PERFORMANCE STATUS OF THE WAVE SCATTEROMETER SWIM

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1. INTRODUCTION

Oceanography greatly benefits from remote sensing satellites for global monitoring and forecast of the sea state. The CFOSAT (China France Oceanography SATellite) mission, whose launch is planned for 2014, should embark two radar payloads to monitor wind and waves over the ocean. One of this two radar instruments is called SWIM (Surface Waves Investigation and Monitoring). It is a Ku-band scatterometer designed to measure ocean waves based on the Jackson et al.'s concept [1,2]. These ocean wave spectra provide information on the distribution of wave energy (or wave height) with respect to wavelength and wave propagation direction.
The phase B (addressing preliminary design) of SWIM will end at the beginning of 2010. An important task to validate this design is a careful analysis of the instrument performances. A very precise analysis of the SWIM performances regarding the estimation of the required geophysical products (such as wave spectra, wave height, wind, etc.) shall be made. In this paper, we summarize all these performance results, as well as the methods which are used to get these analysis results.

2. SWIM INSTRUMENT

SWIM instrument is dedicated to three measurements: the backscattering coefficient from 0° to 10°, the significant wave height and wind speed (estimated from the nadir beam) and the wave directional spectra (with 6°, 8° and 10° beams).

2.1 Scientific requirements

Nadir measures	Wave spectra measures	Backscattering coefficient measures (all beams)
- Accuracy on SWH (Significant Wave Height) better than 10% or 50 cm (maximum), - Accuracy on wind speed about ± 2 m/s	- Resolution cell of 70 x 70 km² for wave spectra - Observable wavelengths of waves in [70m, 500m] - Azimuth resolution of wave : 15° - Accuracy in wave spectra level : 15% inside 3dB bandwidth - Accuracy in wavenumber : 15%	- Absolute accuracy of ±0.5 dB - Relative accuracy between beams ±0.1 dB

2.2 SWIM design

SWIM is a real aperture radar in Ku-band pointing sequentially at six different incidences (from 0° to 10°) with a constant azimuth scanning (see Figure below). The acquisition durations spent on each incidence angle are called the cycles. The global [0-10°] incidence coverage lasts a "macro cycle" of about 215 ms.
The cycle durations are chosen to reduce the registration errors. The characteristics of each beam are summarized in the following table and a detailed instrument description is available in [3].

	0°	2°	4°	6°	8°	10°
B_c (MHz)	320	320	320	320	320	320
PRF (Hz)	2125	2125	2125	6420-6750	6395-6720	6090-6405
N_{imp}	94	60	60	146	185	230
SNR (dB)	26.1	13.7	11.5	9.0	7.1	4.9

Table 1. Characteristics of the 6 beams.

2.3 SWIM measures

The signal received by SWIM is equal to [1,2,4]: $w(r) = \frac{P_e \lambda^2}{(4\pi)^3 R^4} \sigma^0 \iint G_{az}^2(\phi) G_{el}^2(\theta)(1+m(r)) d\theta d\phi$ (1)

with m(r) the modulation defined by: $m(r) = \frac{\int G_{az}^2(\phi) \frac{\delta\sigma}{\sigma} d\phi}{\int G_{az}^2(\phi) d\phi}$ (2)

For 6°, 8° and 10°, it can be shown that the modulation spectrum $P_m(k,\Phi)$, the Fourier transform of the autocorrelation function of m, is linearly proportional to the wave spectrum F(k, Φ) [1]: $P_m(k,\phi) = \frac{\sqrt{2\pi}}{L_y} \alpha^2(\theta) k^2 F(k,\phi)$ (3) with L_y the 3dB beam footprint and $\alpha(\theta) = \text{cotan}\theta - 4\tan\theta + \frac{2\tan\theta}{\nu\cos^2\theta}$, ν the slope variance. α is estimated by the nadir measure.

As explained in [4], with a time averaging over N_{imp} pulses and a range averaging over L_{dis} range bins, the spectrum density of w, P(k, Φ) is equal to: $P(k,\phi) = \delta(k) + R(k) P_m(k,\phi) + \frac{1}{N_{imp}} P_{sp}(k) + \frac{1}{N_{imp} L_{dis}} P_{th}(k)$ (4)

with P_{sp} the speckle spectrum ($P_{sp}(k) = \frac{\Delta x}{4\sqrt{\pi \ln 2}} R(k)$, Δx the ground horizontal resolution), P_{th} the thermal spectrum ($P_{th}(k) = \frac{1}{SNR^2}$) and R the impulse response (whose value is closed to 1). N_{imp} is defined in Tab. 1 and L_{dis} is chosen to get a ground resolution below 25 m (L_{dis}=6 here).

