Application of SAR Wave Mode and Wide Swath Mode for Swell Tracking Across Ocean

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Storm Source Detection

Methodology:

1. Retro-propagation:

Tracing the trajectories of the swell observations back in the past, using linear theory:

- along geodesics,
- at wave group speed,
- with constant peak period

2. Refocusing :

This swell sources are defined by the region where retro-propagated swell observations converge.

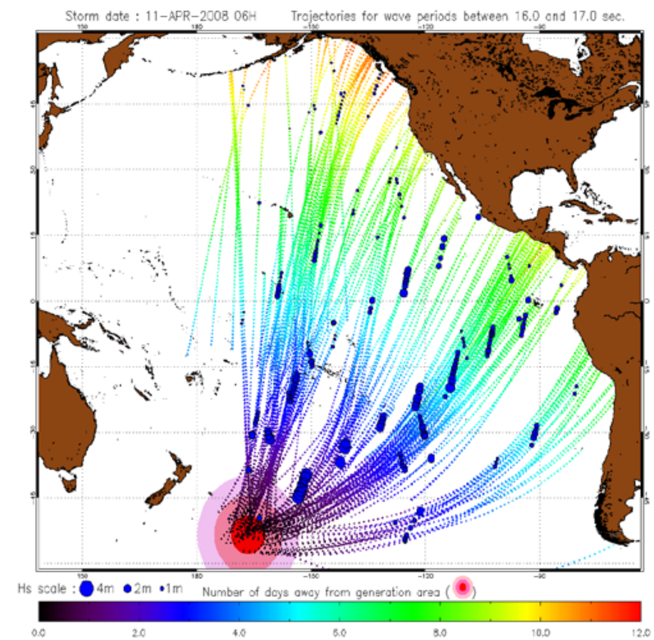
All the retro-propagated observations within the previously detected region are gathered into a set defining a new swell field

3. Swell field analysis :

The previous set of swell observations is divided into sub-sets for which region and time of refocusing are re-estimated with specific focus on swell period dependency,

4. Swell field association :

Gathers previously detected swell fields split into separate refocusing events but belonging to the same event. It is based on a spectral distance criterion.

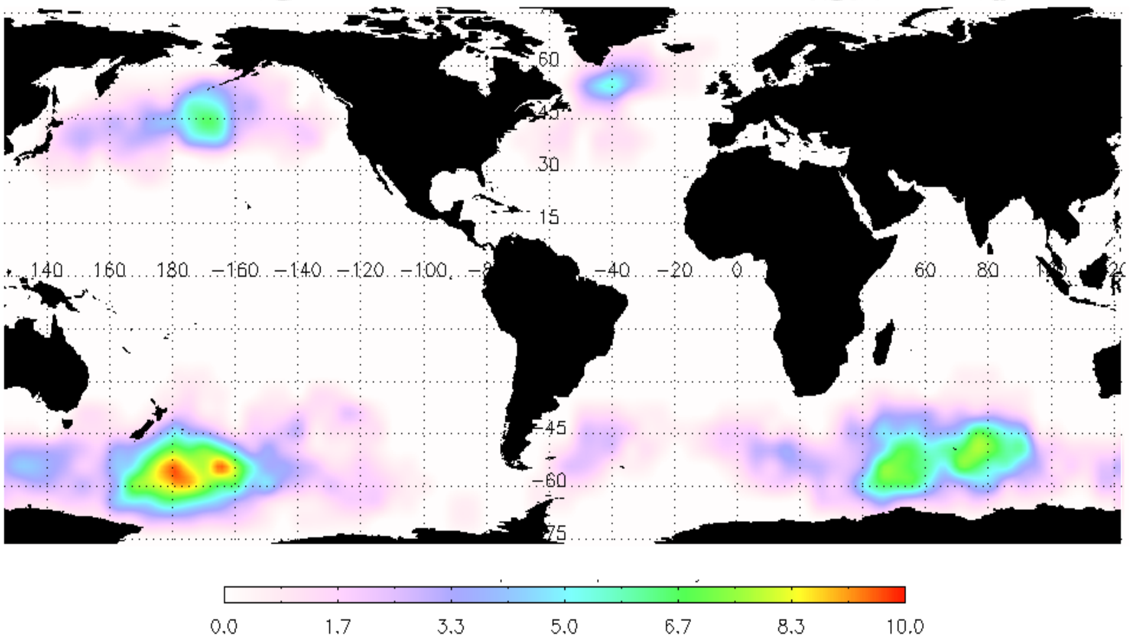


Propagated swell from the SAR observation leaving the storm area (red disk). Colors indicate days of propagation from the source

Storm Source Detection

Over year 2008

• Average wave age at refocusing time equals 1.25
→ correspond to a time of escape (wind forcing vanishes)
• More than 700 storm events
• Among then, more than 250 exhibit different refocusing times depending on swell period :
Multiple scenarii – 63% cases where longer swell refocuses before shorter one
→ Avg dif. = 14 hours - std dev. = 12 hours



Density probability of the location of the 25% storms that generated the longest swell

