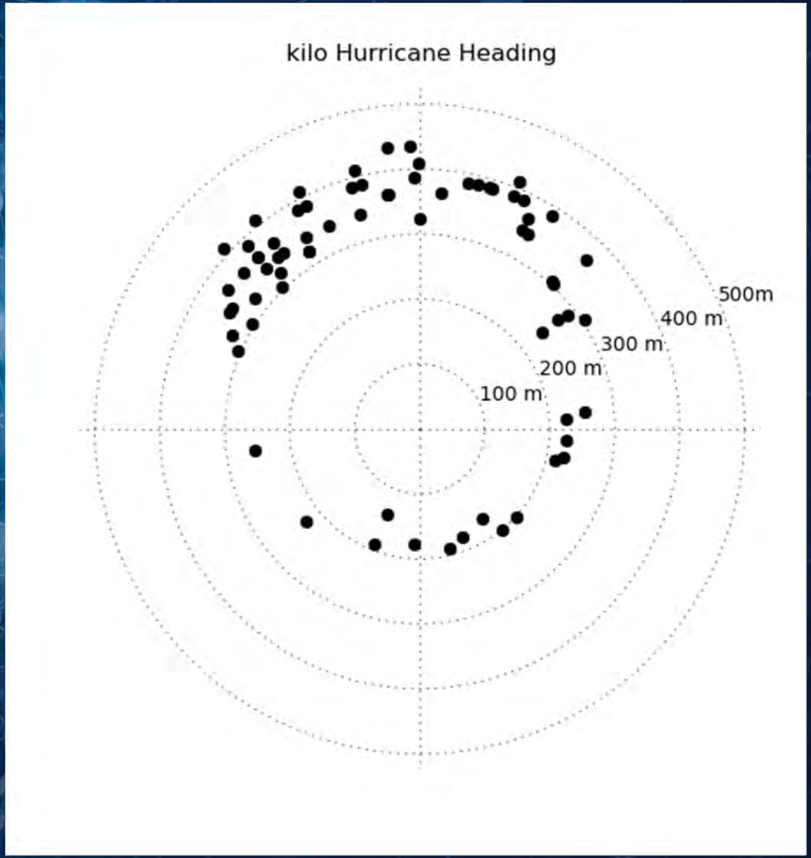
Different wavelengths are observed depending on the swell direction of propagation



