DIRECTIONAL WAVE SPECTRUM ESTIMATION BY SWIM INSTRUMENT ON CFOSAT

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ABSTRACT

SWIM is a Ku-band radar designed for wave directional spectrum estimation. This radar operates at six incidence angles (from 0° to 10°) with a complete azimuth scanning. SWIM is currently in Phase B (concept and design phase). In [1,2], the preliminary design and associated performance analysis have been published taking into account the end of Phase A design. This paper is focused on the performance assessment of the SWIM instrument based on the new developments which occur during Phase B. In addition, major reviews have been carried out on the performance analysis.

Index Terms— Wave spectrum, radar, SWIM, end-to-end simulation, performance, CFOSAT

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 2013, 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 [3].

SWIM, a follow-on concept of VagSAT and SWIMSAT payloads [4], aims at measuring directional ocean wave spectra at a scale of about 70 x 70 km² on a 180 km wide swath. These ocean wave spectra provide information on the distribution of wave energy (or wave height) with respect to wavelength and wave propagation direction. These features are of main interests for ocean wave monitoring and forecast. The selected sun synchronous orbit (characterized by an altitude of 514 km and a 13 days cycle) ensures a nearly full coverage of the oceans.

Section 2 proposes a high level description of SWIM system. The readers can refer to [5] for further details. Section 3 is dedicated to performance analysis. The performance analysis is carried out based on both simulation and theory approaches. In each field, improvements have been made to better model and understand the physics of the instrument measurement. In this paper, the emphasis is put on the wave spectrum estimation provided by the incidences 6°, 8° and 10°.

2. SWIM CONCEPT

2.1. System description

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 218 ms.

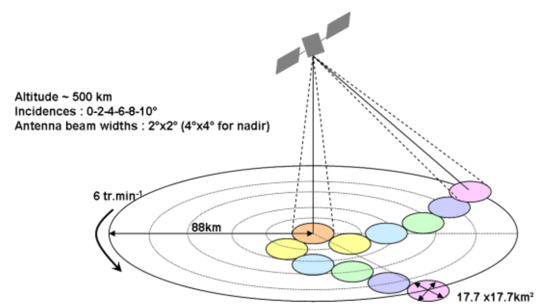

Figure 1. SWIM instrument

SWIM instrument is dedicated to three measurements:

- backscattering coefficient from 0° to 10°,
- significant wave height and wind speed (estimated from the nadir beam),
- wave directional spectra (with 6°, 8° and 10° beams).

The transmitted signal is a chirp, i.e. modulated linearly in frequency, with a 320 MHz bandwidth. For each received beam, the data are compressed in range to reach a range resolution of 47cm.

Due to satellite advection and antenna rotation, the beam footprint is moving during acquisition time (migrations) [3]. The N_{imp} pulses acquired during each cycle are averaged in order to reduce speckle and thermal noise. But the migrations induce range variations from one pulse to the other for the same surface spot. This implies that a

registration has to be performed, so that a good overlap of the echoes is guaranteed between the beginning and the end of each cycle.
For data downlink constraints, the averaging has to be performed on-board and, as a consequence, the registration as well. The registration algorithm is based on chirp scaling [6].
The cycle durations are chosen to reduce the registration errors. The characteristics of each beam are summarized in the following table.

	0°	2°	4°	6°	8°	10°
Integration time (ms)	45	30	30	22.7	30.2	37.8
Bc (MHz)	320	320	320	320	320	320
PRF (Hz)	2000	4000	4000	6637.4	6611.4	6297.8
N_{imp}	90	120	120	145	185	230
SNR (dB)	26.1	13.7	11.5	9.0	7.1	4.9

Table 1. Characteristics of the 6 beams.

For each beam, the PRF (Pulse Repetition Frequency) is selected in order to maximize the number of independent echoes with some constraints, like the duty cycle of the microwave tube or the chronogram.

2.2. Instrument description

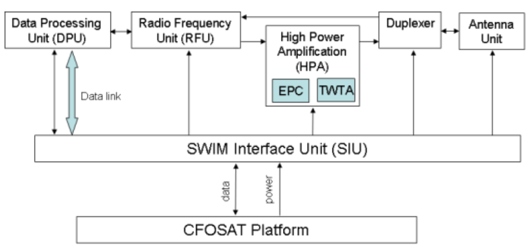

Figure 2. SWIM architecture overview

Fig. 2 summarizes the SWIM architecture. The antenna is a 90cm diameter parabola in offset configuration illuminated by 6 feed horns allowing a 0° to 10° incidence coverage. These sources are on a rotated plate in order to scan all possible azimuth angles. A more detailed instrument description is available in [5].

2.3. SWIM measures

The signal received by SWIM is equal to [3,4]:

$$w(r) = \frac{P_e \lambda^2}{(4\pi)^3 R^4} \sigma^0 \iint G_{az}^2(\phi) G_{el}^2(\theta)(1+m(r)) d\theta d\phi \quad (1)$$

with m(r) the modulation defined by:

$$m(r) = \frac{\int G_{az}^2(\phi) \frac{\delta\sigma}{\sigma} d\phi}{\int G_{az}^2(\phi) d\phi} \quad (2)$$

In addition, speckle (multiplicative noise) and thermal noise (additive) has to be taken into account in eq. (1), which leads to estimation of random variables.