An associated standard deviation has been calculated assuming that the speckle and the thermal noises are Gamma distributed:

$$\sigma_{\hat{P}_m}(k) = \frac{1}{\sqrt{N_s L_k}} \sqrt{\frac{1}{N_{imp}^2} \frac{P_{sp}^2(k)}{R^2(k)} + \frac{2}{N_{imp}} \frac{P_{sp}(k) P_m(k)}{R(k)} + \frac{1}{N_{imp}^2 L_{dis}^2} \frac{P_b^2(k)}{R^2(k)}} \quad (5)$$

with an averaging in frequency domain over L_k wave number bins and over N_s modulation spectrums.

3. CONTRIBUTIONS TO PERFORMANCE RESULTS

The contributions to the performance (output of the instrument) are different for each kind of measures (backscattering coefficient, nadir and wave spectra).

The backscattering coefficient accuracy is firstly linked with the SNR: $\delta\sigma^0 = 10\log(1+K_p)$ and $K_p = \frac{1}{\sqrt{N}}(1+\frac{1}{SNR})$

The absolute accuracy depends then on the bias (fixed and random) of the emission and reception chain. Calibration paths have been implemented to determine as far as possible all these biases. The relative accuracy is linked to the components which are different for each incidence (switches and feed horns)

For the Nadir beam, accurate estimation of SWH and wind speed may require some atmospheric correction. As no radiometer is embarked on CFOSAT, the corrections should be performed by using global atmospheric models or observations from other radiometers (AMSU, etc.).

Wave spectrum depends on: the sea state, the SNR, the impulse response stability, the accuracy in ground projection (i.e. accuracy in the knowledge of the position on orbit and of the satellite attitudes) and the averaging parameters (L_{dis}, N_{imp}, L_k, N_s). It is important to underline that the sea state has a strong impact on the final accuracy (see eq. (5)).

4. TOOLS FOR PERFORMANCE ANALYSIS

4.1. Theoretical analysis for wave spectra measurement

Wave spectrum accuracy based on theoretical analysis is quantified through the calculation of two criteria indicated hereafter: an integrated criterion ΔE (relying on differences of energy) and a wavelength by wavelength criterion ε(k) (error computed for each wavenumber).

$$\varepsilon(k)=\frac{\overline{\sigma}_{\hat{P}_m}(k)}{P_m(k)} \quad \text{and} \quad \Delta E=\left|\frac{E}{E_{ref}}-1\right|=\frac{\int_{k_{\min}}^{k_{\max}}\frac{\overline{\sigma}_{\hat{P}_m}}{k}dk}{\int_{k_{\min}}^{k_{\max}}\frac{P_m}{k}dk} \quad \text{with} \quad E=\int_{k_{\min}}^{k_{\max}}\frac{\hat{P}_m(k,\phi)}{k}dk=\int_{k_{\min}}^{k_{\max}}\frac{P_m(k,\phi)+\overline{\sigma}_{\hat{P}_m}(k)}{k}dk \tag{7}$$

E_{ref} is computed with analytical shape of P_m. $\hat{P}_m$ is the estimated modulation spectrum. The computation of ΔE is made for a worthiest case, i.e. assuming that the estimation is equal to the reference spectrum P_m plus the standard deviation: $\hat{P}_m=\overline{\sigma}_{\hat{P}_m}+P_m$. The energy E criteria has been introduced in [4] to link the wave spectrum F with significant wave height: $\int F(k)kdk \propto H_s$ and $P_m \propto k^2F$. Therefore, the energy error refers to an error on the H_s estimation.

4.2 Simulations

4.2.1 Nadir beam simulations

An efficient simulator of nadir acquisition has been developed for all the altimetry missions (TOPEX, JASON, JASON-2, AltiKa/SARAL). It is partially reused here to quantify the estimation of the SWH and wind from nadir.

4.2.2 Wave beams simulations

Besides the theoretical analysis, an end-to-end simulator (i.e. from the surface modeling to the wave spectrum estimate), called SimuSWIM, has been developed based on [2]. Therefore, it enables to simulate the sensor parameters and geometry of observation, the signal acquisition, the on-board and on-ground processing. Details on this simulator can be found in [4].

Specific criteria are defined on the 2D wave spectra to quantify the quality of the estimation. The very first step is a partitioning one [5] to detect the main sea state.