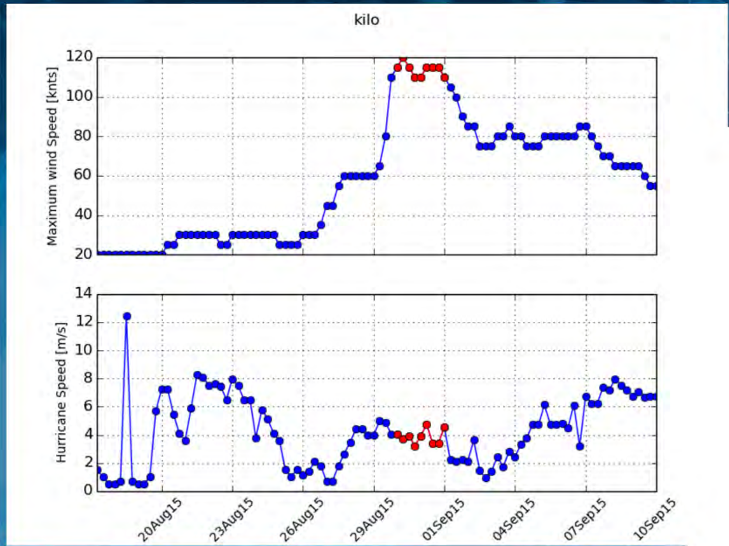
Kilo wave generation : trapping fetch

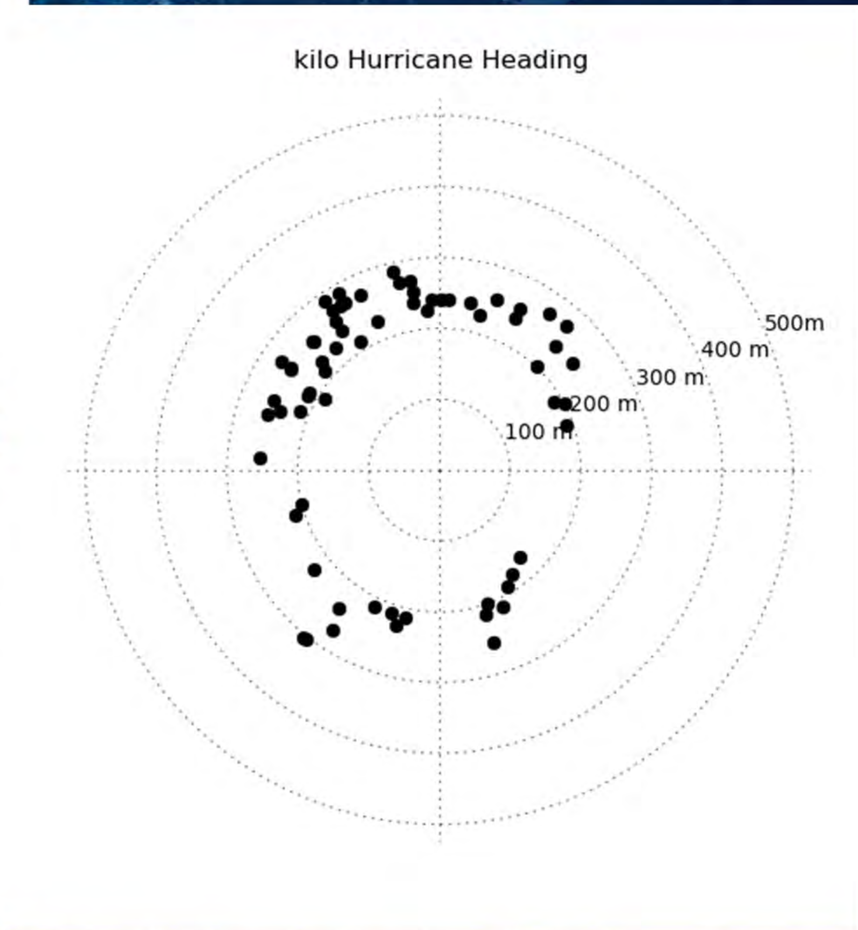


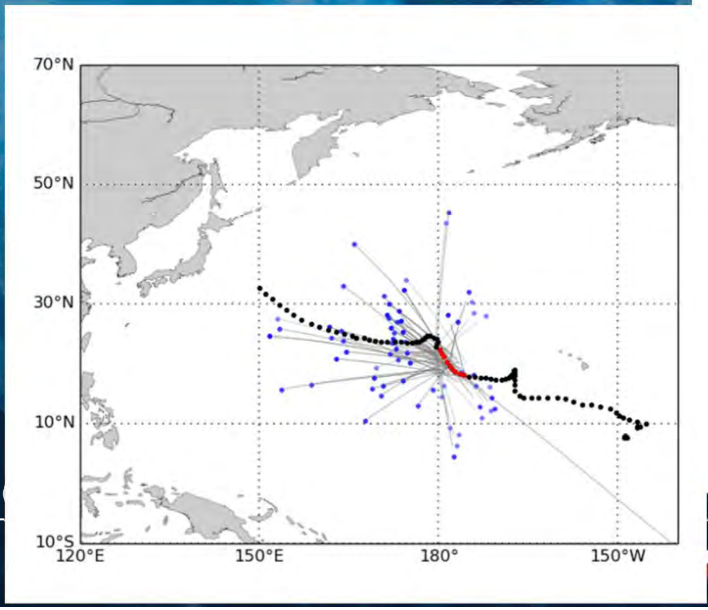




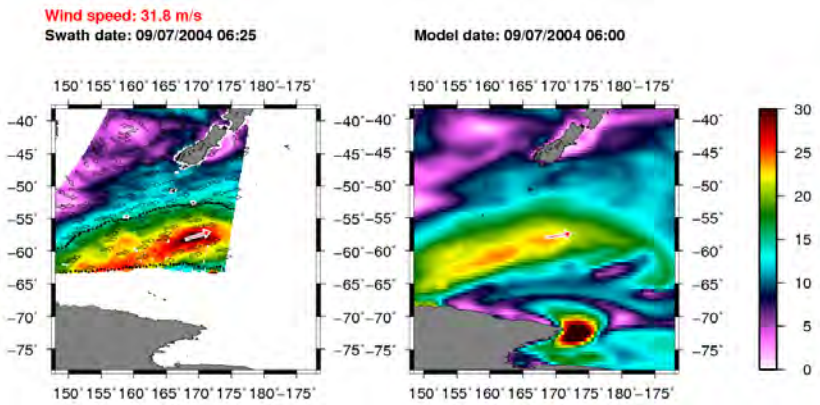
Kilo wave generation : intensity peak

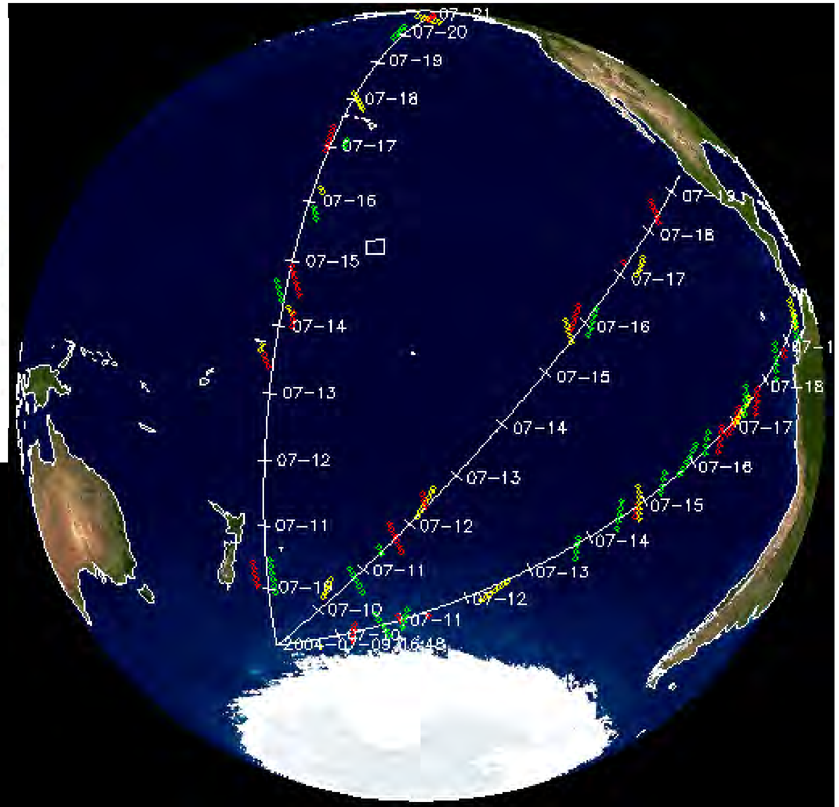






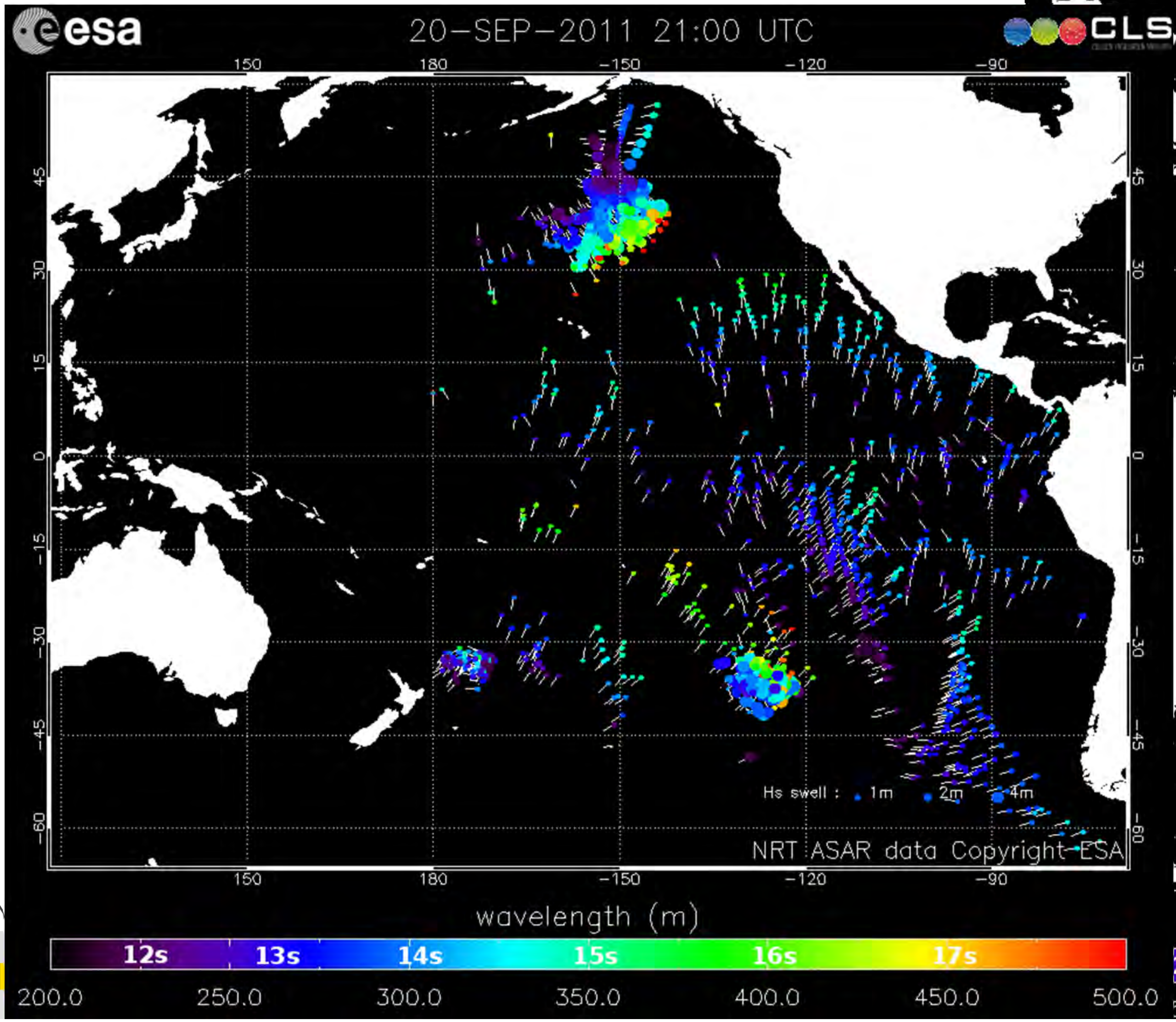
Stormwatch + wavetracker

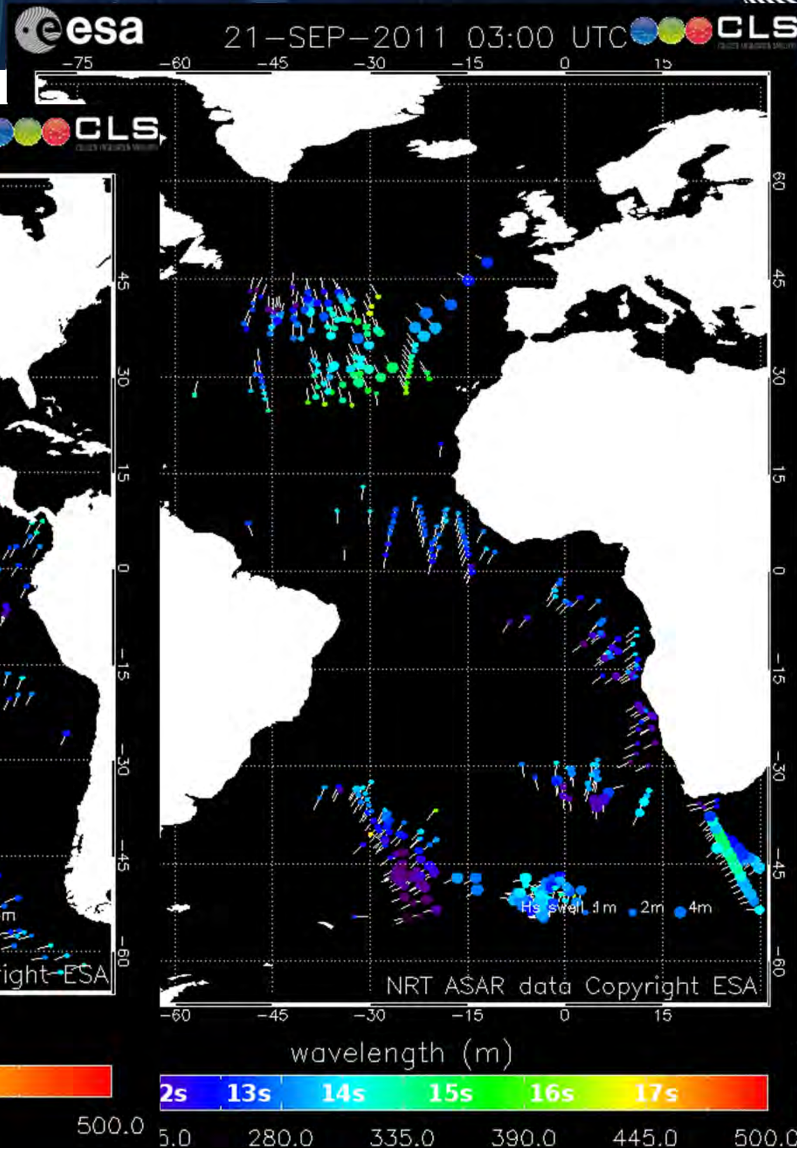




RED : ENVISAT ASAR
GREEN : ENVISAT RA2
YELLOW : JASON ALTIMETER

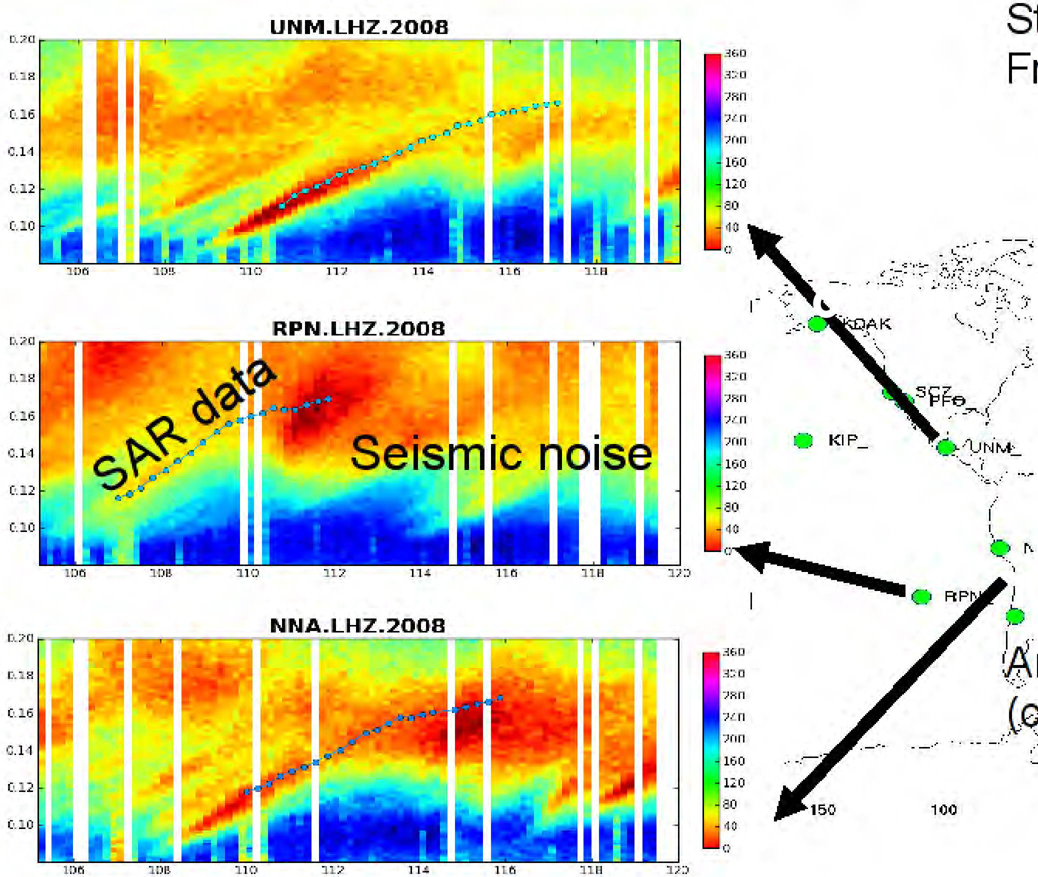
Fireworks


esa
20-SEP-2011 21:00 UTC
CLS
Hs swell : 1m 2m 4m
NRT ASAR data Copyright ESA
wavelength (m)
12s 13s 14s 15s 16s 17s
200.0 250.0 300.0 350.0 400.0 450.0 500.0

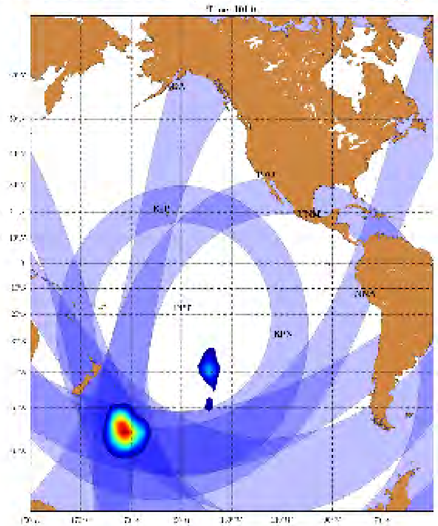

esa
21-SEP-2011 03:00 UTC
CLS
Hs swell 1m 2m 4m
NRT ASAR data Copyright ESA
wavelength (m)
13s 14s 15s 16s 17s
280.0 335.0 390.0 445.0 500.0

Consistency and storm severity

Example of seismic - SAR synergy

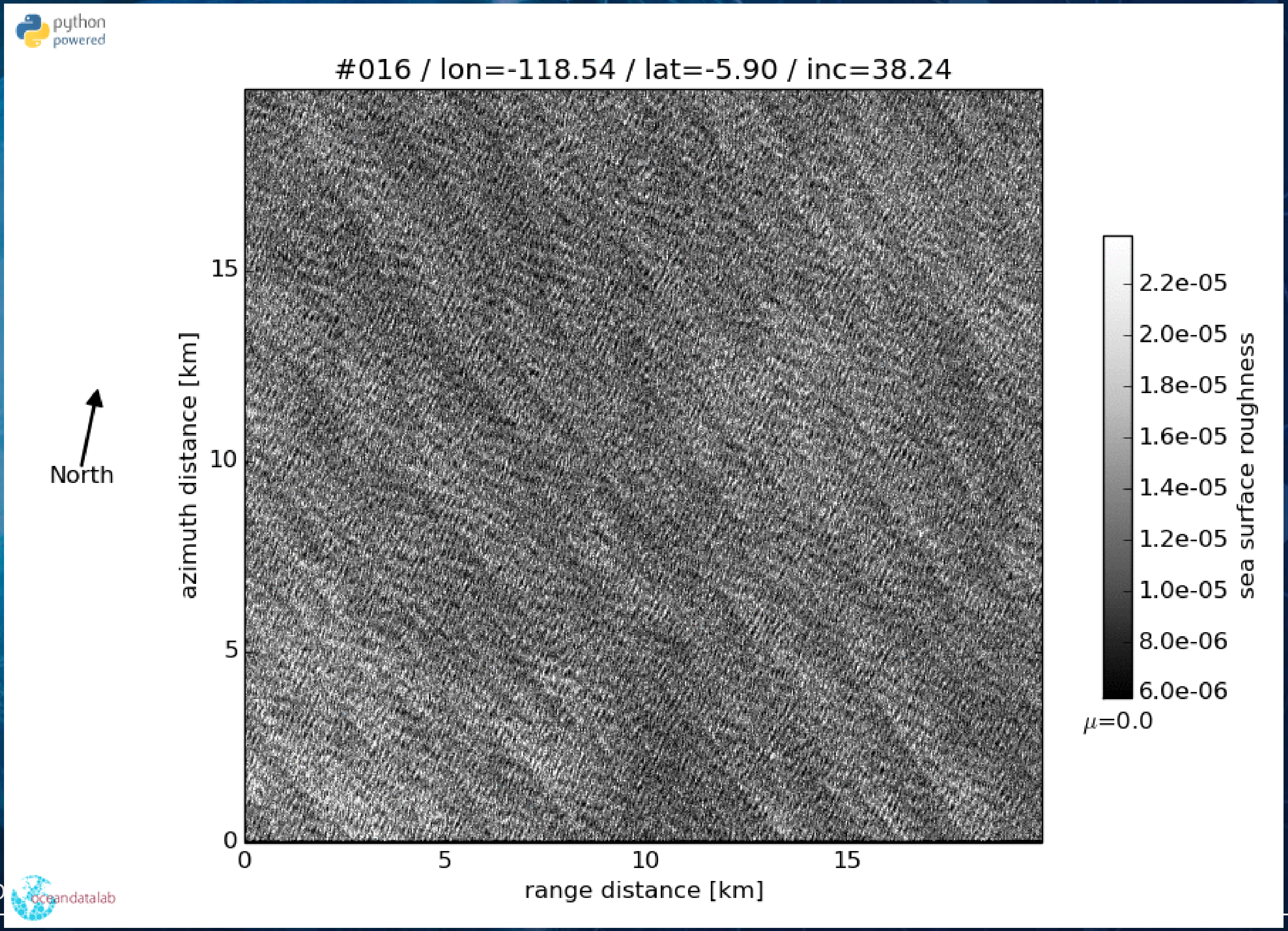


Storm location
From seismic (blue bands)

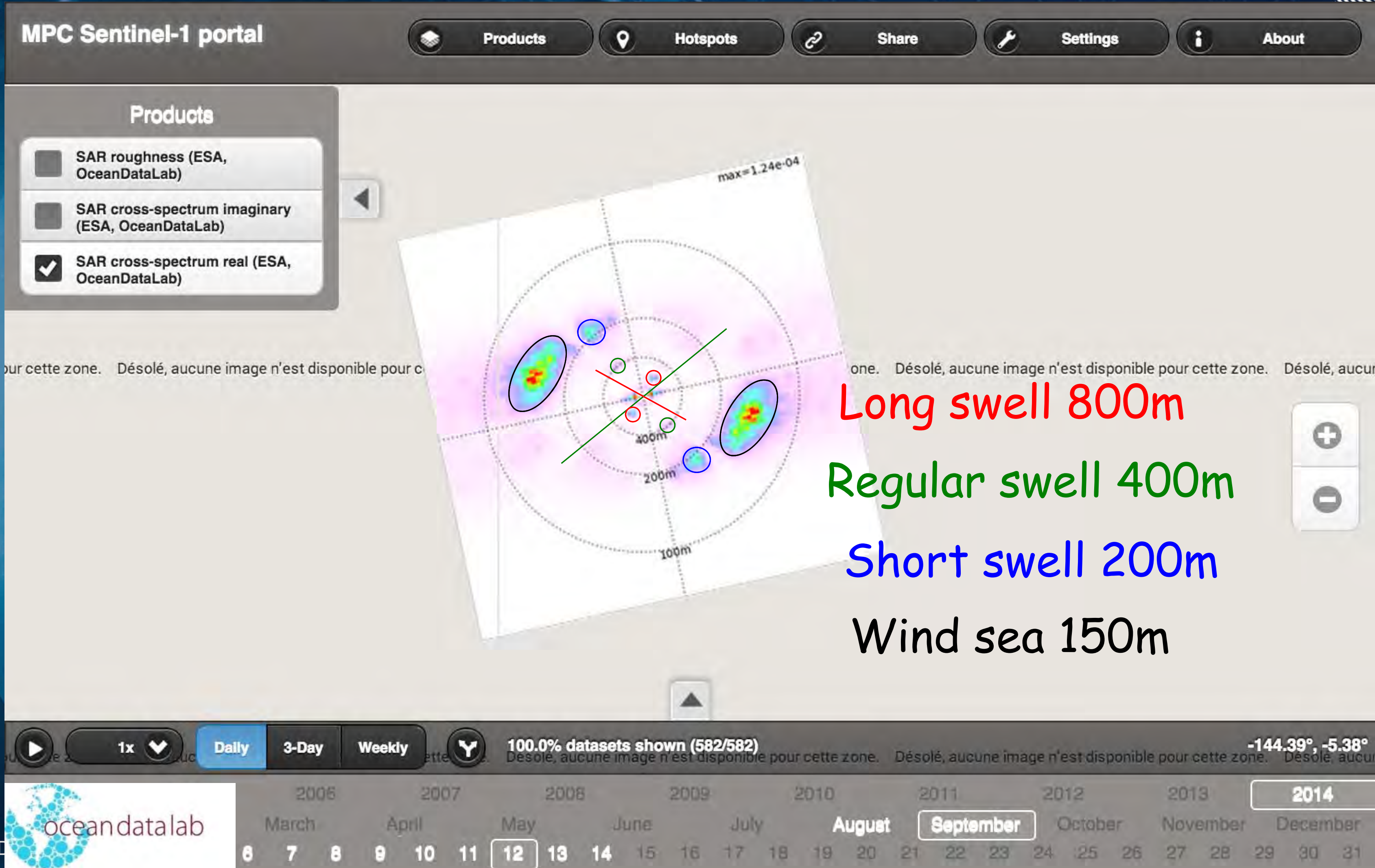


And location from SAR (colors)

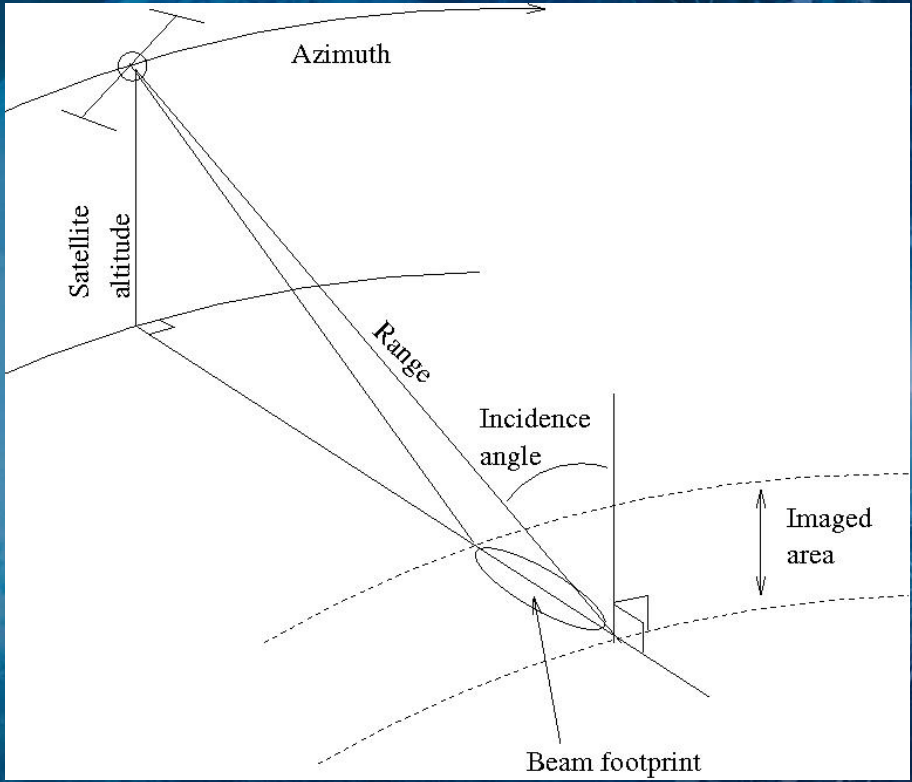
S1 Imagette #016 from first track over Pacific