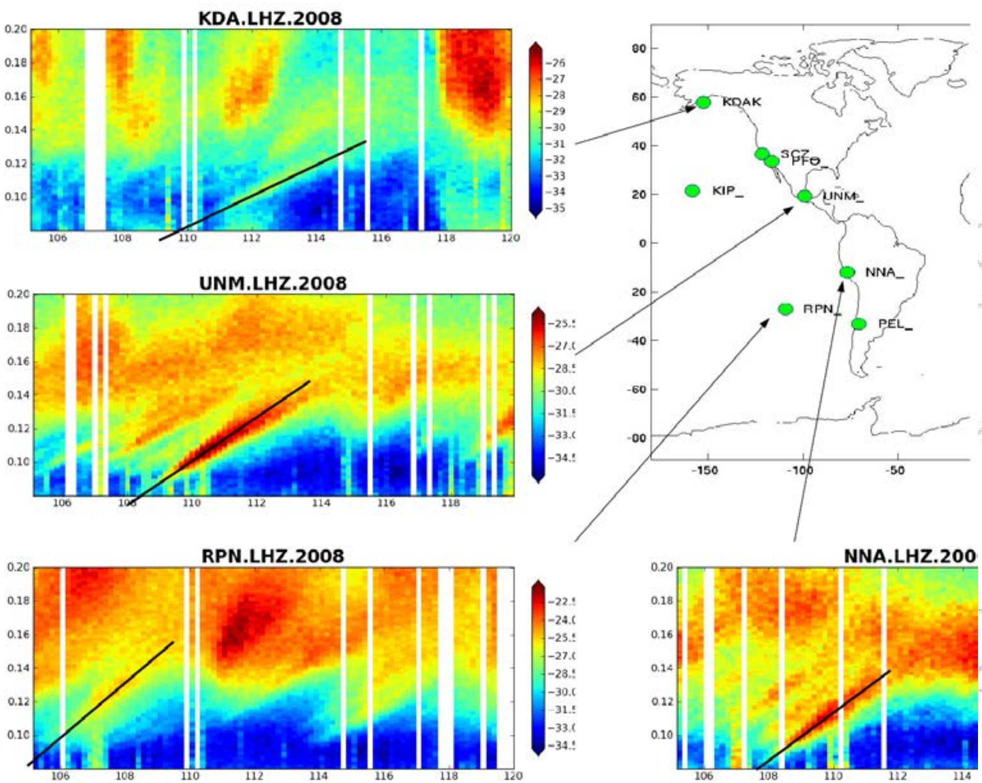
Validation with Micro-seismic noise

Micro seismic data sensitive to waves ranging from 12 to more than 25 seconds

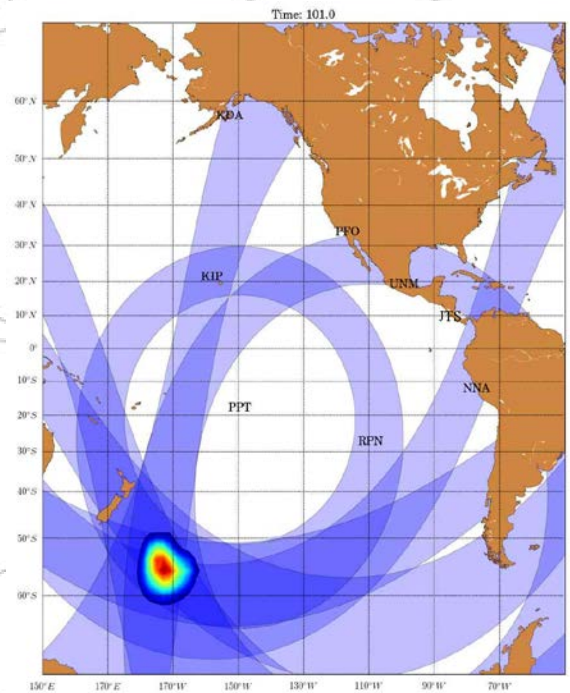
Swell hits the coast and interfer with the opposite propagating swell at same period

→ generates unattenuated pressure oscillation at twice the wave frequency that can be sensed by coastal seismometer

SAR can image waves ranging from 10 to more 18 seconds



Spectra at different seismic stations showing ridges, corresponding to swell arrival. Differential arrival times depending on the frequency is represented by a black line



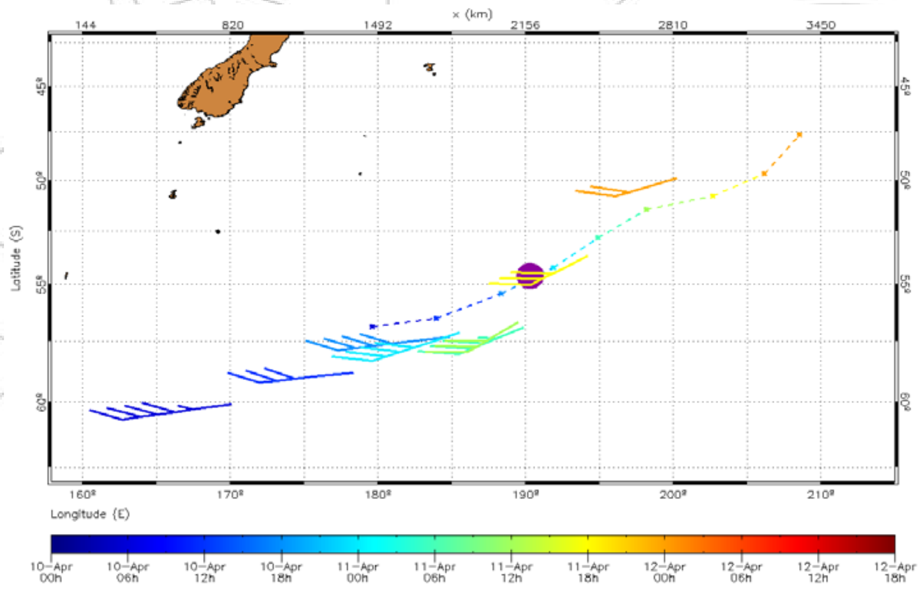
Blue bands are placed at distance of expected strom location from the seismometer. Doing so for each of them, exact location is triangulated and correspond to that given by the SAR (Red region).

Storm Watch

Storm regions detected using scatterometer data with conditions :
max. wind speed > 20m/s
area of wind speed > 15m/s

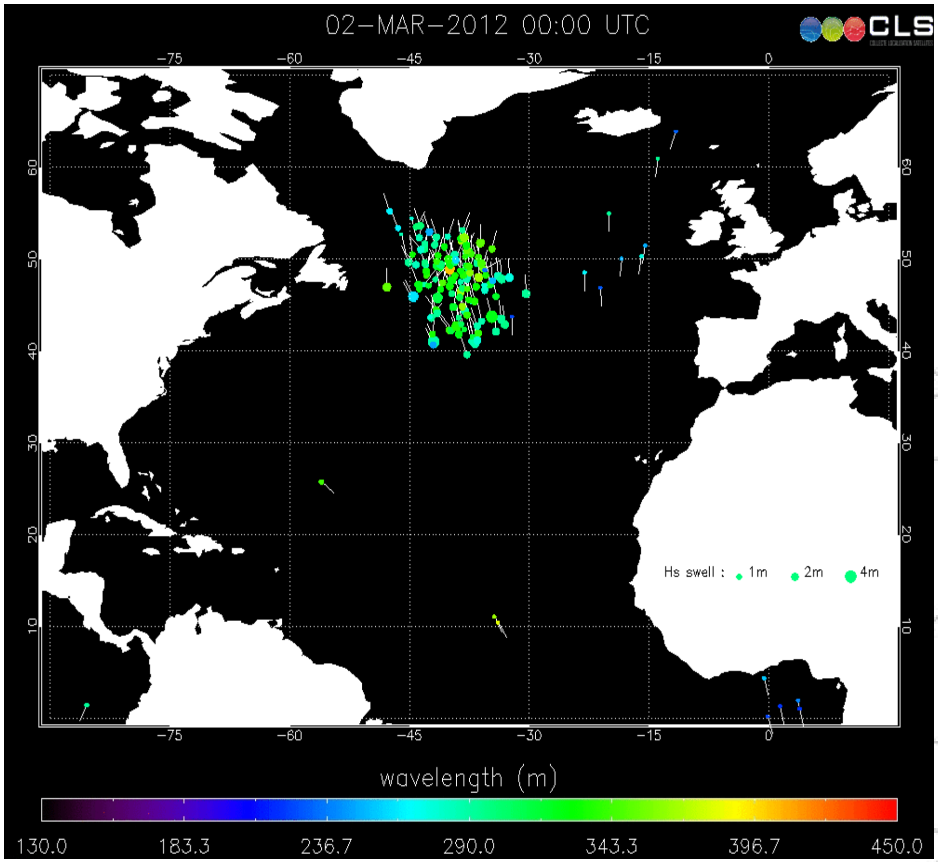
Storm regions detected by SAR co-located with Stormwatch results using QuikScat data over year 2008 under conditions:
- max estrangement < 700 km,
- scatterometer max. wind direction within 60° of refocusing area moving direction.