For 6°, 8° and 10°, it can be shown that the modulation spectrum $P_m(k,\Phi)=|FT(m)|^2$ is linearly proportional to the wave spectrum $F(k, \Phi)$:

$$P_m(k,\phi) = \frac{\sqrt{2\pi}}{L_y} \alpha^2(\theta) k^2 F(k,\phi) \quad (3)$$

with $\alpha(\theta) = \text{cotan}\,\theta - 4\tan\theta + \frac{2\tan\theta}{\nu\cos^2\theta}$, ν the slope variance, L_y the 3dB beam footprint.
Therefore, the SWIM measure w enables well to retrieve the wave spectrum. The inversion method of w to P_m is explained in [4].

3. SWIM PERFORMANCE

SWIM design has to be analyzed with respect to the scientific requirements. Analyses are conducted based on theory and on simulations. The useful SWIM parameters are summarized in Tab. 1.

3.1. Theoretical analysis of the wave estimation accuracy

3.1.1 Analytical expression of estimated Pm

From eq (1) and (2) and 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 :

$$P(k,\phi) = \delta(k) + R(k) P_m(k,\phi) + \frac{1}{N_{imp}} P_{sp}(k) + \frac{1}{N_{imp} L_{dis}} P_{th}(k) \quad (4)$$

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).
Until now, the thermal spectrum has been neglected [1,3,4]. Yet, thermal noise is a random noise, classically assumed as a Gamma distributed noise. When processing w to estimate P_m, the average thermal noise value is subtracted. But, as it is a random noise, some contributions remain. The mean random noise is now zero mean but the standard deviation is still the same. A Gamma distributed noise has a standard deviation equal to its mean divided by the averaging factor ($N_{imp}L_{dis}$ here). As a result, the estimated spectrum should include a thermal spectrum P_{th}.

3.1.2 Standard deviation of estimated Pm

Eq. 4 provides a mean value. An associated standard deviation has been calculated assuming that the speckle and the thermal noises are Gamma distributed. With the central limit theorem, it can be shown that P is distributed with a non centered Chi-2 law because P is the sum of independent non centered Gaussian distributions. As a result, the standard deviation of P_m is equal to:

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

The standard deviation is the sum of a speckle contribution, a thermal contribution and a cross modulation-speckle contribution.

In order, to reduce this standard deviation an averaging in frequency domain is performed: over L_k wave number bins and over N_s modulation spectrums. As a result, the final standard deviation is:

$$\bar{\sigma}_{\hat{P}_m}(k) = \frac{1}{\sqrt{N_s L_k}}\sigma_{\hat{P}_m}(k) \quad (6)$$

Regarding antenna rotation speed and required azimuth resolution of 15°, N_s =2. L_k is adapted to each k to get a wavelength resolution better than 10%.

3.1.3 Quality criteria

Wave spectrum accuracy 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).

$$\varepsilon(k) = \frac{\bar{\sigma}_{\hat{P}_m}(k)}{P_m(k)}$$

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

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: $\hat{P}_m = \bar{\sigma}_{\hat{P}_m} + P_m$.

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 $P_m \propto k^2 F$. Therefore, the energy error refers to an error on the H_s estimation.

The scientific requirements over these criteria are ΔE ≤ 20% 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. This interval is plotted in Fig. 3 (b) by the black dashed lines.

Sea states	Estimation error (ε) on the 3dB wavelength domain	Energy error (ΔE) on the 3dB wavelength domain
Scientific requirements	< 15%	<20%
PM – U=13 m.s^{-1}	< 15%	< 20%
PM – U=10 m.s^{-1}	< 15%	<20%
Jonswap – U=13 m.s^{-1}	<<15%	<< 20 %
Jonswap – U=10 m.s^{-1}	<<15%	<< 20 %
Swell – U=13 m.s^{-1} Hs=4m	<<15%	<< 20 %
Swell – U=13 m.s^{-1} Hs=2m	<15%	<< 20 %
Swell – U=5 m.s^{-1} Hs=1m	NOK (<20%)	< 20 %

Table 2. Quality criteria for different sea states

Fig. 3 illustrates the both criteria for a sea wind case. Seven sea states (sea wind + swell) have been tested to check the compliance of SWIM design with satisfying results (see table below). Only one considered sea state appears non fully compliant because the sea energy is very low in this case.

3.2. Simulation tool

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 [4]. Therefore, it enables to simulate the sensor parameters and geometry of observation, the signal acquisition, the on-board and on-ground processing.

The sea surface is generated from an analytical form of the wave spectra. The received power is computed taking into account this sea surface (slopes and heights) and the sensor geometry. The received energy is integrated over each range cell using a GO approximation model.