Forerunners Mid Pacific ocean : WV, VV pol, Sept 12



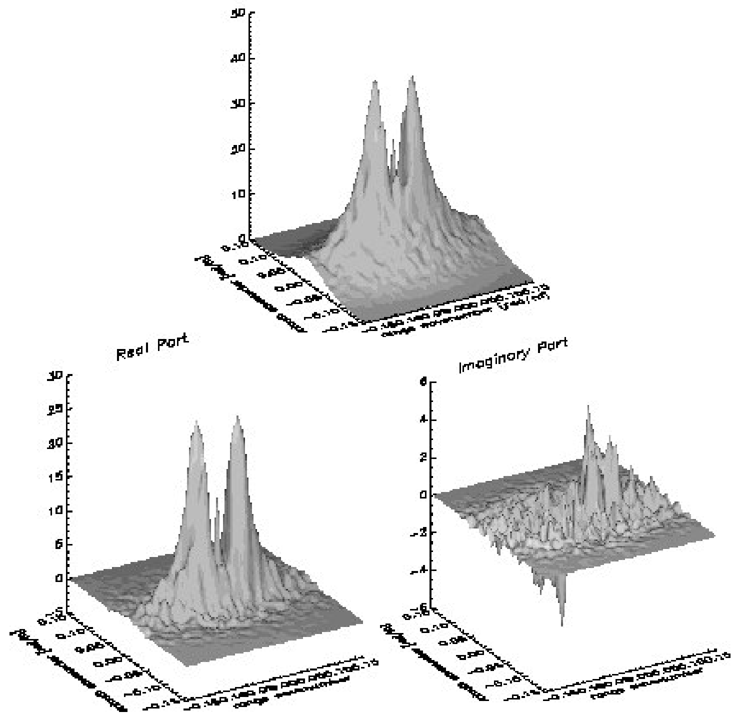
Synthetic Aperture Radar (SAR)



- Side-looking
- Active antenna that transmits/receives electromagnetic radiation in VV, HH, VH, HV pol. (C-band 5.6 cm)
- Records both signal amplitude and phase
- Works both day and night
- Can "see" through clouds

A decisive breakthrough : the cross-spectral analysis

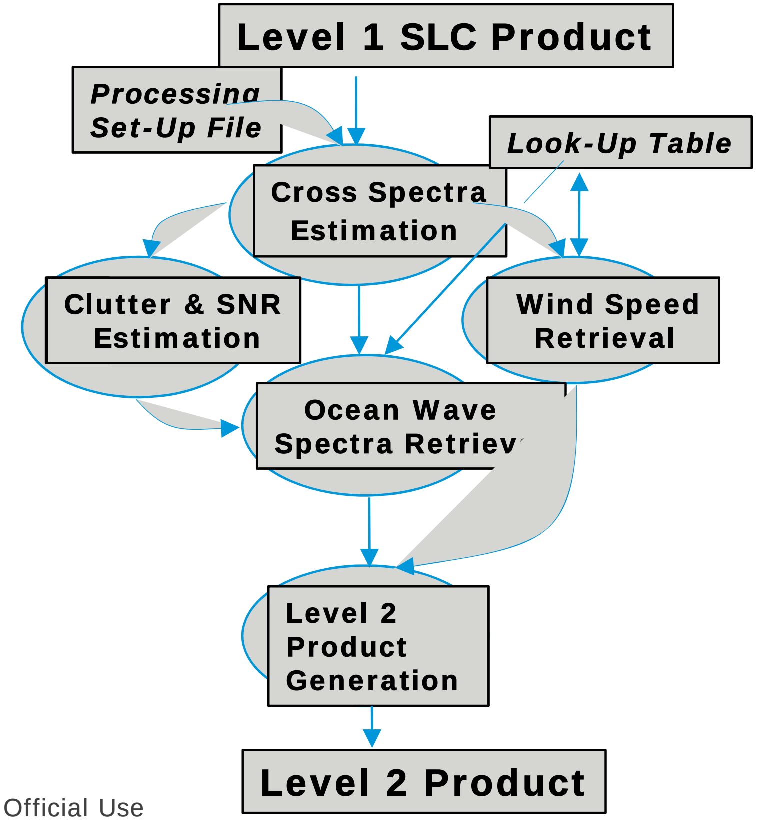
- Based on ERS Image products, G. Engen and H. Johnsen (NORUT) proposed the use of Single Look Complex (SLC) products, to separate looks (SAR products at 2 different epoch times) and to using cross-spectra methodology (*Engen et al., 1995, TGARS*)



Improvements:

- Direct uncorrelated noise removal
- Hands-off resolved wave propagation ambiguity i most cases (85%)

SAR Wave algorithm philosophy



Inversion Model:

$$\chi(\underline{k},\tau) = \left|T(\underline{k})\right|^2 S_{wave}(\underline{k}) e^{i\omega_{|\underline{k}|}\tau} + \chi^{nlin}(\underline{k};U_{10})$$

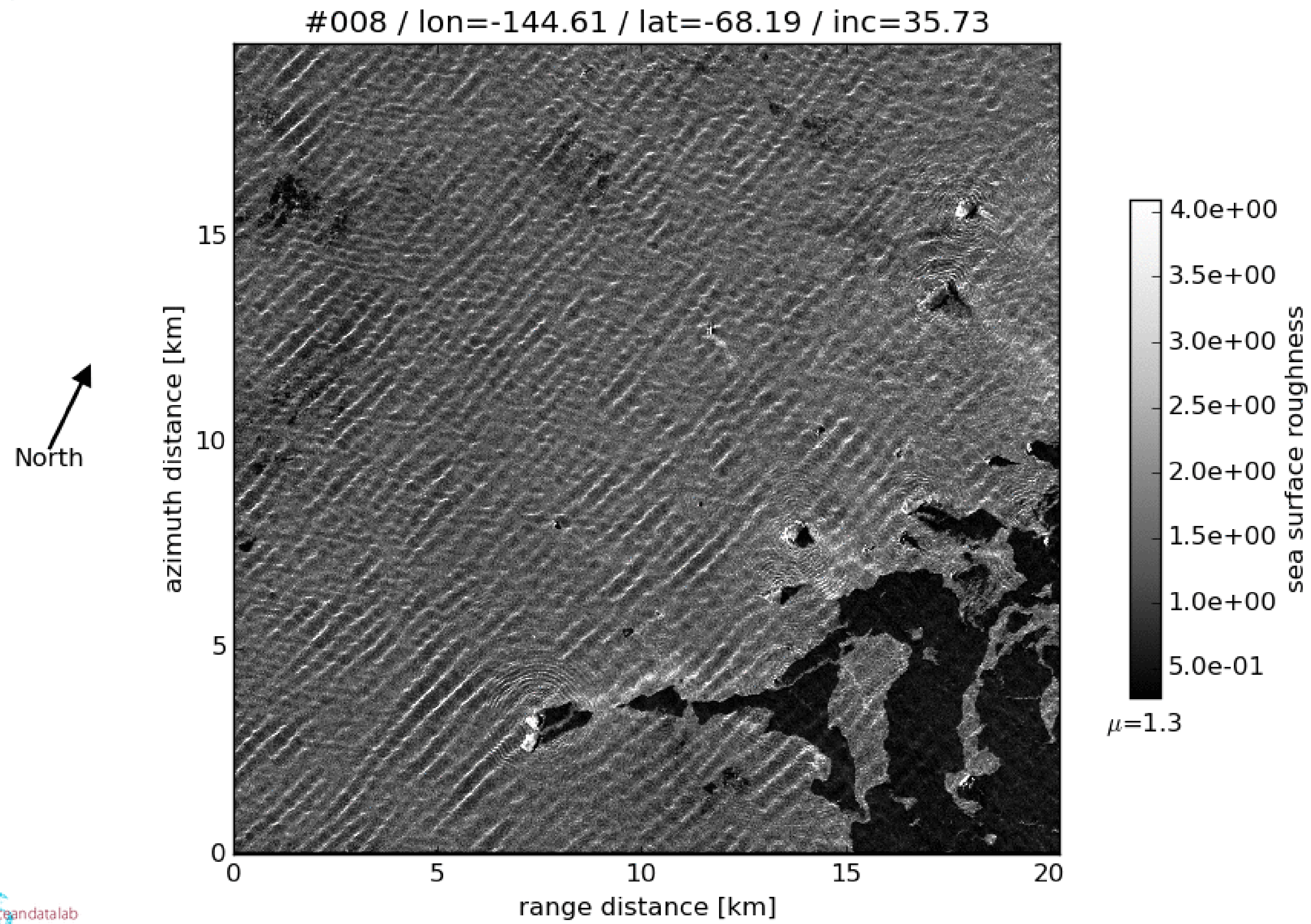
where

$$\chi^{nlin}(\underline{k};U_{10}); \quad from\ look-up\ table$$

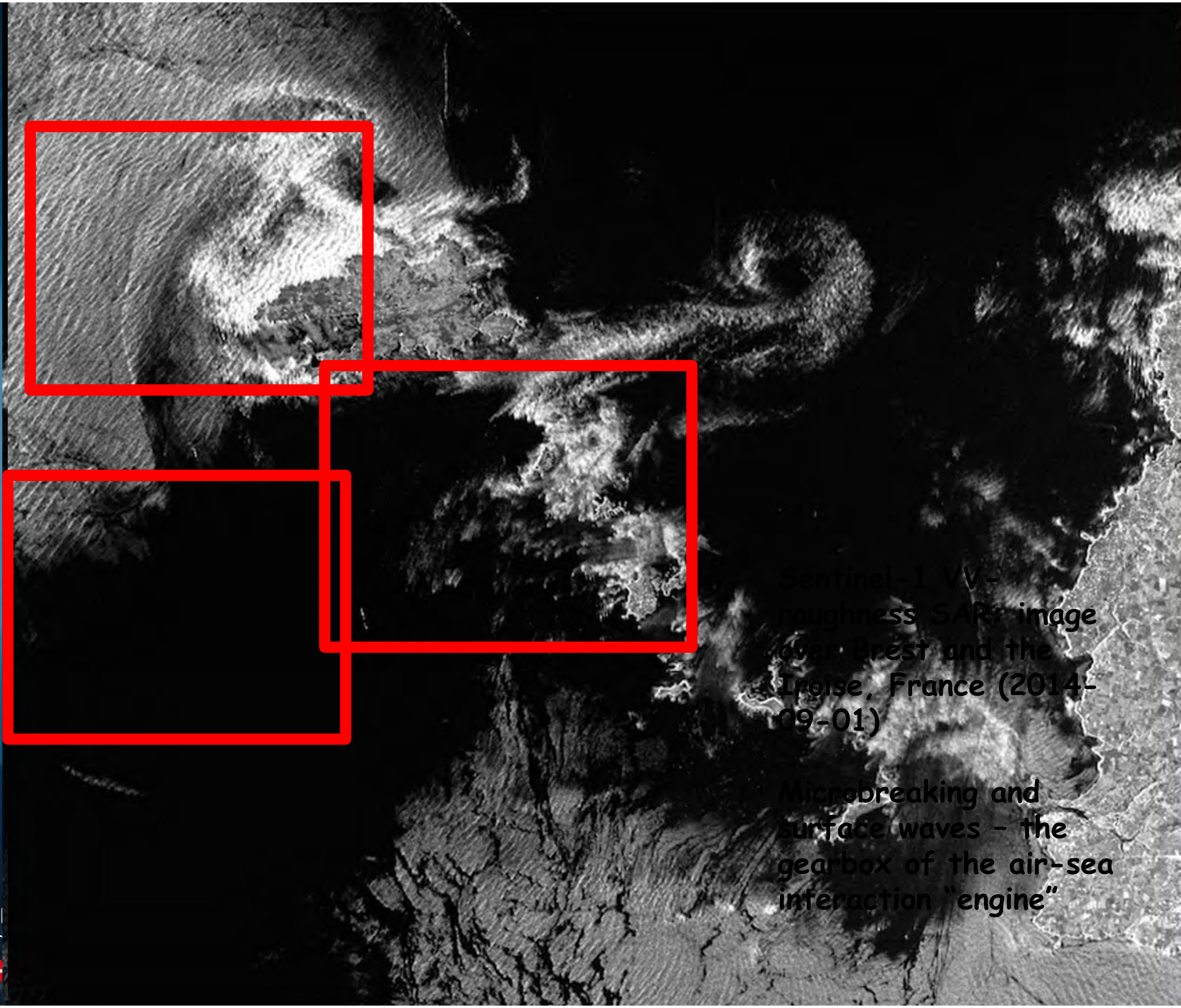
$$T(\underline{k}) = \left\{ i k_y \frac{R}{V}\omega_k + 2k_{rad} k_x \nabla\sigma \right\} G(\theta)$$

$$G(\theta) \equiv \frac{k_x}{|\underline{k}|} \sin\theta + i\cos\theta$$

$$\nabla\sigma \equiv \frac{\Delta\sigma_{\mathrm{cmod}}}{\Delta\theta} \frac{1}{\sigma_{\mathrm{cmod}}} \frac{1}{2k_{rad}\cos\theta}$$



North
#008 / lon=-144.61 / lat=-68.19 / inc=35.73
azimuth distance [km]
range distance [km]
0
5
10
15
20
4.0e+00
3.5e+00
3.0e+00
2.5e+00
2.0e+00
1.5e+00
1.0e+00
5.0e-01
μ=1.3
sea surface roughness