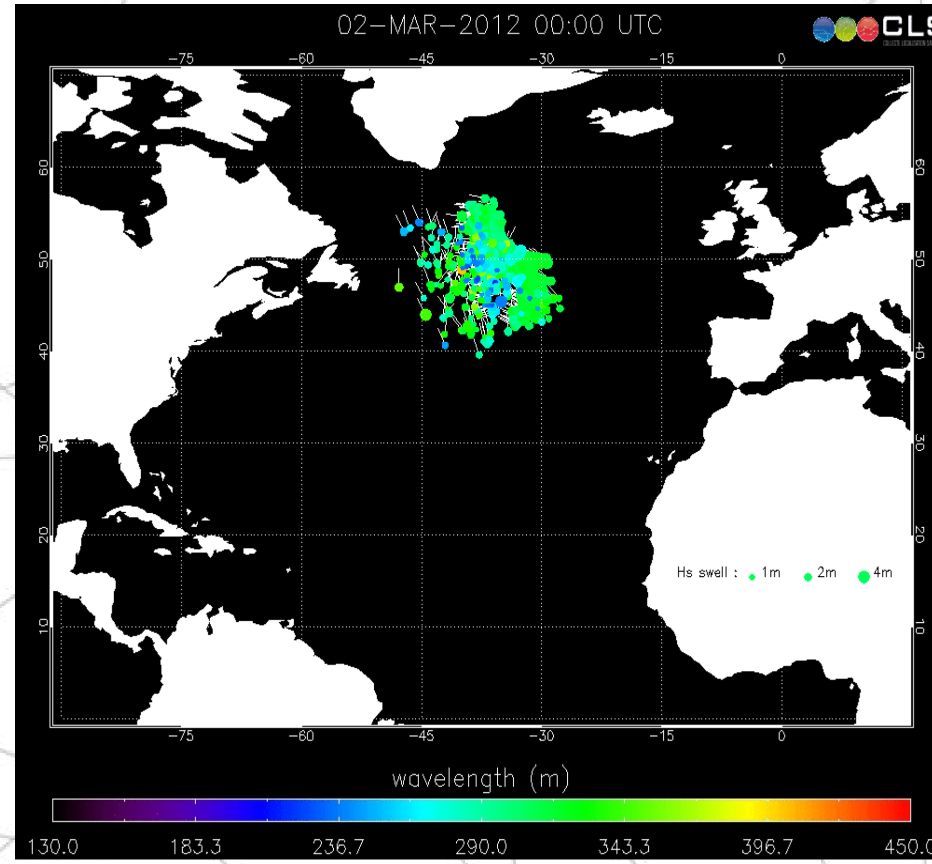
→ Among all storms, 96% coïncidence. Remaining 4% can be explained by satellite passes aside the strongest wind conditions.



Storm refocusing path with maximum wind measurements from QuikScat & Stormwatch – Color indicate time.
→ Refocusing is ahead the maximum wind region

Fireworks


02–MAR–2012 00:00 UTC
CLS
–75 –60 –45 –30 –15 0
60 50 40 30 20 10
Hs swell : 1m 2m 4m
wavelength (m)
130.0 183.3 236.7 290.0 343.3 396.7 450.0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Hs swell : 1m 2m 4m
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Stroboscopic Swell imaging

Definition :

occurs when satellite ground track displacement from one day to next is close to distance for which the swell has propagated during the same duration

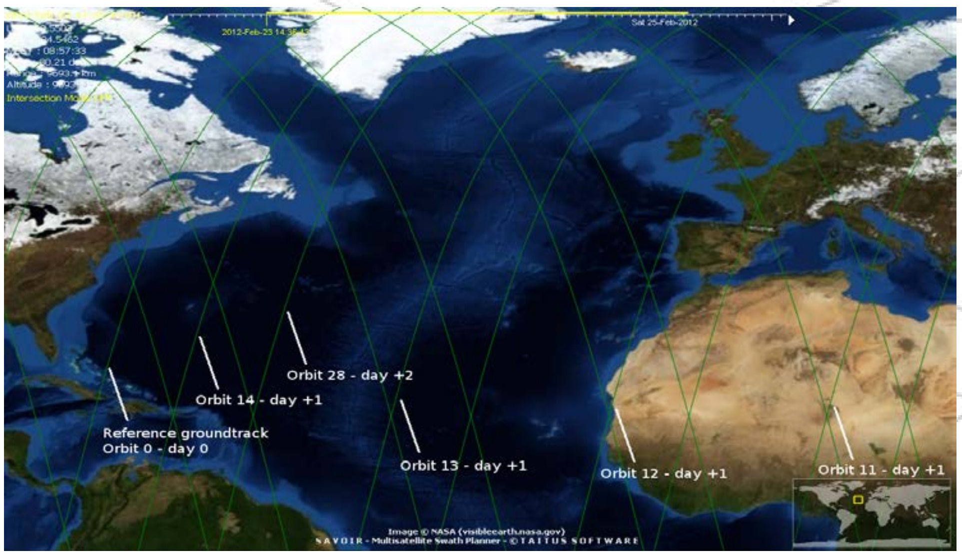
→ **For ENVISAT orbit :**

occurs when considering **East** propagating swell with periods ranging from **8 to 14 s.**

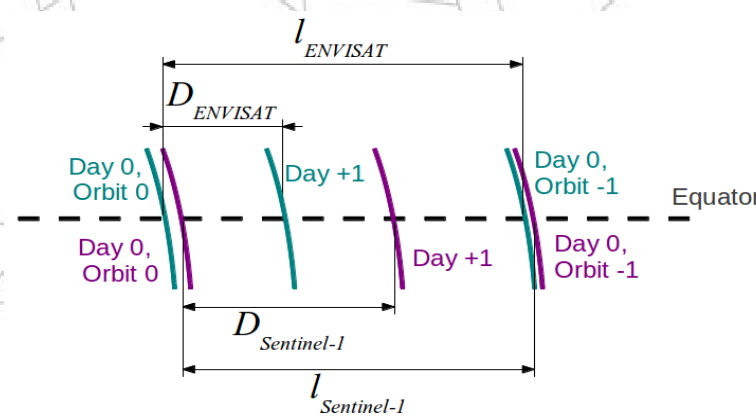
→ **For Sentinel-1 orbit :**

occurs when considering **West** propagating swell with periods ranging from **11 to 18 s.**

Near Stroboscopic conditions, swell is either imaged at **every repeat pass** or **never**