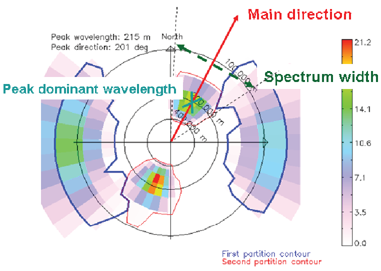

Figure 1. Geophysical parameters estimated on the 2D spectrum.

5. PERFORMANCE RESULTS

These results are preliminary. They will be updated for the final version of the paper with the very last results on SWIM design.

5.1 Performance based on analytical criteria

The scientific requirements over these criteria are ΔE ≤ 15% and ε ≤ 15% on the 3dB wavelength domain. This domain is defined like the wavelength or wavenumber interval where the modulation spectrum is higher than max(P_m)/2. Tab. 2 summarizes the compliance towards the requirements for seven sea states representing a wide range of condition.
Seven sea states (wind sea + swell) have been tested to check the compliance of SWIM design with satisfying results (Tab. 2). Only one considered sea state appears non fully compliant because the sea energy is very low in this case.

5.2 Performance based on simulations

Simulations have been performed to check the compliance of the SWIM design with the scientific requirements at nadir (Fig 2.) and for wave spectrum beams (Fig 3. and Tab. 3). For wave spectrum estimation, automatic detection of the sea states has been made and the errors on the estimated direction of propagation and on the estimated wavelength have been computed.

Sea states	Estimation error (ε) per k on the 3dB wavelength domain	Energy error (ΔE) on the 3dB wavelength domain
Scientific requirements	<15%	<15%
PM – U=13 m.s-1	~10-15 %	~10%
PM – U=10 m.s-1	~15-20 % (20% for k<0.06)	~15-20 %
Jonswap – U=13 m.s-1	~5 %	~5 %
Jonswap – U=10 m.s-1	~5 %	~5 %
Swell – U=13 m.s-1, Hs=4m	~10 %	~10 %
Swell – U=13 m.s-1, Hs=2m	~15 %	~15 %
Swell – U=5 m.s-1, Hs=1m	~20 %	~20 %

Table 2. Quality criteria for different sea states. Here, PM=Pierson Moskowitz (wind sea case). For swell, the wind speed is only used to compute the alpha parameter, there is no addition of sea wind at this stage.

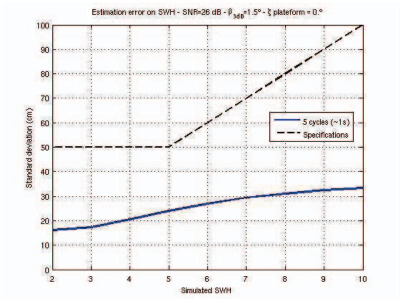

Figure 2. Simulated precision on SWH estimation from Nadir beam.

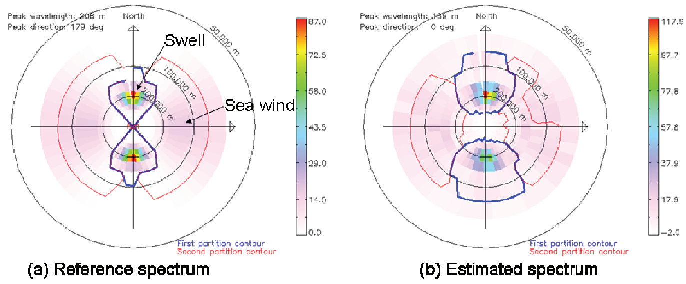

Figure 3. Simulated 2D spectra at 10°. Case of a mixed sea condition (U=13 m/s, Hs=4m): a swell propagating at 0° and a sea wind at 90° (Pierson-Moskowitz). *More cases will be run in the final version.*

	SWELL (Partition 1)		SEA WIND (Partition 2)	
	Propagation direction	Wavelength	Propagation direction	Wavelength
Reference	180°	204 m	89°	123 m
Estimation	180°	182 m	93°	126 m
Error	0%	10%	4°	9%

Table 3. Precision obtained on geophysical parameters estimated on the 2D spectra of Fig. 3

6. CONCLUSION

The design of SWIM defined during phase B is fully compliant with the scientific requirements. The difficulty of the characterization of wave spectra estimation is that it is linked with the sea state conditions. Therefore the requested accuracies are reached only for sea states which carry out enough energy. A lot of compromises have still to be made on the ground processing, e.g. on the filters and averaging method, to enhance the results. Nonetheless, the defined architecture promises a good characterization of the sea state conditions.

7. REFERENCES

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