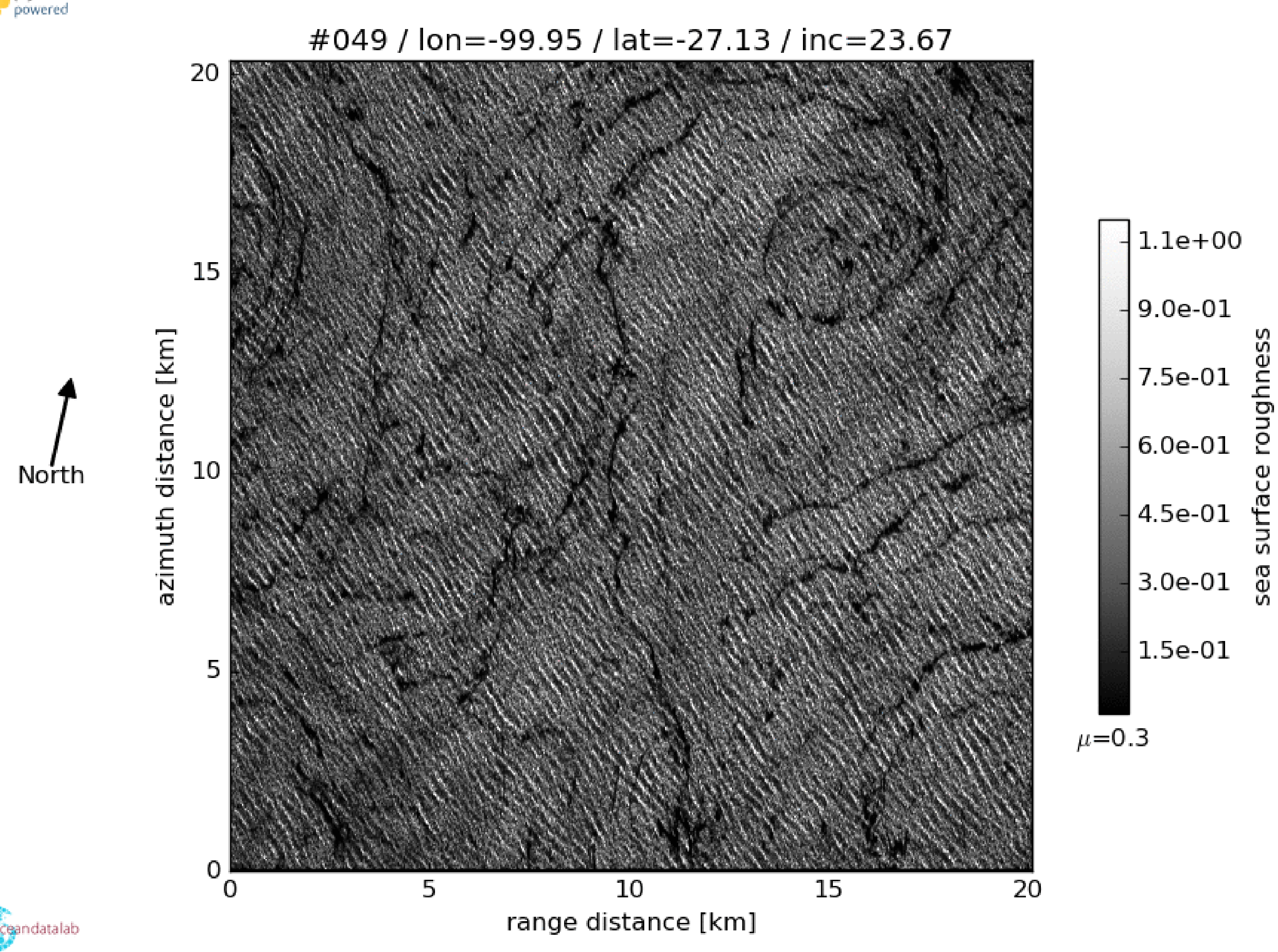


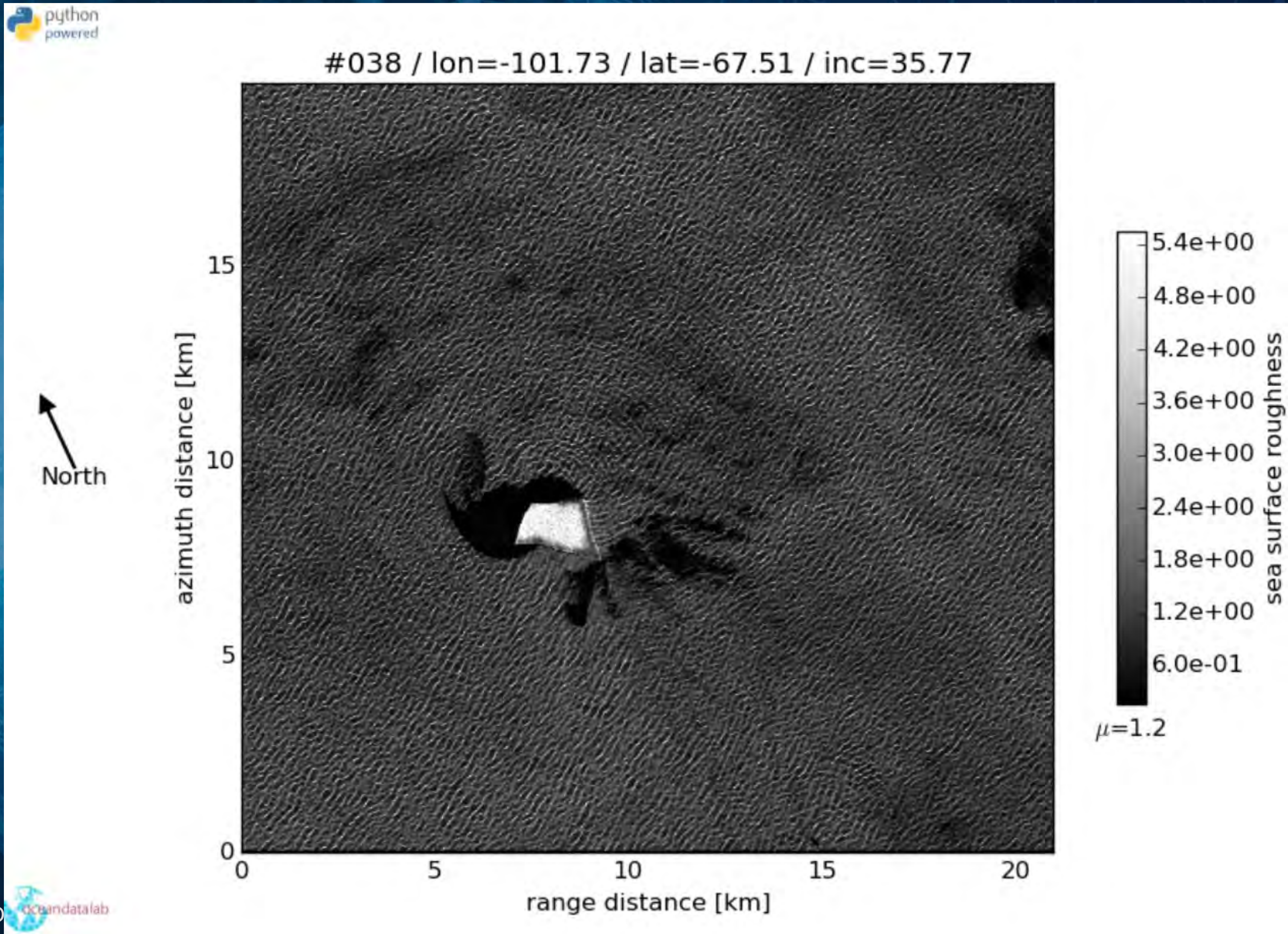
Sentinel-1 VV-roughness SAR image over Brest and the Iroise, France (2014-09-01)

Microbreaking and surface waves – the gearbox of the air-sea interaction "engine"

Lisbon from Sentinel-2A MSI 05/05/2017 & 27/09/16

Band B8 (842nm)
Stretched for glitter


python powered
#049 / lon=-99.95 / lat=-27.13 / inc=23.67
North
azimuth distance [km]
range distance [km]
sea surface roughness
μ=0.3
0
5
10
15
20
1.1e+00
9.0e-01
7.5e-01
6.0e-01
4.5e-01
3.0e-01
1.5e-01
oceandatalab

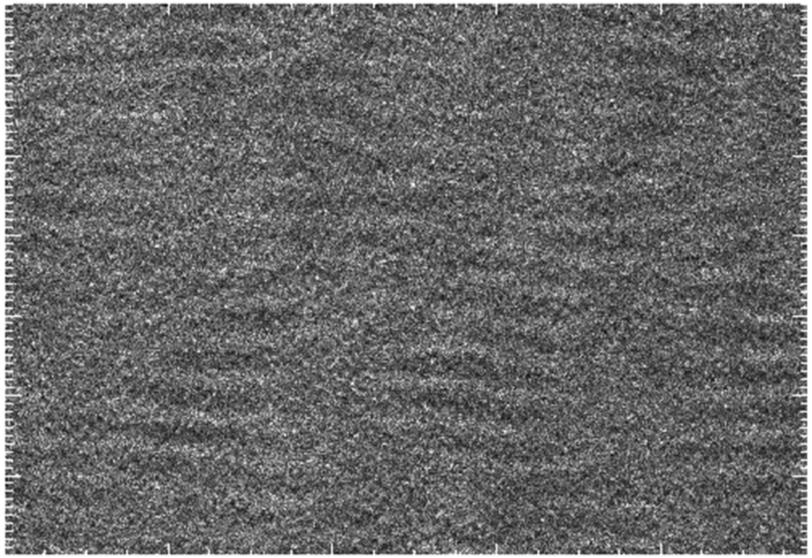

python powered
#038 / lon=-101.73 / lat=-67.51 / inc=35.77
North
azimuth distance [km]
range distance [km]
0
5
10
15
20
5.4e+00
4.8e+00
4.2e+00
3.6e+00
3.0e+00
2.4e+00
1.8e+00
1.2e+00
6.0e-01
sea surface roughness
μ=1.2
oceandatalab

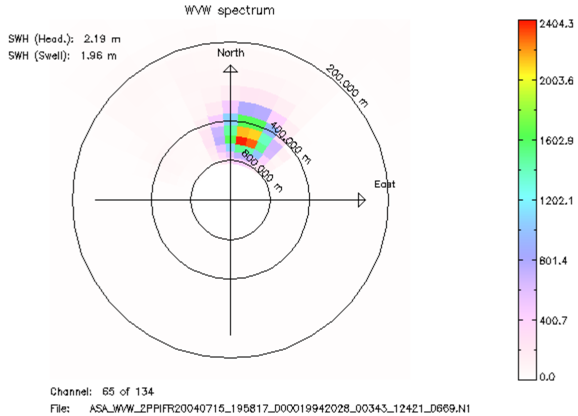
Waves across the Pacific revisited

« A comparison with meteorological events in the Southern Ocean would be far more meaningful if such Observations could be made at a time when a weather satellite is in suitable orbit » (Munk et al. 1963)

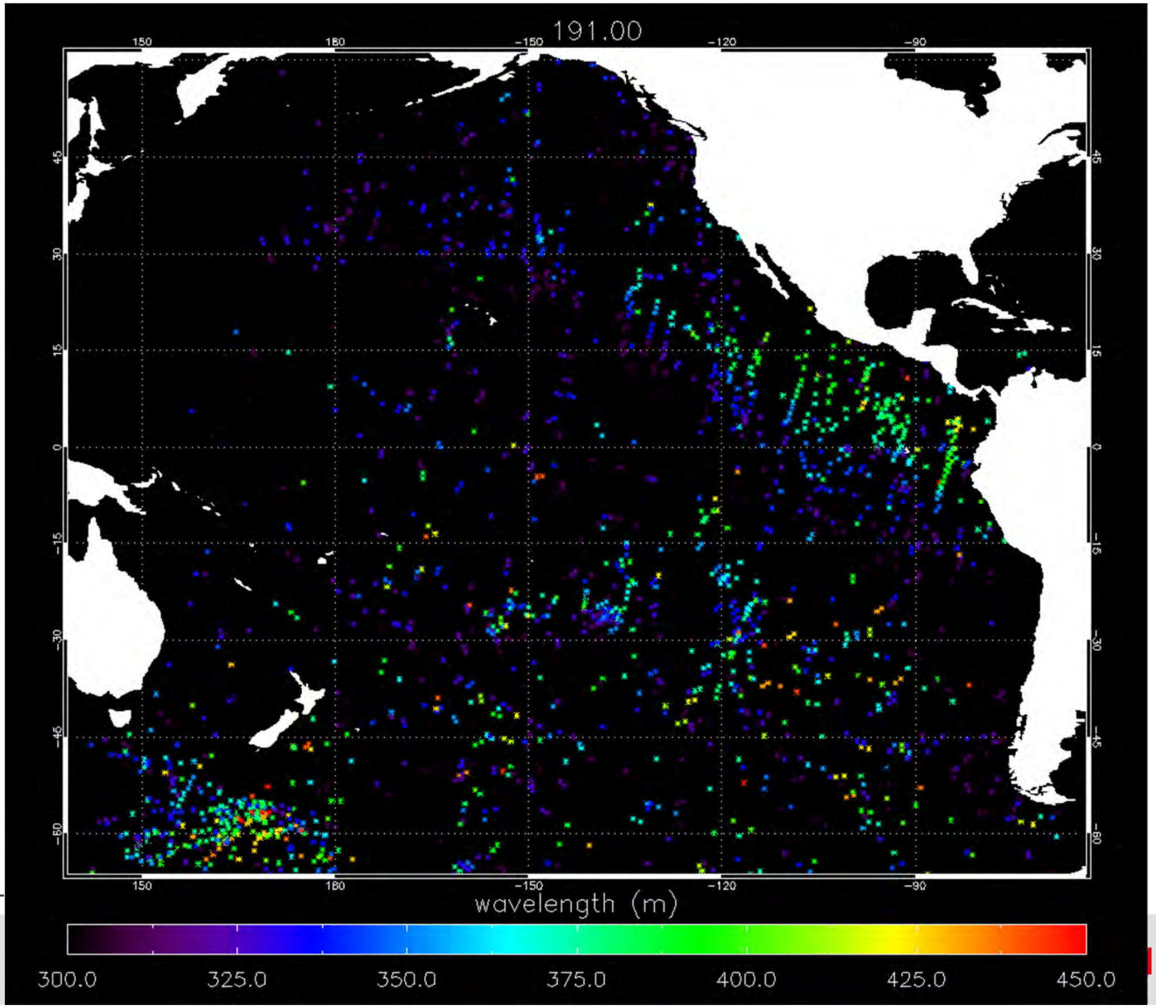
Data sources:
NDBC buoys
ENVISAT ASAR
Altimeters
(+propagation models)