Envisat ground track

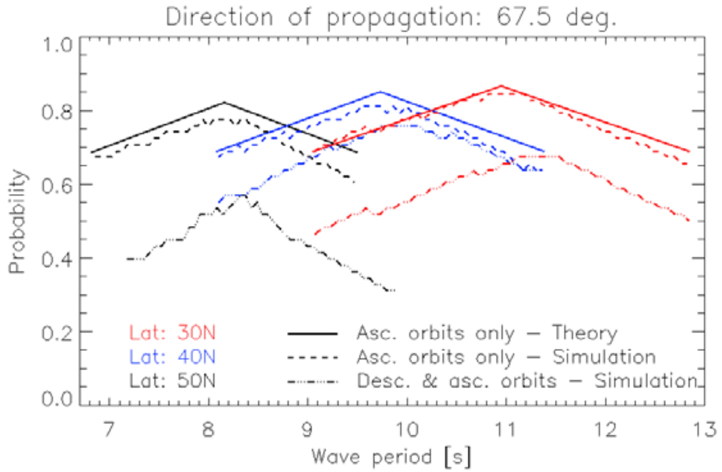


Ground track configurations comparison for ENVISAT and Sentinel-1

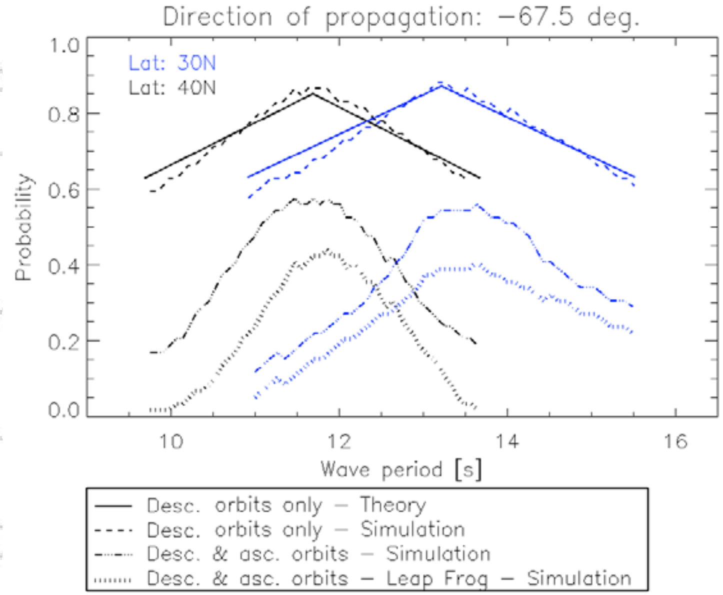
Stroboscopic Swell imaging

For a given satellite orbit, **Stroboscopic imaging conditions** are expressed in terms of the quadruplet :
- ascending *or* descending passes
- starting latitude
- wave propagation direction
- wave period

If last two conditions are very similar for same starting latitude & satellite pass
→ ascending & descending pass do not compensate



Envisat



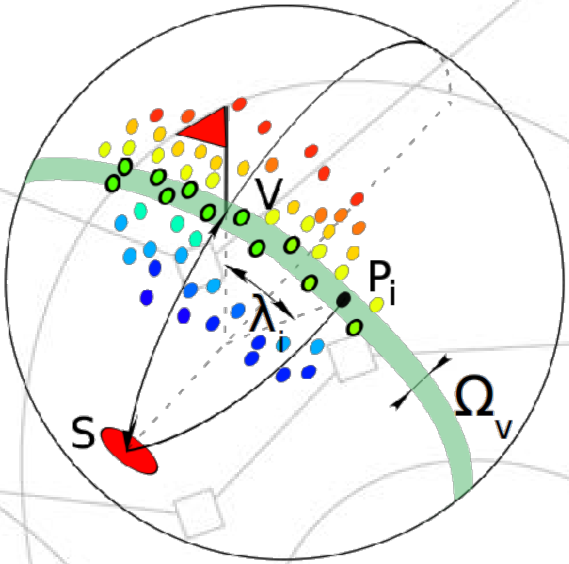
Sentinel-1

For given SI conditions, probability that a swell system is never imaged, wrt. wave period around SI wave period

For each swell field, significant swell height, H_{ss}, peak period, T_p, and peak direction, D_p, time series given by a virtual buoy are estimated at certain control points (buoys, arbitrary locations). E.g for period :

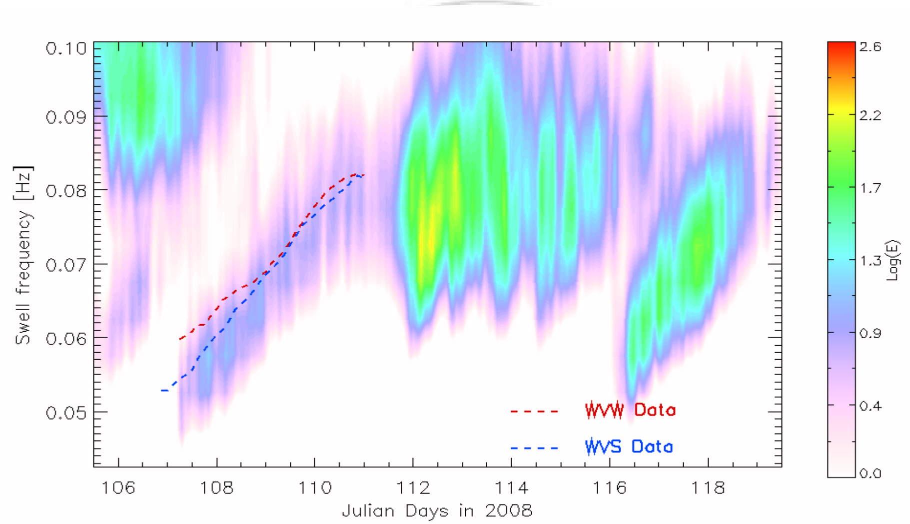
$$T^V(t_j) = \frac{\sum_{i,P_i \in \Omega_v} c_i(t_j)\, T_i(t_j)}{\sum_{i,P_i \in \Omega_v} c_i(t_j)}$$

$$c_i(t_j) = N_{0,\sigma_t^2}(t_{i_0} - t_j) + N_{0,\sigma_\lambda^2}(\lambda_i(t_j))$$



Weighted mean of the propagated observation in the virtual buoy vicinity. Weights, c_i, depend on:

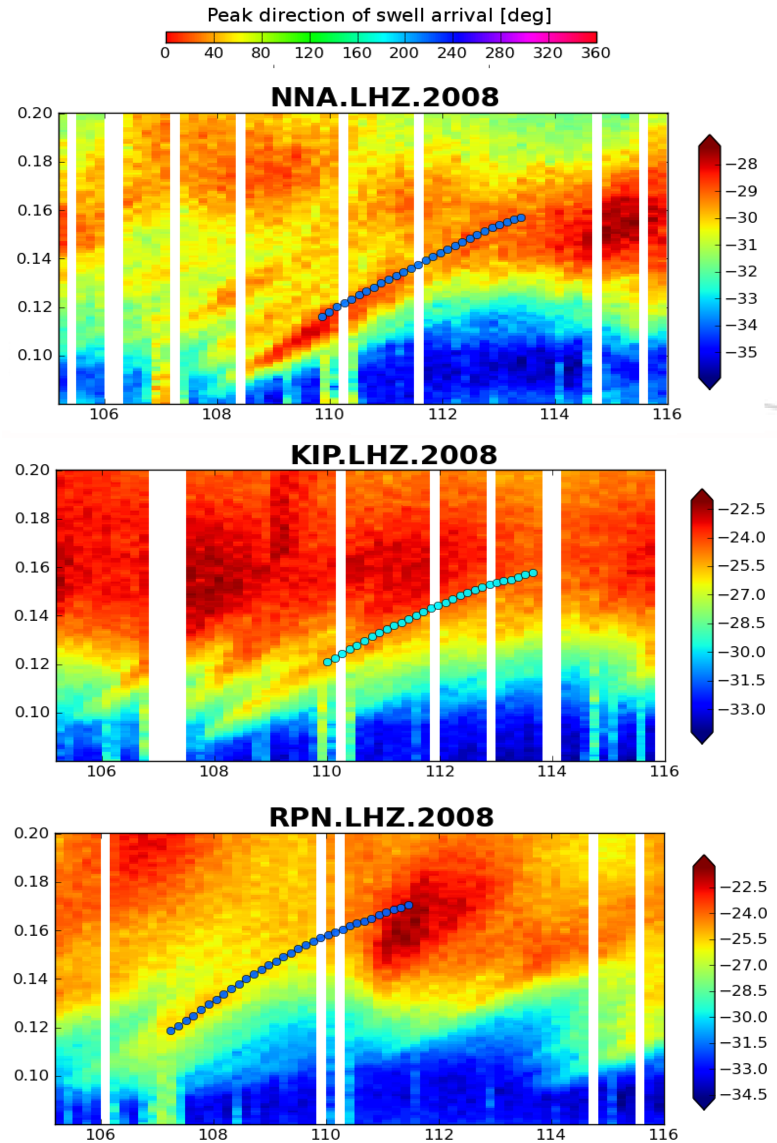
- the estrangement to the virtual buoy
- the time of propagation since observation



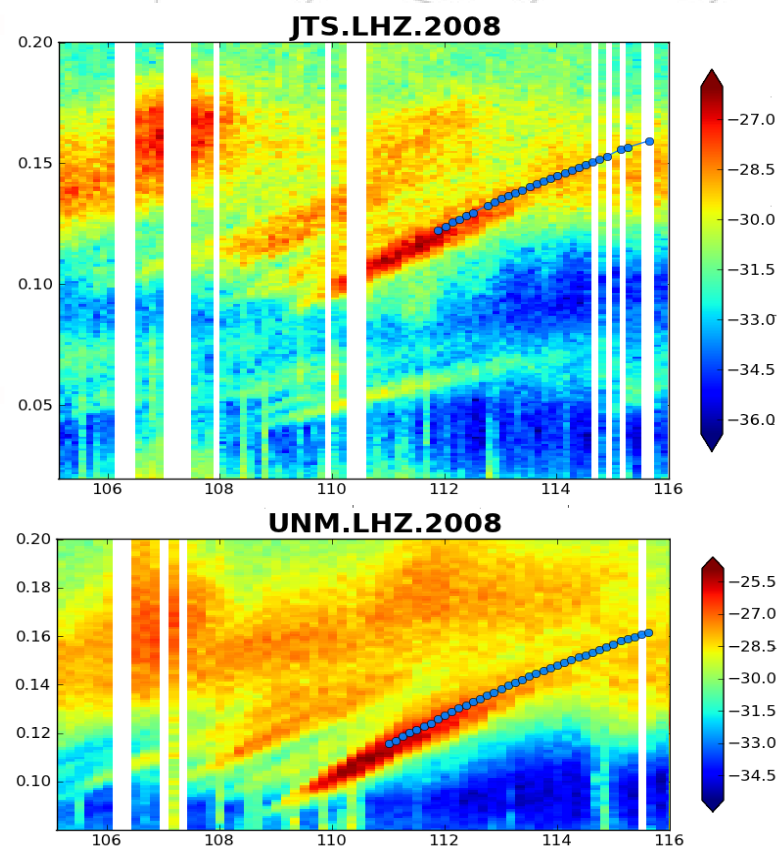
Swell arrival time as measured by the virtual buoy using Wave mode level 2 (red dashed line) and Wave mode level 1b (blue dashed line) over buoy spectrum (integrated over all direction.

→ Low frequencies are under-estimated

Virtual Buoy – Comparison with micro-seismic data at twice the frequency



- Virtual buoy and micro-seismic noise agree within their common frequency range
- Why is the very long swell signature absent from the wave mode Level 2 products?