Of course, SimuSWIM enables to test all the incidence angles and all the azimuth orientations to get a 2D spectrum. Fig. 4 and 5 present some results obtained with this simulator. We have reached similar conclusions than with the analysis based on theory. Current work aims at defining an automatic partitioning method to get the main wave spectrum features (Fig. 5).

4. CONCLUSION

SWIM is currently under Phase B developments. Performance analyses, based on theory and simulations, are conducted to check whether the proposed design is compliant with scientific requirements or not. The first results lead to an overall validation of the concept. Now iterative analyses based on simulations are performed to optimize specific parameters of the design (e.g. side lobes level of the impulse response or pointing accuracy of the platform).

5. REFERENCES

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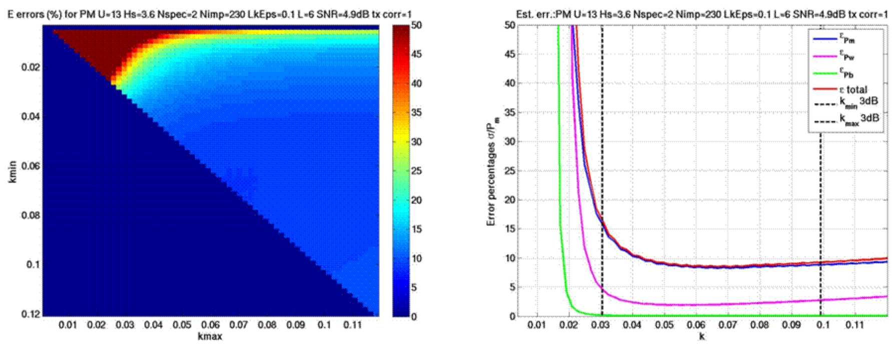
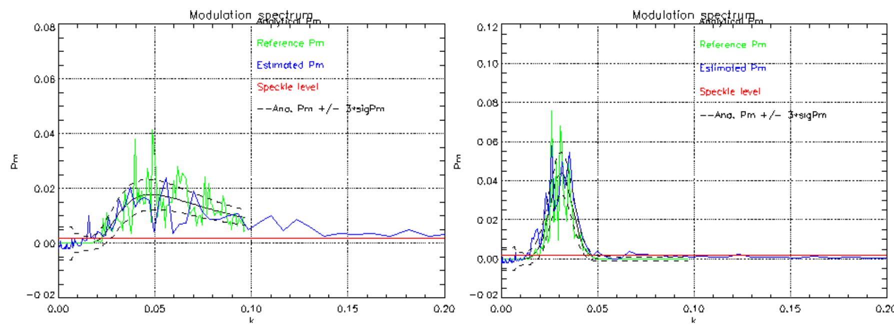


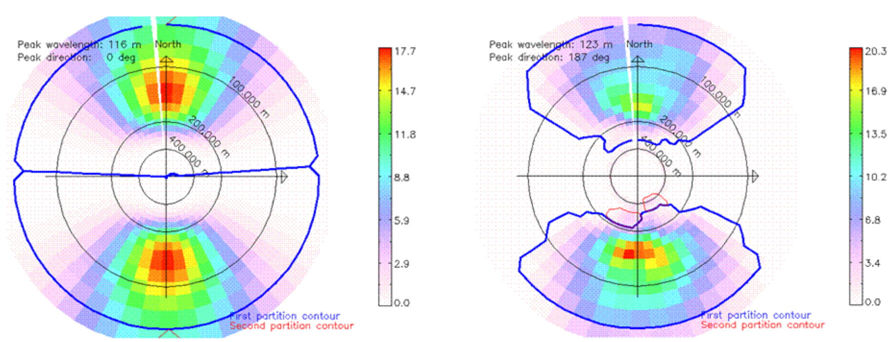
(a) ΔE for every (k_{min},k_{max}) value (b) ε

Figure 3. Analytical quality criteria for a sea wind cases (U=13 m.s^{-1} – Pierson-Moskowitz model). The computation has been performed for the Phase B design of SWIM.



(a) Sea wind (Pierson-Moskowitz) U=13 m.s^{-1} (b) Swell Hs=2m

Figure 4. Simulations of estimated modulation spectrum (blue lines) for a sea wind (left) and a swell case (right). The solid black line is the analytical form of the wave spectrums used to generate the sea surface. The dashed blue lines are the standard deviation (at 3 sigma) associated to the analytical form). The green curves are the reference spectra(obtained by a bandpass of the sea surface by the beam footprint. The oscillations of the green curves are Gibbs effect due to the way of simulating the sea surface and not due to physical phenomena. The blue solid line corresponds to the spectra obtained after inversion.



(a) Reference 2D wave spectrum (b) Estimated 2D wave spectrum

Figure 5. Simulated 2D wave spectra for Pierson-Moskowitz model (U=13 m.s^{-1}) after inversion (right) compared to the analytical reference (left). The blue curves are the result of the automatic partitioning. The resulting peak wavelength and peak direction are noted on the figure (left top). 180° ambiguity in direction is not removed in the example.