SAR is *the* swell instrument
-SAR wave mode products

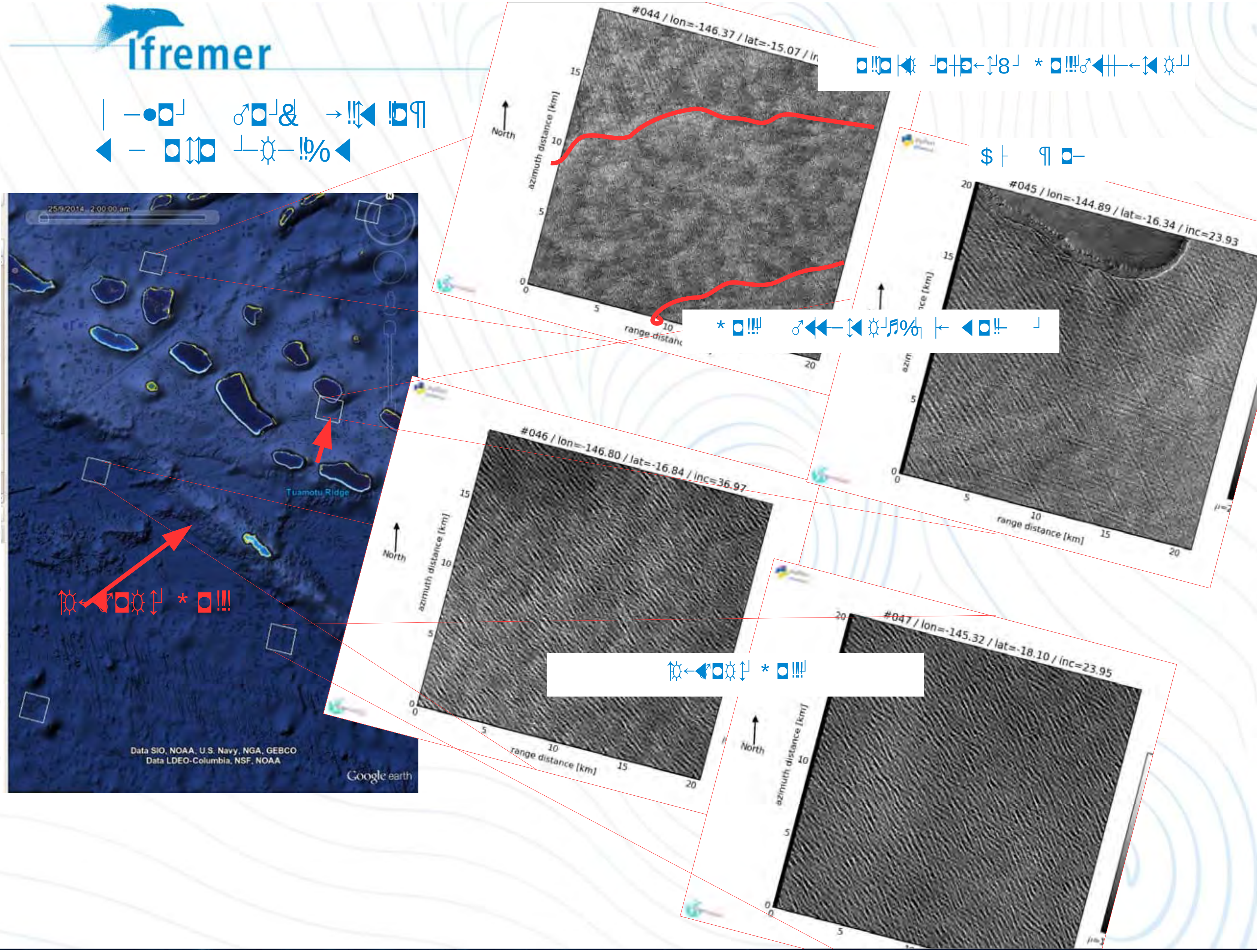




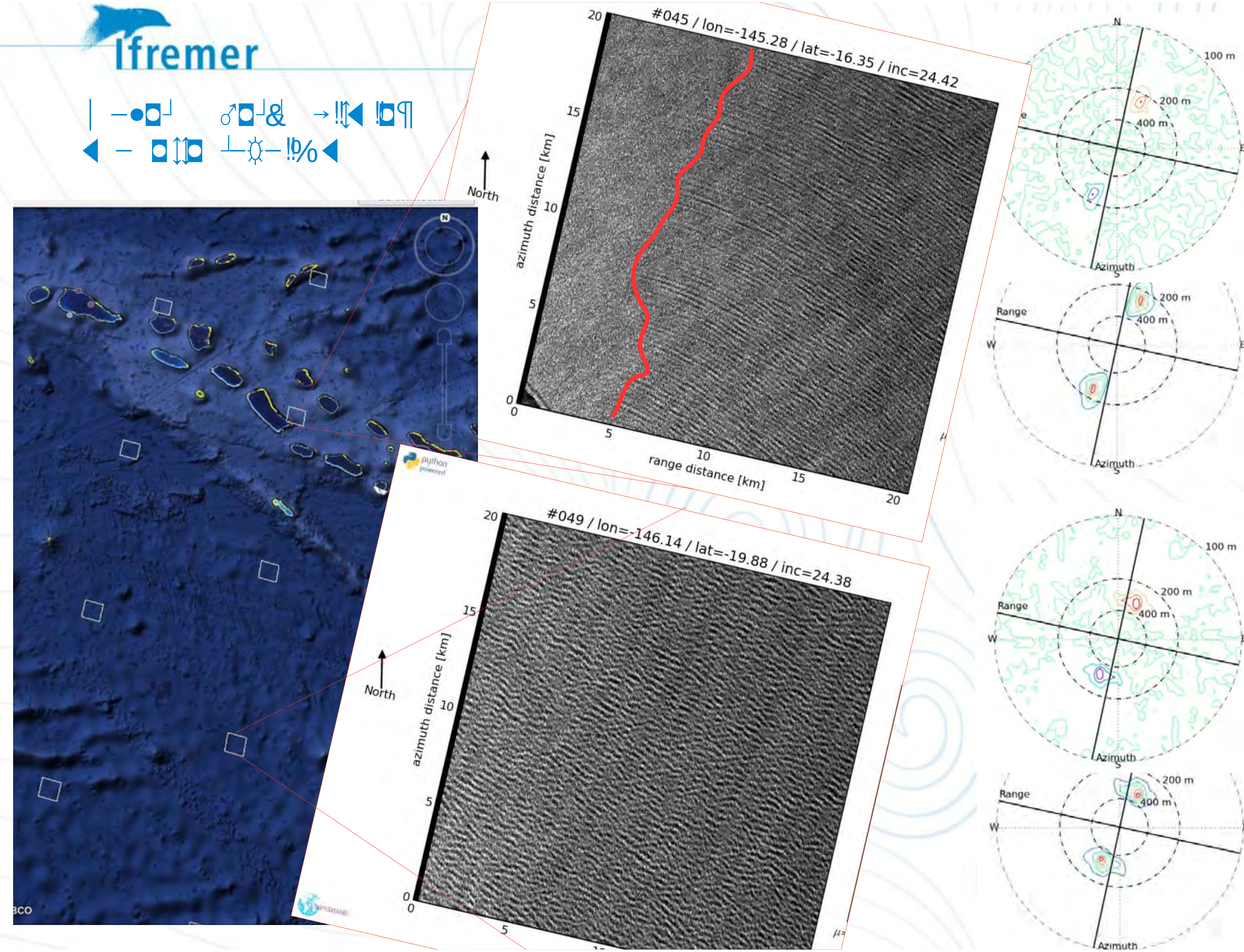
Observed propagation of 13s to 17s swell from July 8 to July 20, 2004



- 6 hour time step
- Wavelength from 300 to 450m
- Wave period from 13 to 17 seconds



Ifremer
25/9/2014 2:00:00 am
Tuamotu Ridge
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
Google earth
#044 / lon=-146.37 / lat=-15.07 / in
#045 / lon=-144.89 / lat=-16.34 / inc=23.93
#046 / lon=-146.80 / lat=-16.84 / inc=36.97
#047 / lon=-145.32 / lat=-18.10 / inc=23.95
North
azimuth distance [km]
range distance [km]

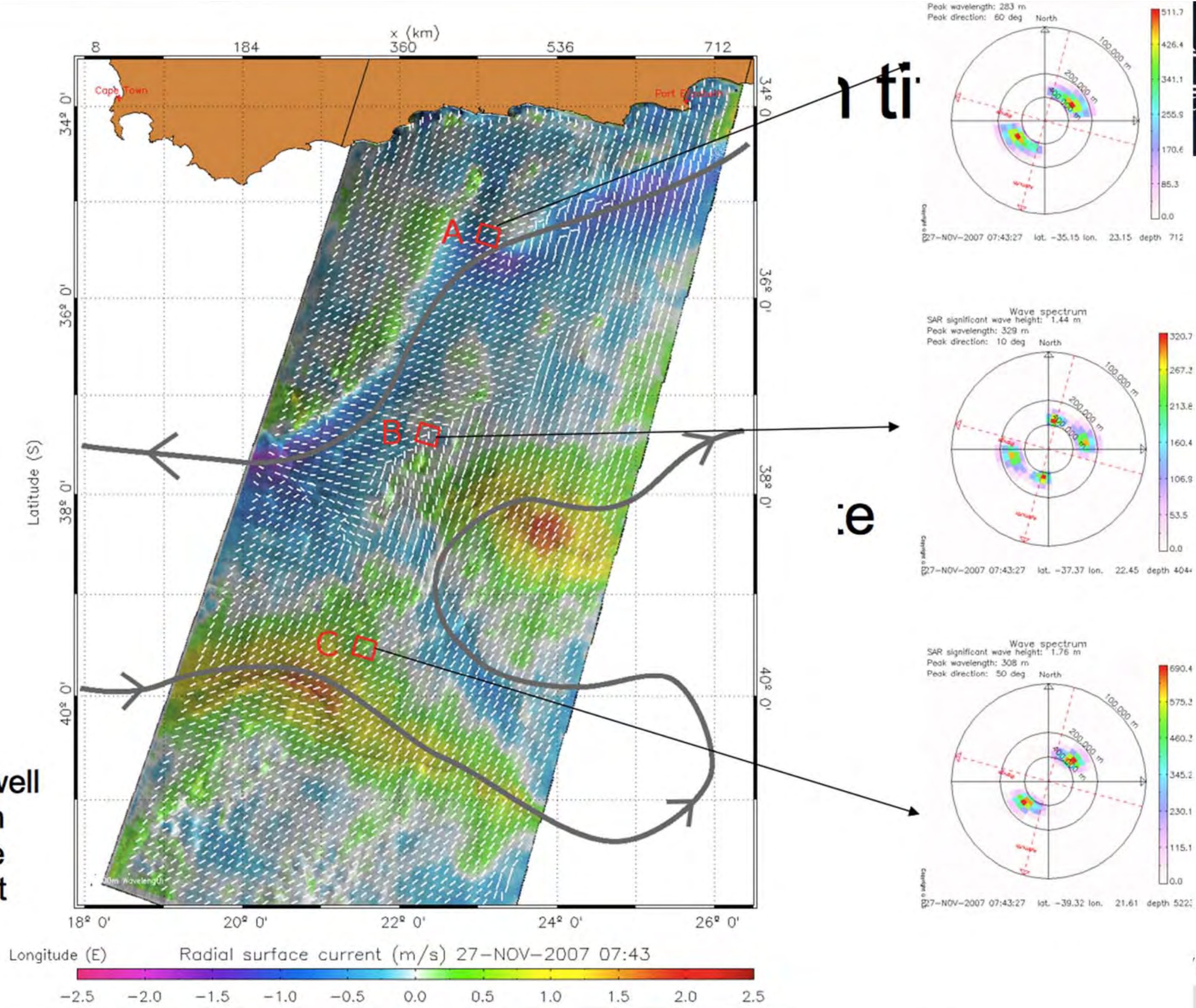


#045 / lon=-145.28 / lat=-16.35 / inc=24.42
North
azimuth distance [km]
range distance [km]
#049 / lon=-146.14 / lat=-19.88 / inc=24.38
100 m
200 m
400 m
Range
Azimuth
N
S
W
E

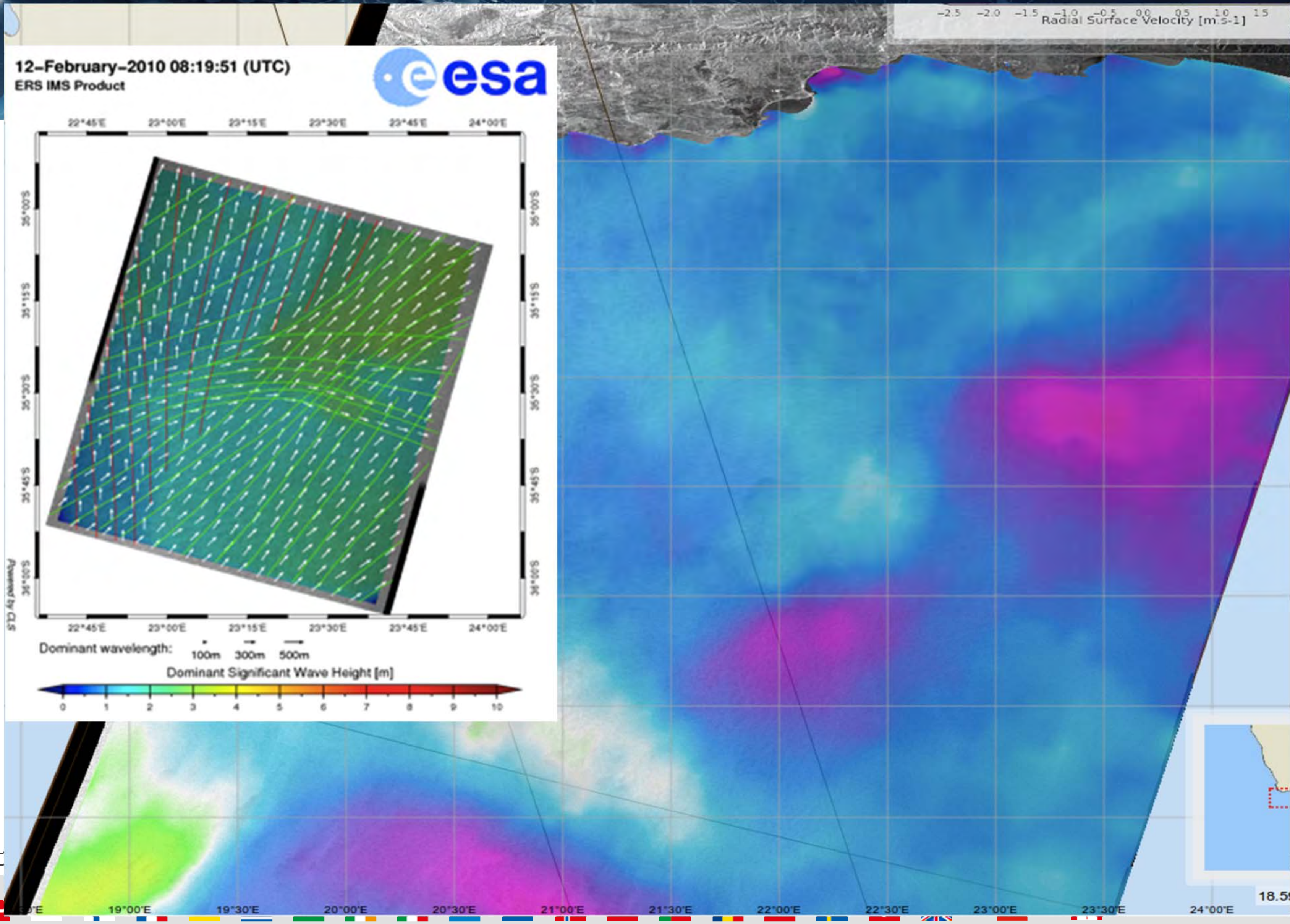
The interaction of (peak) waves on deep water with spatially varying currents may be described by ray theory, with the wave amplitudes determined by the conservation of wave action .