Storm in South Pacific Ocean generated a very energetic swell field

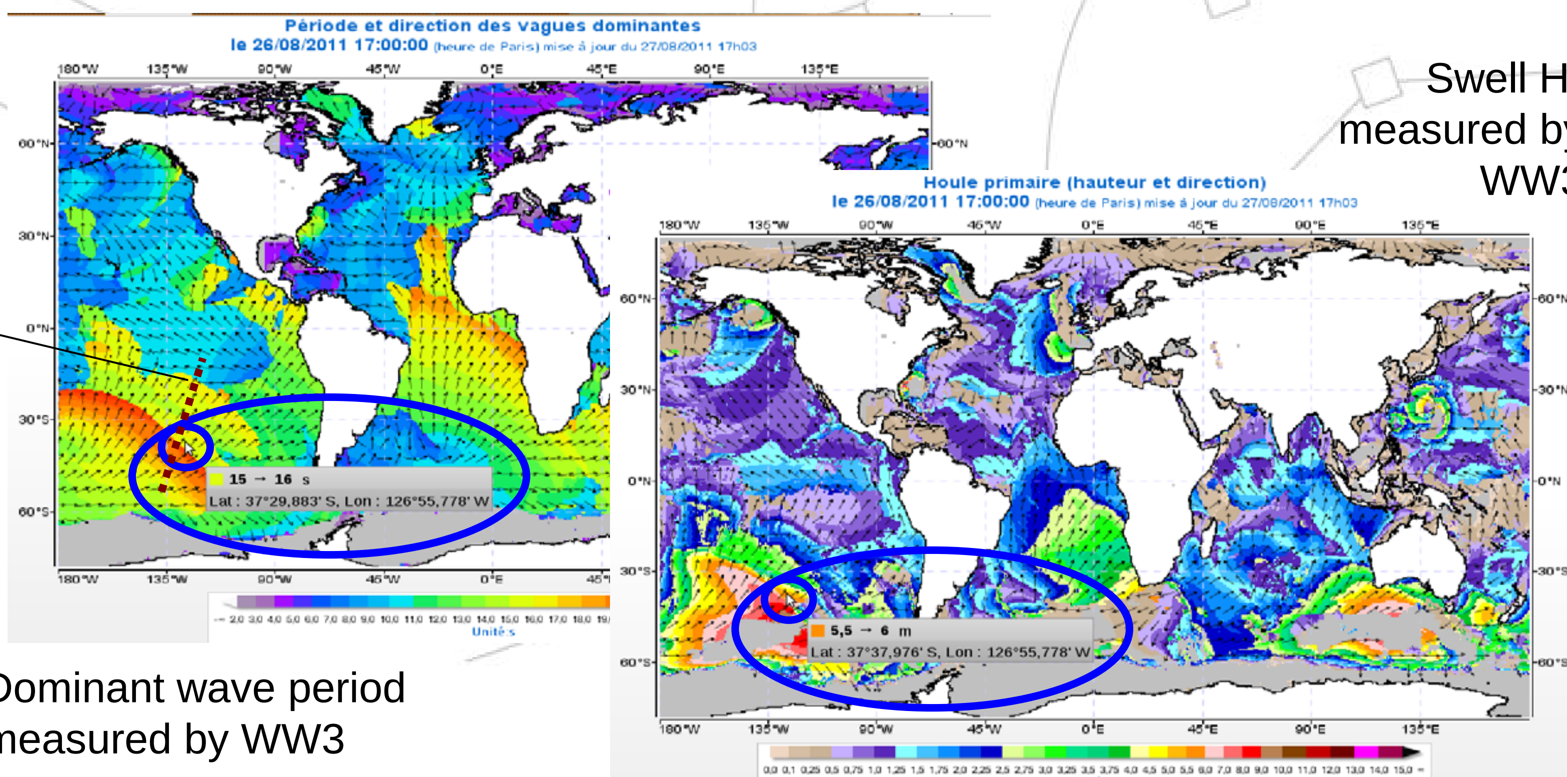
Maximum Total Hs above 15m as seen by WW3 - on 24th August 2011, SE of New Zealand

On 26th August, during a descending orbit, the SAR wave mode cuts through the swell field along its propagating direction

→ swell wavelength more than 950 meters long is detected (24.7 seconds)!

Wave mode sampling path

Swell H_s measured by WW3



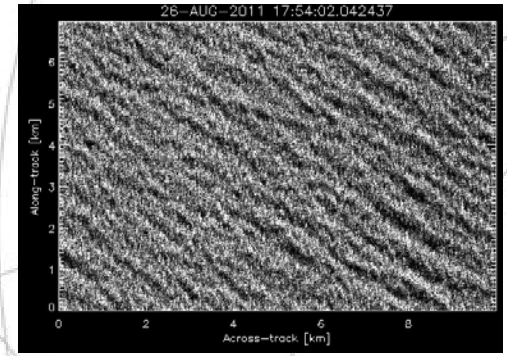
Dominant wave period measured by WW3

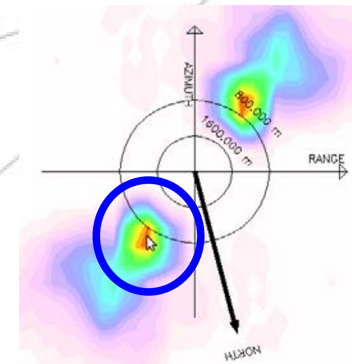
Virtual Buoy – Comparison with micro-seismic data at twice the frequency

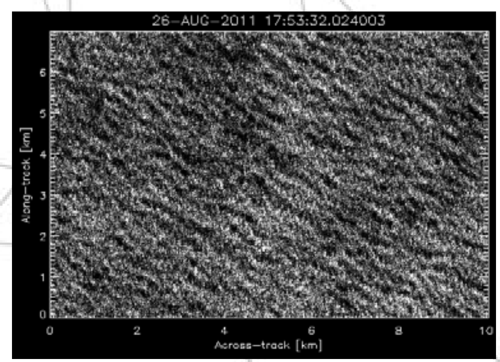
- Using ancillary data, e.g. micro-seismic noise or wave model, very long swell signatures can be searched in wave mode level 1 products at expected time and location.

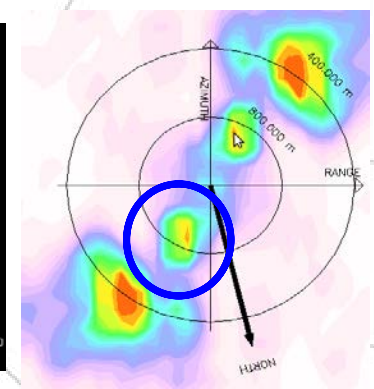
E.g :

- Storm in South Pacific Ocean
- Maximum Total Hs above 15m (WW3) on 24th August 2011, SE of New Zealand
- On 26th August, ENVISAT pass over the swell field with two imagettes :
  - peak wavelength > 700m (21.2 sec.)
  - peak wavelength > 950m (24.7 sec.)







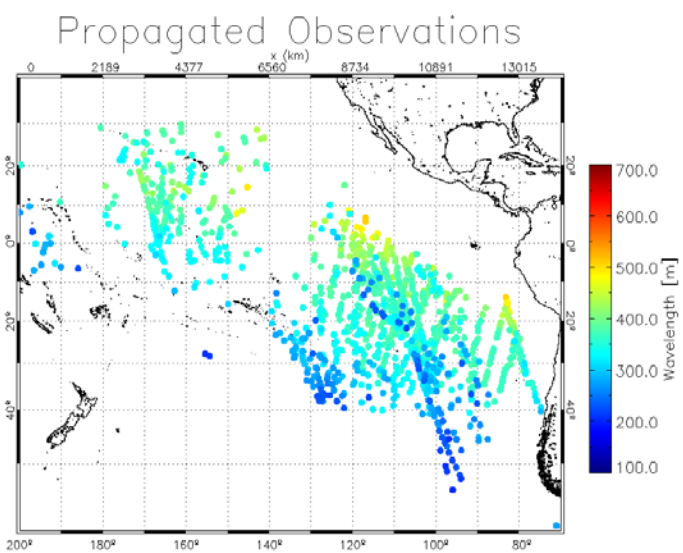


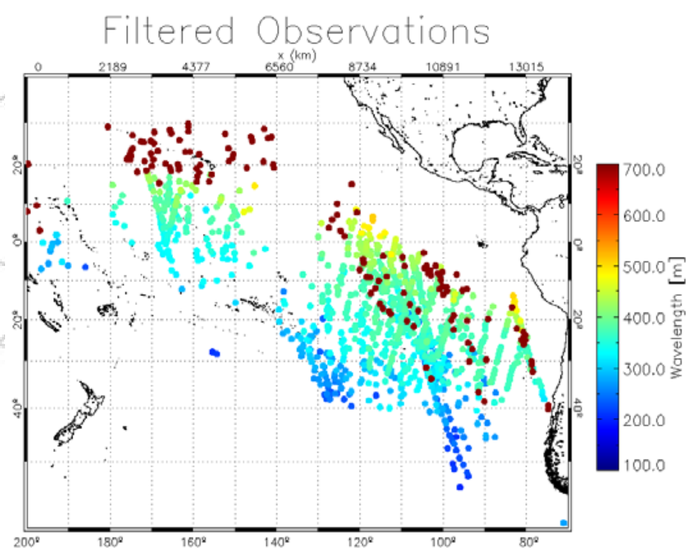
The Concept :

- From a reconstructed swell field given by the SAR analysis, combine the discrete and irregularly sampled swell information provided by the SAR propagated observations into a regularly sampled set over space and time.
- In average, a reconstructed swell field contains more than a thousand propagated observations
  → a smart selection and combination of the most accurate ones is necessary.