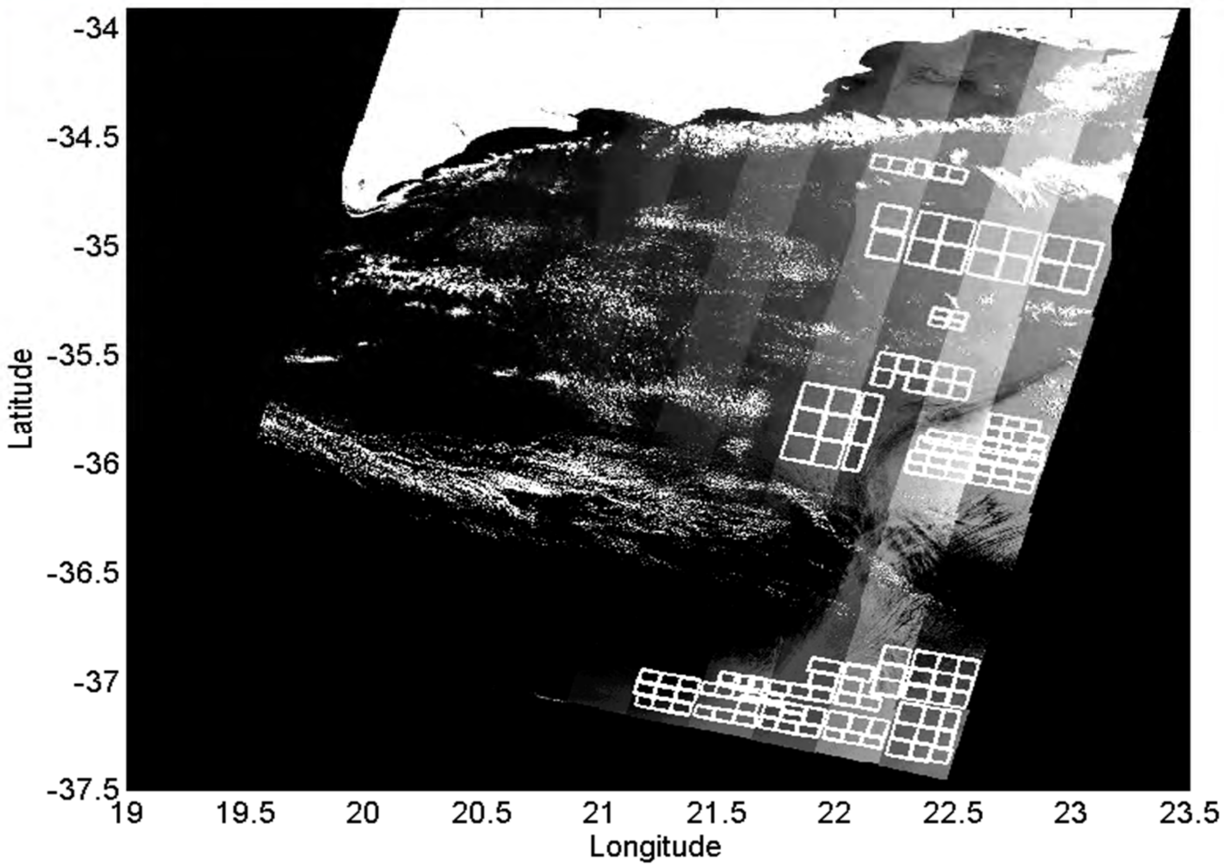
$$\frac{\partial \theta}{\partial t} + \Omega(\boldsymbol{x}, \tilde{\nabla}\theta) = 0. \qquad \Omega = \bar{\Omega} + \boldsymbol{k} \cdot \tilde{\boldsymbol{U}}.$$

$$\frac{\mathrm{d}\bar{\boldsymbol{x}}}{\mathrm{d}t} = \Omega_{,k}(\bar{\boldsymbol{x}}, \bar{\boldsymbol{k}}), \quad \frac{\mathrm{d}\bar{\boldsymbol{k}}}{\mathrm{d}t} = -\tilde{\nabla}\Omega(\bar{\boldsymbol{x}}, \bar{\boldsymbol{k}}),$$

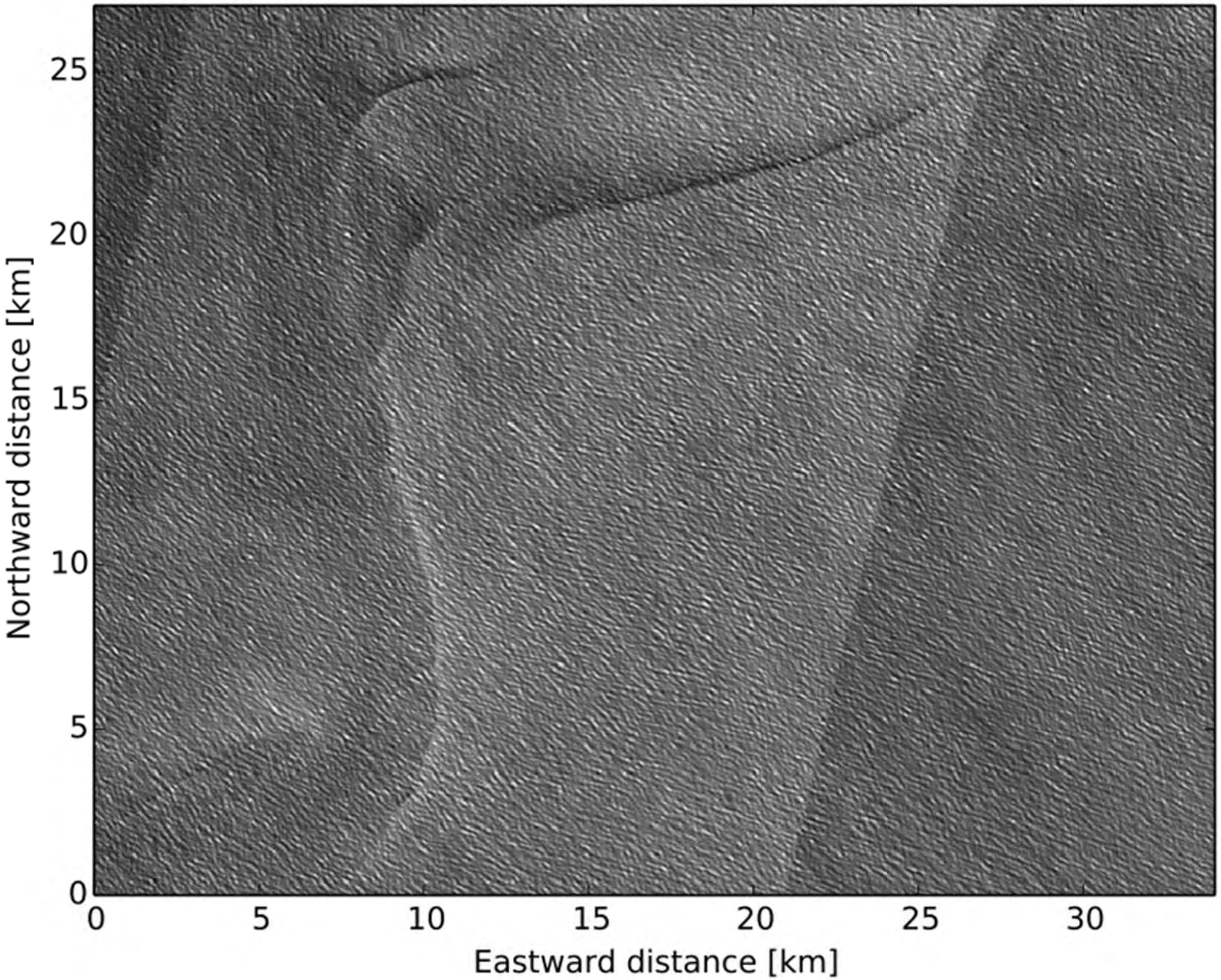


Local swell
direction
As white
segment

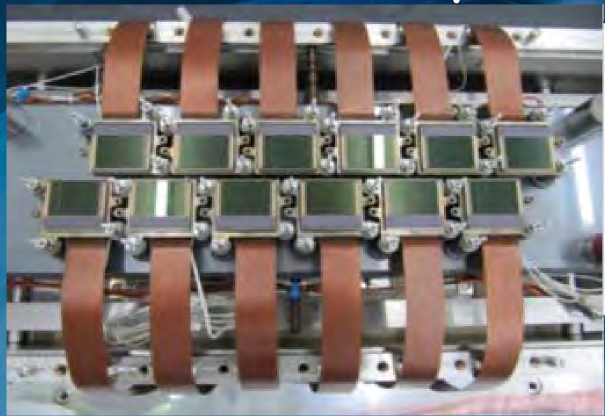

12-February-2010 08:19:51 (UTC)
ERS IMS Product
esa
Dominant wavelength:
100m 300m 500m
Dominant Significant Wave Height [m]
0 1 2 3 4 5 6 7 8 9 10
22°45'E 23°00'E 23°15'E 23°30'E 23°45'E 24°00'E
Radial Surface Velocity [m.s-1]
19°00'E 19°30'E 20°00'E 20°30'E 21°00'E 21°30'E 22°00'E 22°30'E 23°00'E 23°30'E 24°00'E



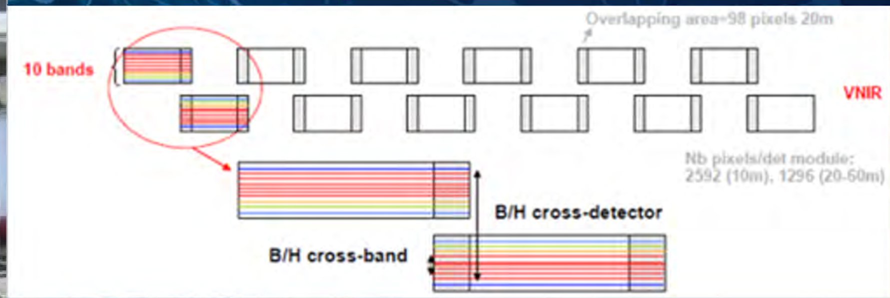
Sentinel-2 image, January 4rth 2016. The stripes results from the specific instrumentation and configuration of S2 multi-channel detectors. It enables to derive 2D directional wave spectra for wavelength range > 20 m, and to also assess the local dispersion relation

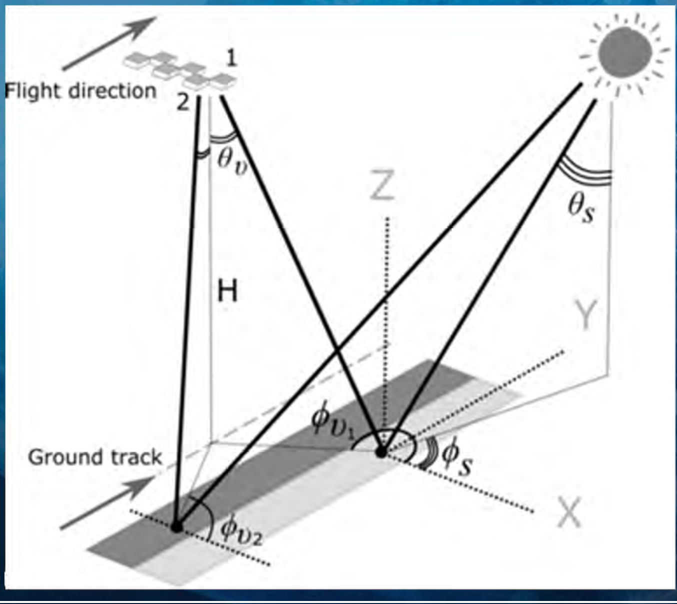

Northward distance [km]
Eastward distance [km]
0
5
10
15
20
25
30

Sentinel-2 MSI Features = New Opportunities to image ocean surface waves and dispersion properties



Sentinel-2 detectors





12 clusters (detectors), 13 lines of sensors (bands) in each

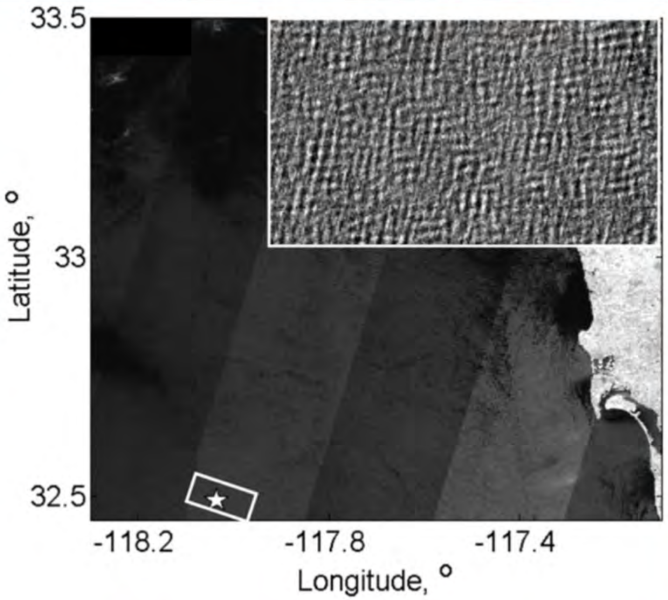
Odd clusters are looking forward, even clusters are looking backward, spectral channel sensors also have relative displacement

Parallax angle between the two alternating odd and even clusters of detectors results in a shift along track of approximately 46 km (maximum).

Inter-band measurement parallax amounts to a maximum along track displacement of approximately 14 km.

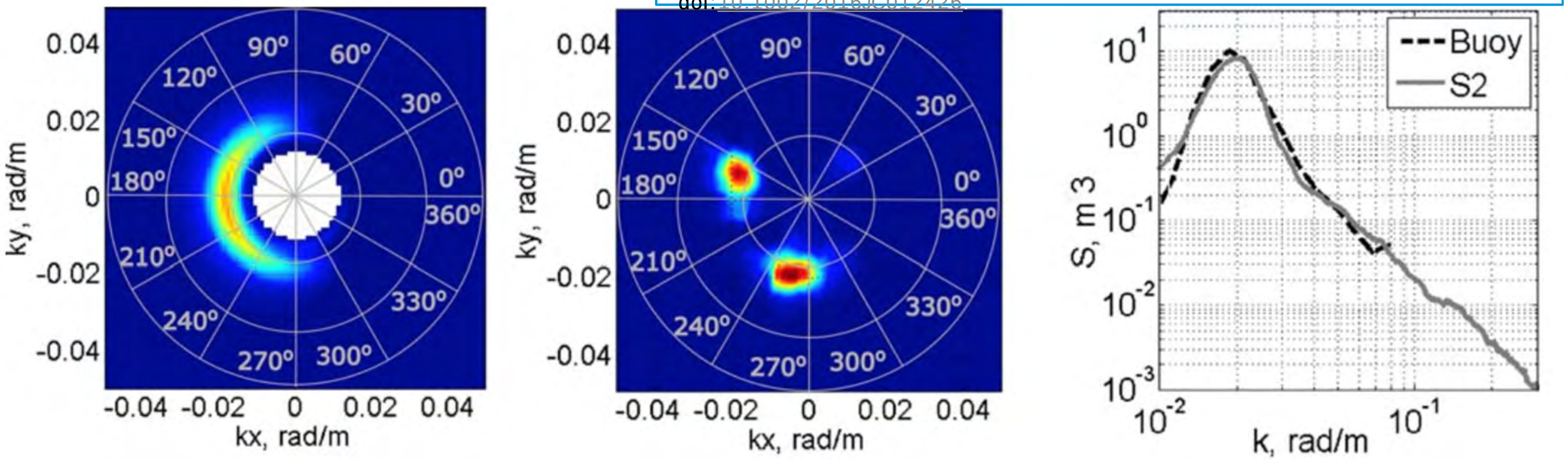
Left: S2 B04 (665nm) Imagette off the Californian coast used to extract 2D wave spectrum

Bottom: (a) In situ buoy wave spectrum (b) Sentinel-2 wave spectrum (c) Comparison of S2 and buoy spectra.

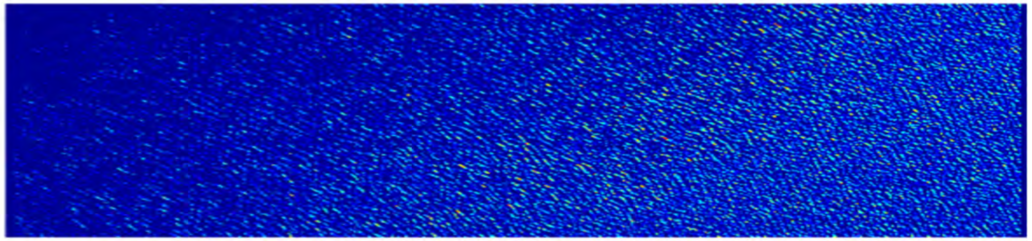


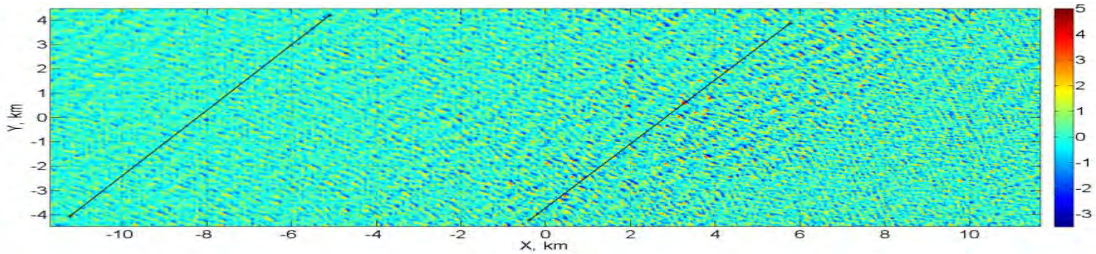
Kudryavtsev, V., Yurovskaya, M., Chapron, B., Collard, F. and Donlon, C. (2017), **Sun glitter imagery of ocean surface waves: 1. Directional spectrum retrieval and validation**. . Geophys. Res. Oceans, 122, 1369–1383, doi:10.1002/2016JC012425.

Kudryavtsev, V., Yurovskaya, M., Chapron, B., Collard, F. and Donlon, C. (2017), **Sun glitter imagery of surface waves: 2. Waves Transformation on Ocean Currents**. J. Geophys. Res. Oceans. J. Geophys. Res. Oceans, 122, 1384–1399, doi:10.1002/2016JC012426

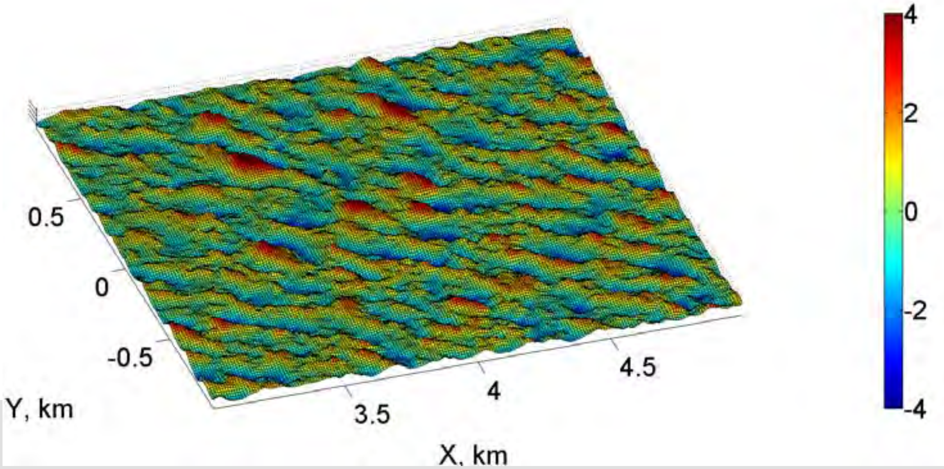


(a) (b) (c)

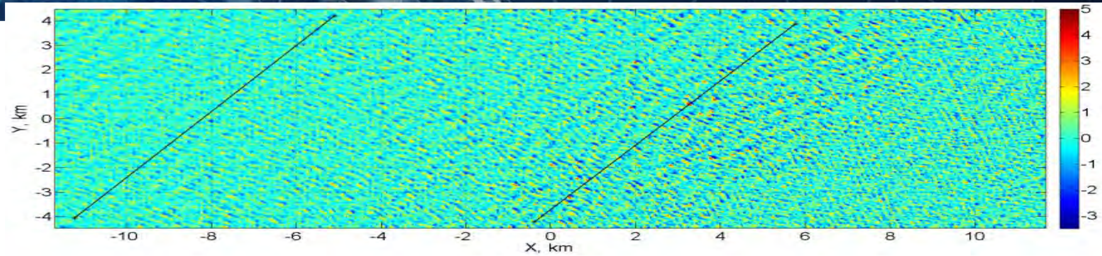


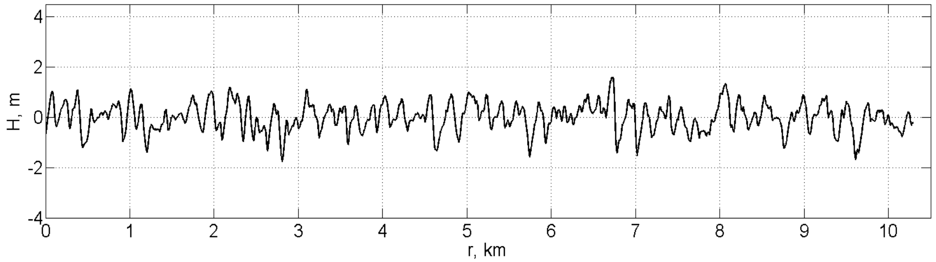


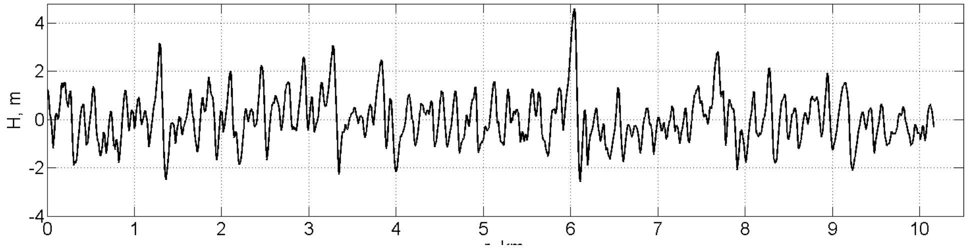
Y, km
X, km
4 3 2 1 0 -1 -2 -3 -4
-10 -8 -6 -4 -2 0 2 4 6 8 10
5 4 3 2 1 0 -1 -2 -3

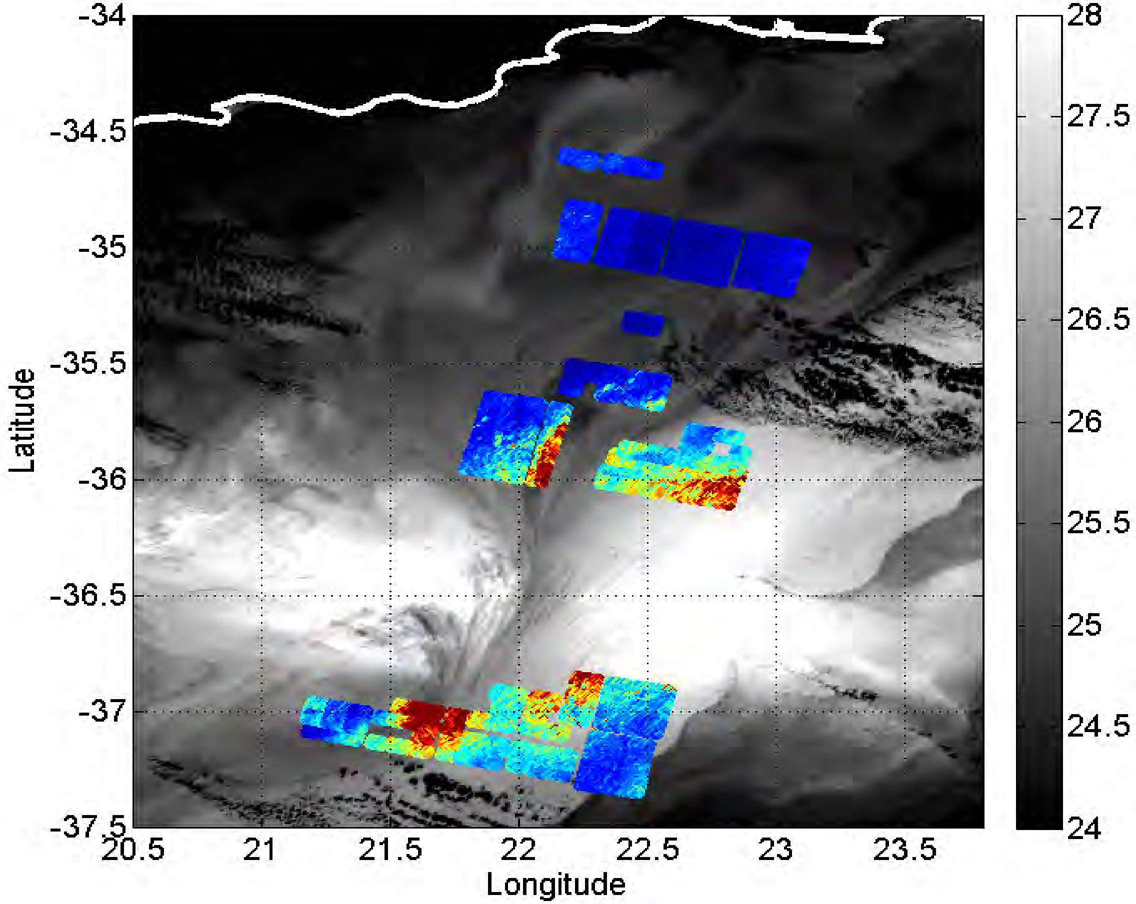


0.5
0
-0.5
Y, km
3.5
4
4.5
X, km
4
2
0
-2
-4

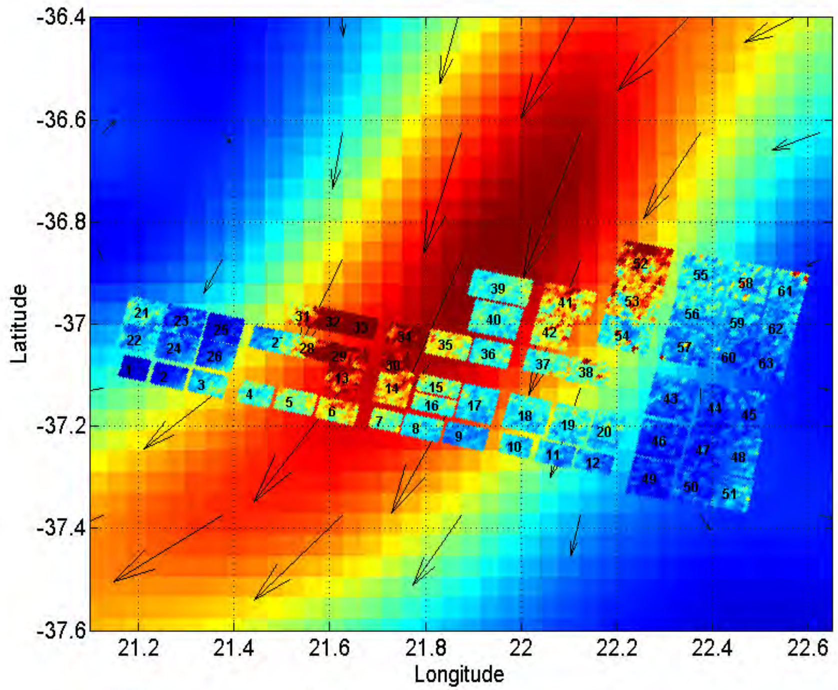

Y, km
X, km


H, m
r, km

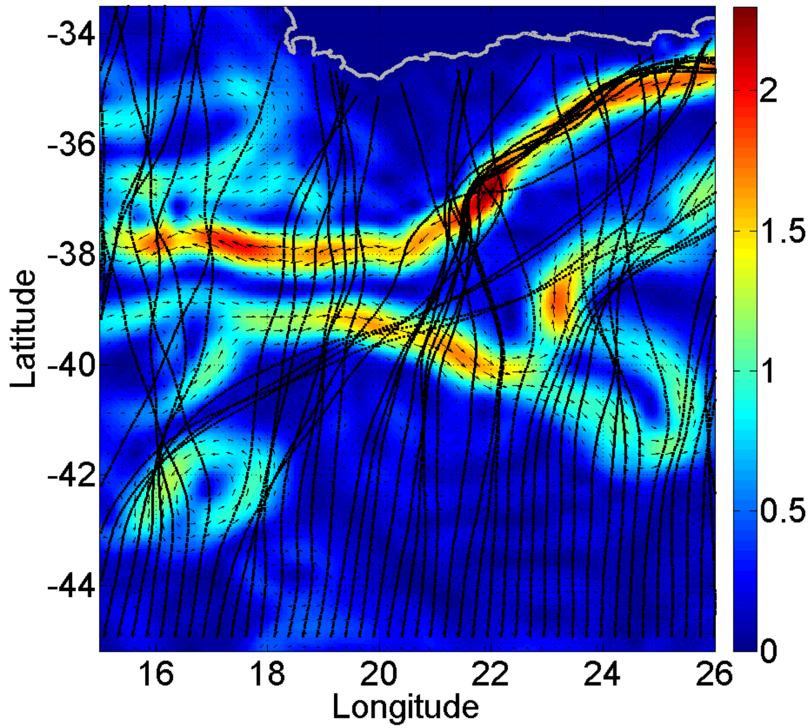

H, m



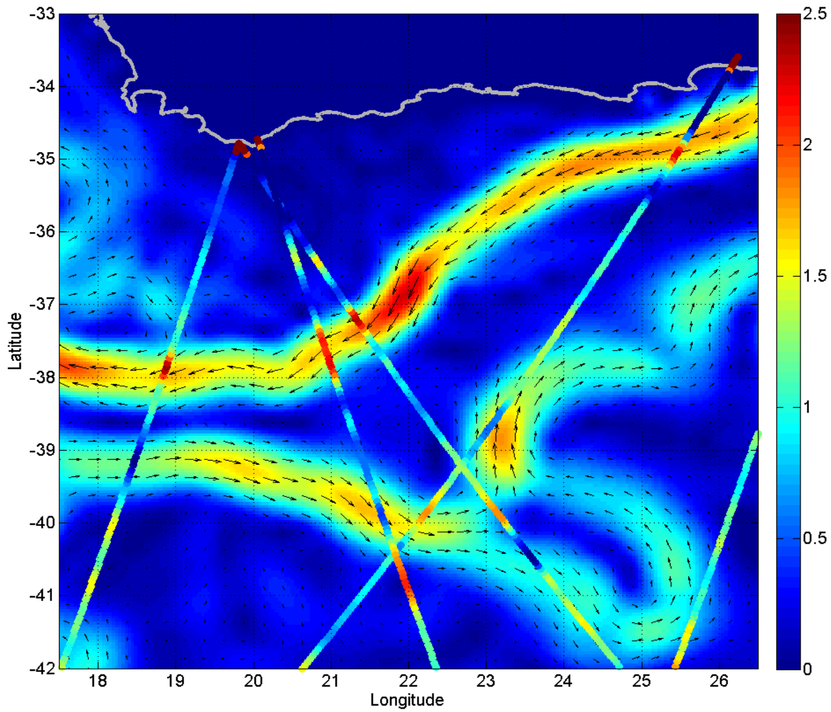
SST field, January 04, 2016, 12:20 GMT . Overlaid, color-coded wave energy derived from S2 imagettes



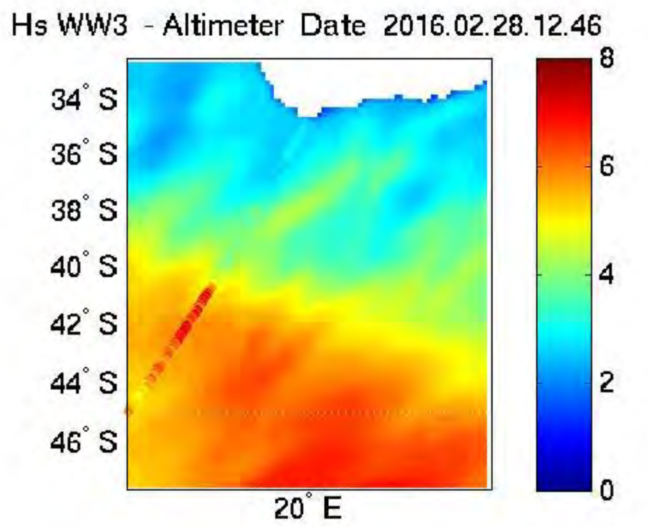
Set of selected S2 imagettes overlaid on the altimeter geostrophic current.
Imagettes are color-coded according to the derived wave energy level