1. Inconsistent measurements are filtered out.

Swell observation that may belong to previously generated swell systems are not considered

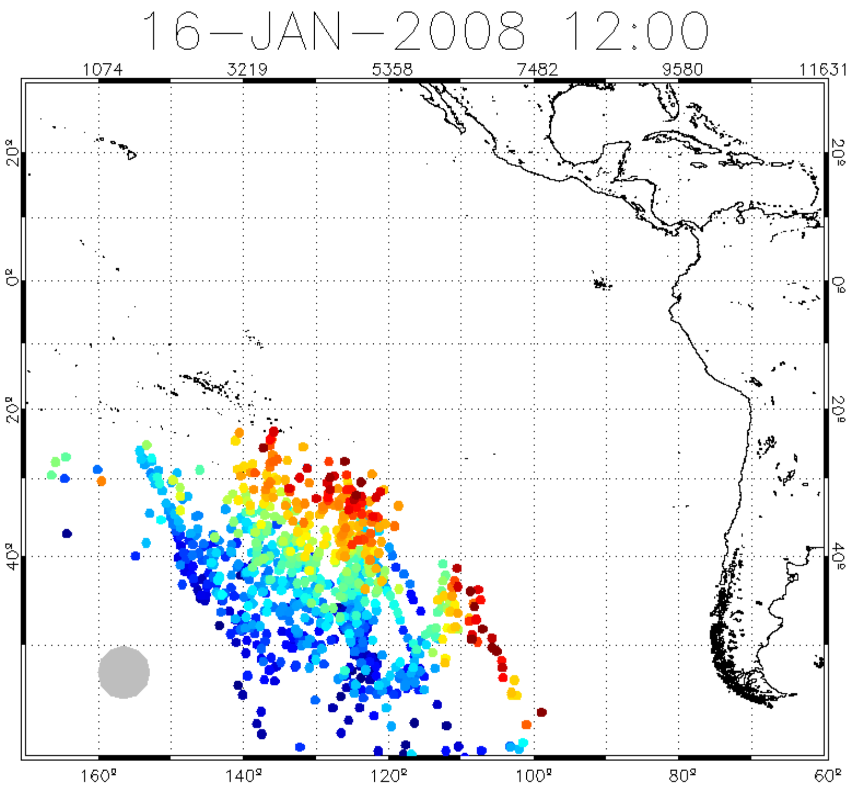


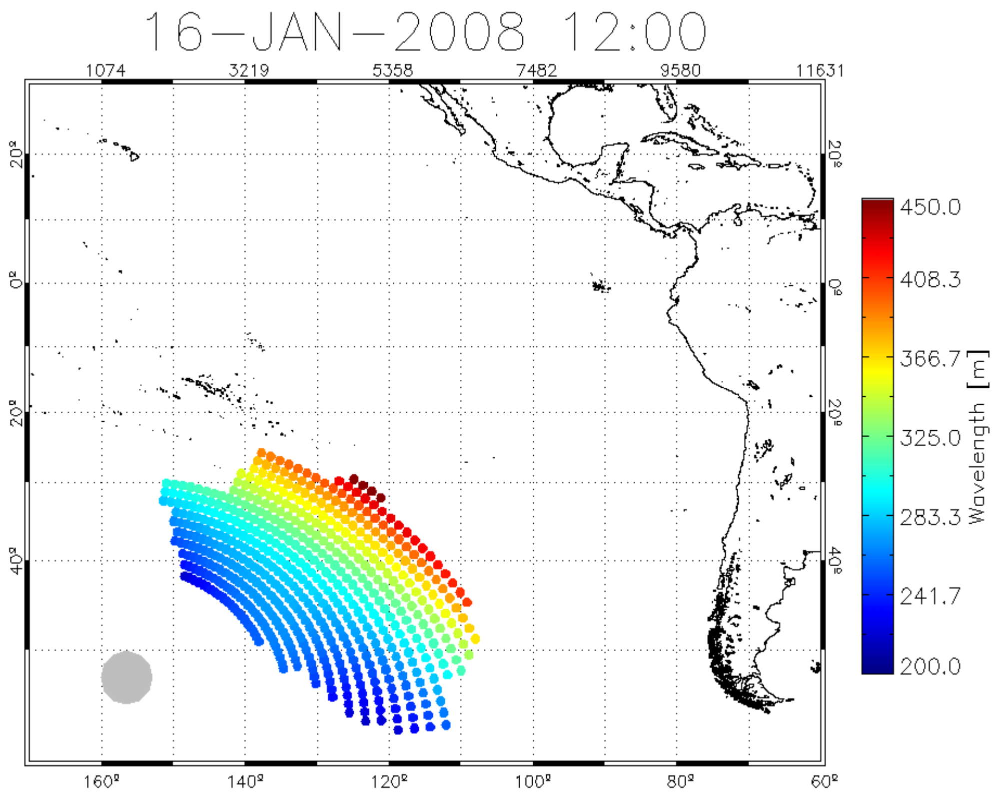


2. Surface fit

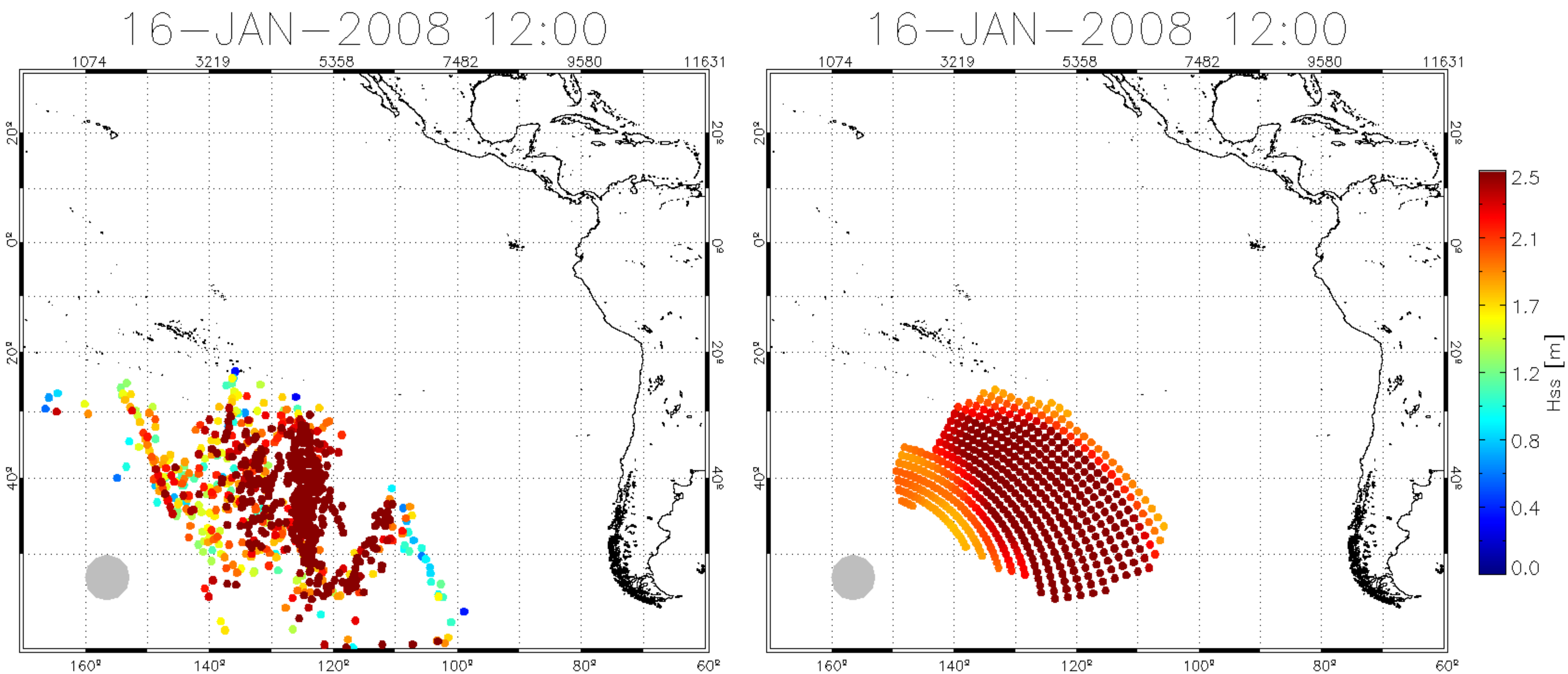
- We defined a radial axis (R, θ) with :
  - R and θ, distance and azimuth to storm source
- Different methods are explored :
  - polynomial regression → very fast and confidence in each swell observation can be taken into account (weight regression)
  - Kriging → slower but should better represent high variability (local estimator)
- For wavelength and propagation direction: data is already partly filtered by refocusing → polynomial regression
- For significant swell height, data is very noisy. Both methods are experimented
- Not considering data in island shadow for the moment

Synthetic Swell Field : Dominant wavelength





Synthetic Swell Field : significant swell height



3. Validation at directional waverider buoy

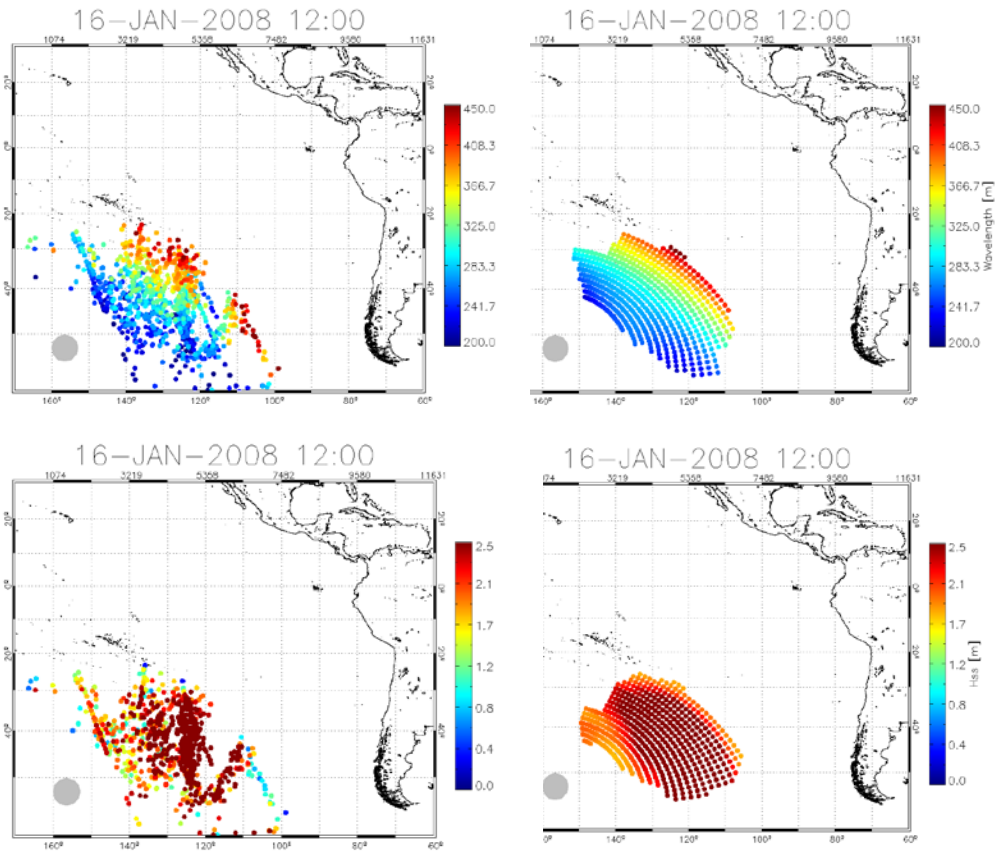
- For a given time, synthetic field integral parameters are compared to partitioned buoy spectrum
- Buoy partitions are associated to their corresponding synthetic field estimation.
- Accuracy depends on the propagated observations density. For densely imaged swell field :

	D_p [deg]	T_p [s]	H_{ss} [m]
RMSE	11.2	0.40	0.26
NRMSE		2.9%	20.4%
Bias	-2.8	-0.10	-0.02

- Should be compared with the accuracy obtained for individual Level 2 observations :

	D_p [deg]	T_p [s]	H_{ss} [m]
RMSE	16	0.70	0.31
NRMSE		5.1%	22.7%
Bias	2.6	-0.12	0.01

Perspectives



Swell evolution over large distance can provide a control over generation, diffraction and attenuation/dissipation processes to complement and improve the model physics (wave generation under extreme wind condition, wave-current interactions, air/sea fluxes, …)

Synthetic swell field can be assessed from only a few sparse opservations in space and time. -> Swell characterisation and forecast. Efficient assimilation

Swell systems are fingerprints of the most powerful ocean storms -> quantitative climate indicators and evolution trends if studied over ERS/ENVISAT 20 years archive