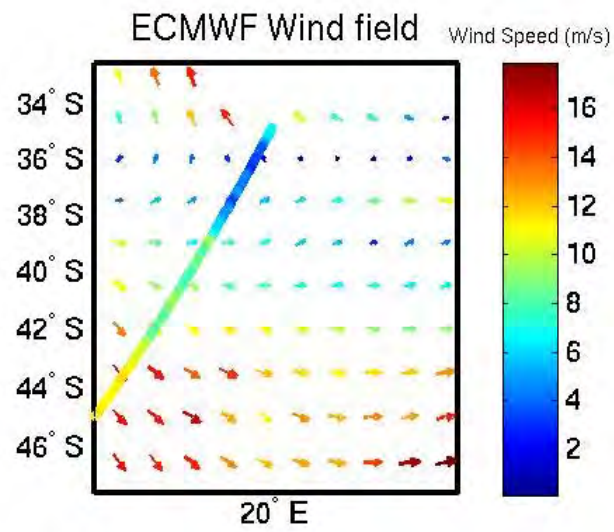


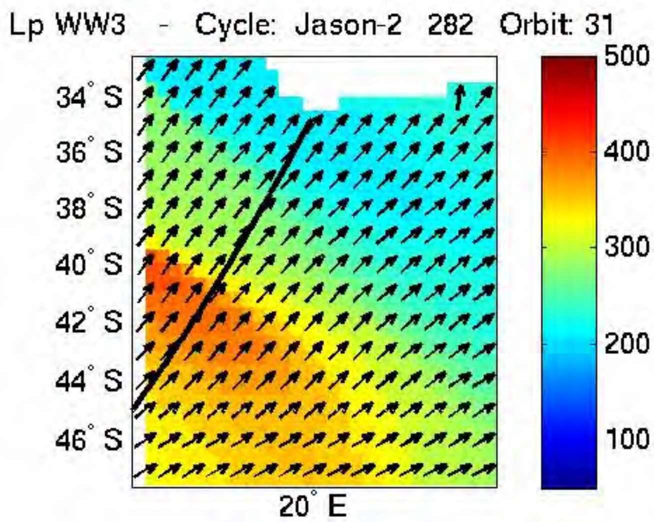
Wave-rays of an incoming 75 degree (counter clockwise from the East) 250 m swell at -45 degree latitude,

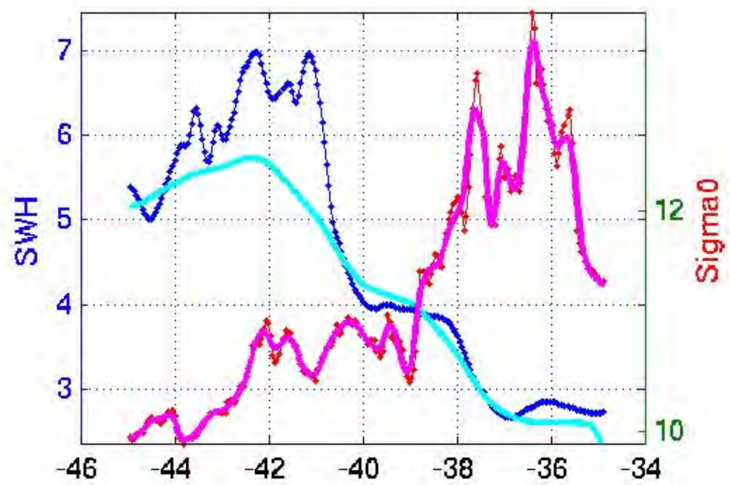


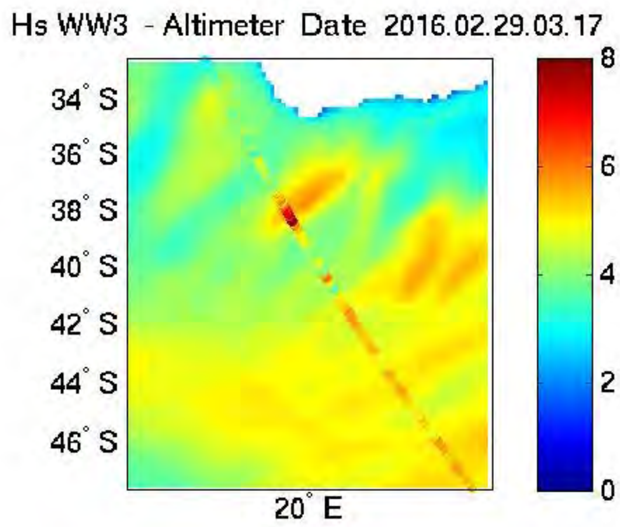
Geostrophic surface current velocity corresponding to January, 4rth 2016, and SWH anomalies, , along the altimeter tracks, from a 250 km moving average along the altimeter track.

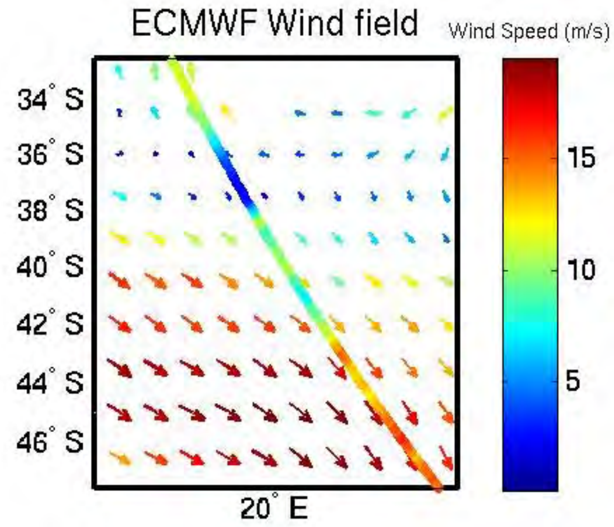

Hs WW3 - Altimeter Date 2016.02.28.12.46
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
0
2
4
6
8

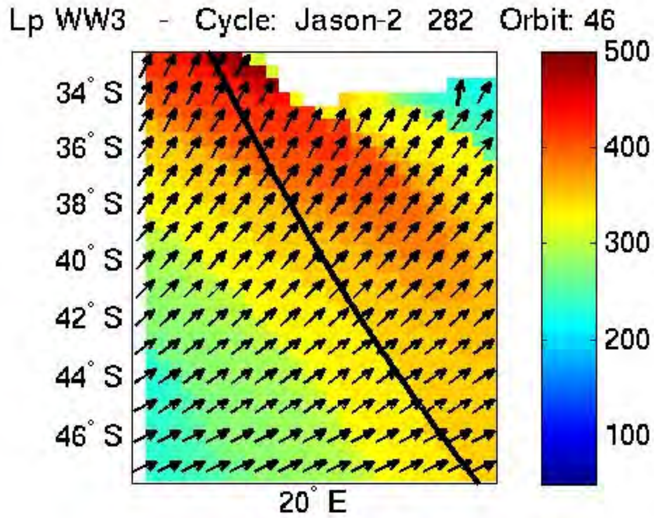

ECMWF Wind field
Wind Speed (m/s)
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
2
4
6
8
10
12
14
16

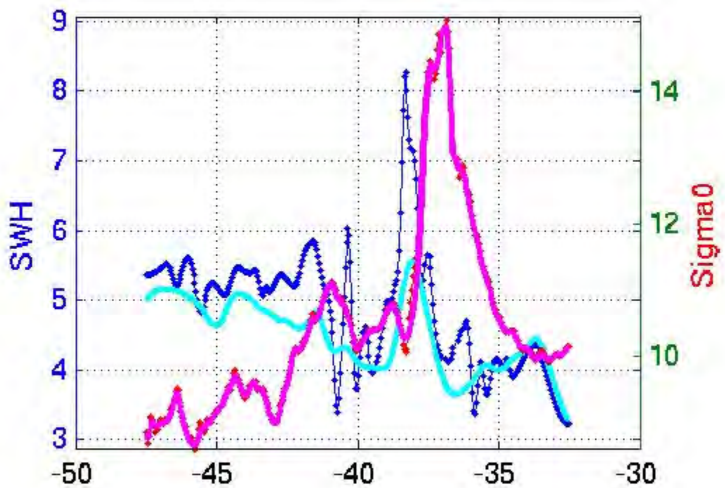

Lp WW3 - Cycle: Jason-2 282 Orbit: 31
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
100
200
300
400
500

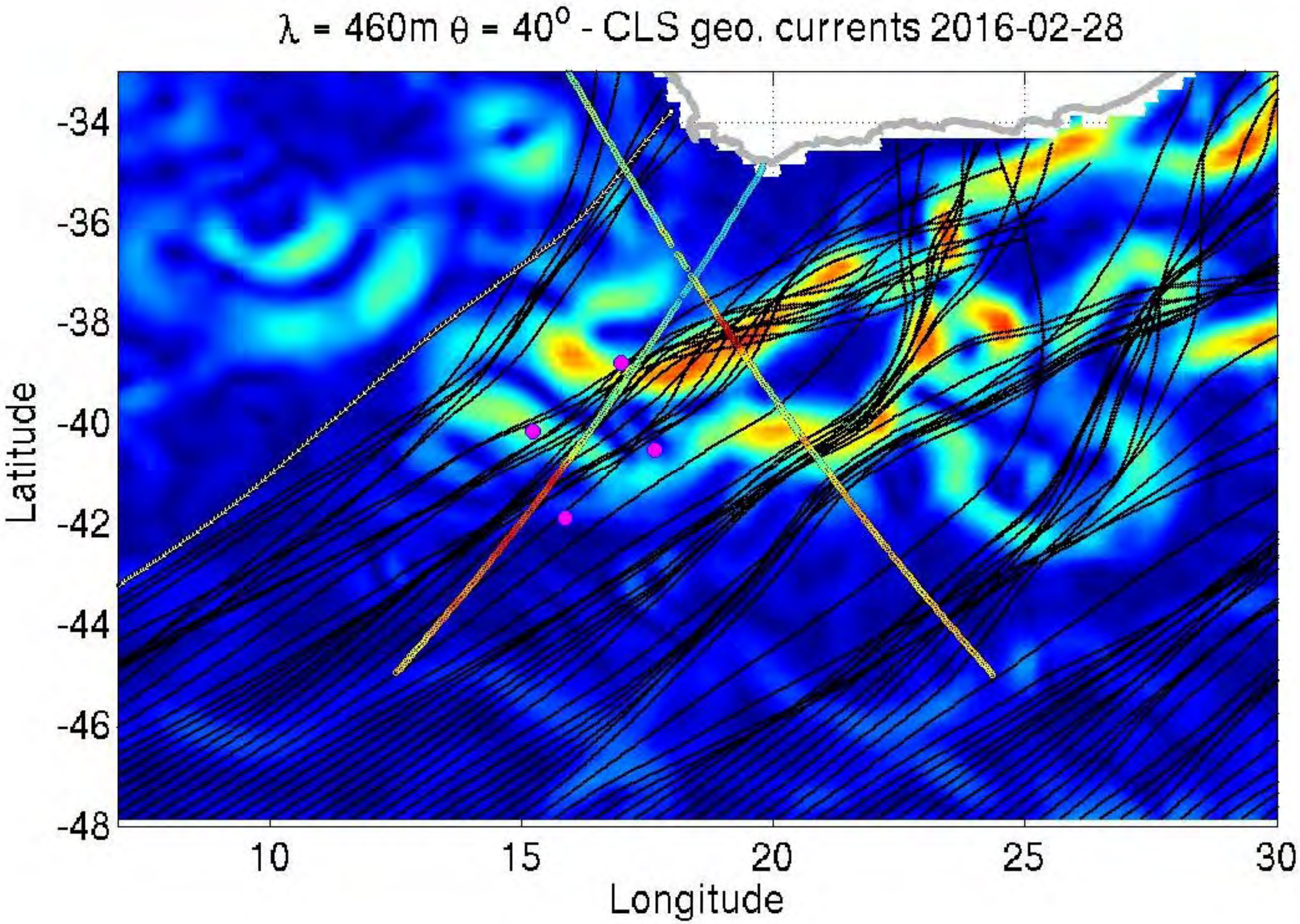

SWH
3
4
5
6
7
Sigma0
10
12
-46
-44
-42
-40
-38
-36
-34


Hs WW3 - Altimeter Date 2016.02.29.03.17
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
0
2
4
6
8

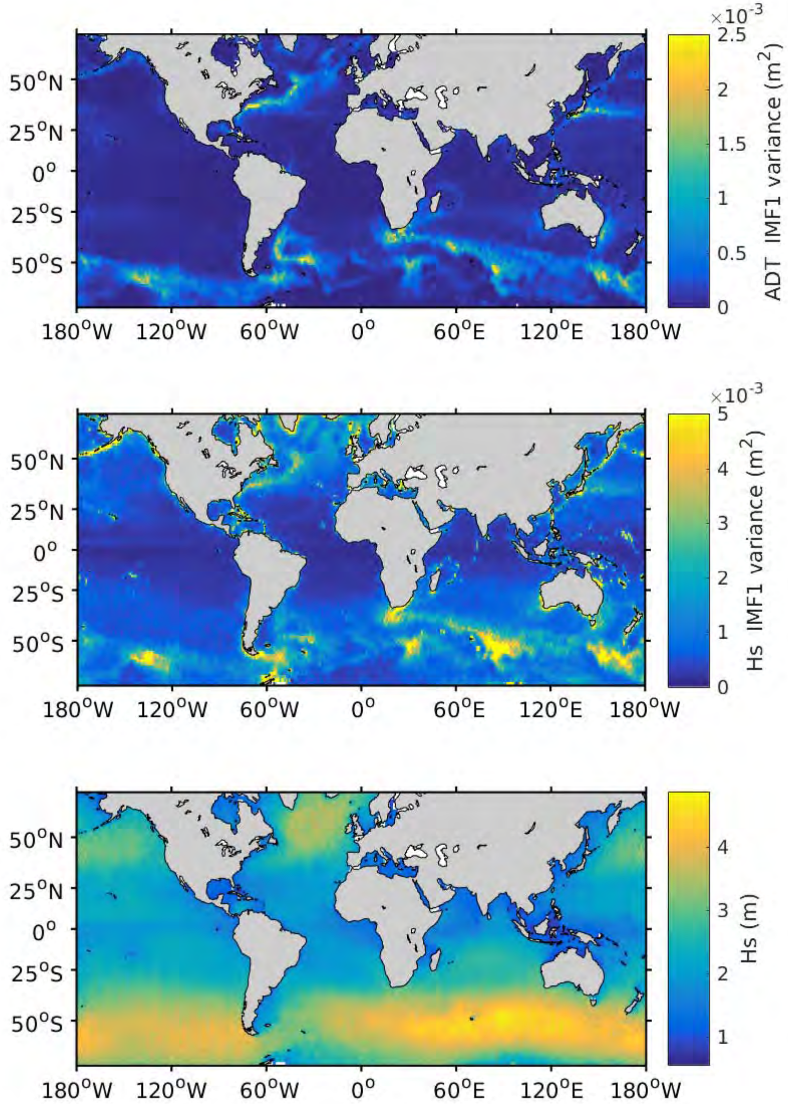

ECMWF Wind field
Wind Speed (m/s)
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
5
10
15


Lp WW3 - Cycle: Jason-2 282 Orbit: 46
34° S
36° S
38° S
40° S
42° S
44° S
46° S
20° E
100
200
300
400
500


SWH
Sigma0
3
4
5
6
7
8
9
10
12
14
-50
-45
-40
-35
-30



λ = 460m θ = 40° - CLS geo. currents 2016-02-28
Latitude
-34
-36
-38
-40
-42
-44
-46
-48
10
15
20
25
30
Longitude



×10-3
2.5
2
1.5
1
0.5
0
ADT IMF1 variance (m2)
50°N
25°N
0°
25°S
50°S
180°W 120°W 60°W 0° 60°E 120°E 180°W
×10-3
5
4
3
2
1
0
Hs IMF1 variance (m2)
50°N
25°N
0°
25°S
50°S
180°W 120°W 60°W 0° 60°E 120°E 180°W
4
3
2
1
Hs (m)
50°N
25°N
0°
25°S
50°S
180°W 120°W 60°W 0° 60°E 120°E 180°W