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He Wang*[a], Jing Wang[b], Biao Zhang[c], Jianhua Zhu[a]
[a] National Ocean Technology Center, Ministry of Natural Resources, Tianjin 300112, China;
[b] Shanghai Lizheng Satellite Application Technology Co., Ltd, Shanghai 201100, China;
[c] School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China.

ABSTRACT

In 2016, the first Chinese synthetic aperture radar (SAR), the Gaofen-3 (GF-3) satellite, was launched. Unlike the single-polarized wave mode SARs in Europe, GF-3 is the first satellite acquiring the quad-polarized SAR data in wave mode configuration, which could benefit the ocean wave estimation. Here, the ocean wave spectra estimation from quad-polarized GF-3 wave mode is presented and its performances are evaluated. For the period from January to October in 2017, the ocean wave spectra were inverted from GF-3 wave mode data. The quad-polarized SAR-ocean spectra inversion scheme was utilized, in which the azimuthal and range wave slopes are obtained from the vertically and linearly polarized normalized radar cross sections and then converted to ocean wave slope spectra. The validation was also performed through comparisons against directional wave buoy observations. The spatio-temporal criteria of 100 km and 0.5 h, yield 87 match-ups. Two representative cases illustrate the consistency between the GF-3 SAR ocean wave spectra and buoy measurements. Statistical assessment shows the root mean square error (RMSE) of 0.35 m, 19.52 m and 24.89 ° for the significant wave height, peak wavelength and wave direction, respectively. Evaluation results indicate that the quad-polarized algorithm is suitable for spectral ocean wave estimation from GF-3 wave mode, and encouraging for operational implementation.

Keywords: Gaofen-3, synthetic aperture radar, quad-polarization, ocean wave spectra, buoy, assessment

1. INTRODUCTION

Ocean surface wave is one of the most important ocean properties. The spectral ocean wave measurements, based on which integral wave parameters of wave height, wavelength, and propagating wave direction could be derived, are valuable for various areas, e.g., navigation, ocean engineering, ocean modelling assimilation and climate assessment. For decades, the space-borne synthetic aperture radars (SARs) have demonstrated the capability to provide ocean wave spectra at a fine spatial resolution under all weather conditions [1]. Especially, the so-called wave mode, adopted by European SARs aboard ERS-1/2, Envisat, and Sentinel-1A/B, can offer spectral ocean swells in open ocean at a global scale since 1990s [2].

On 10 August 2016, the first Chinese C-band (~5.3 GHz) multi-polarization SAR, the Gaofen-3 (GF-3) satellite, was successfully launched by the China Academy of Space Technology. Up to now, primary investigations of oceanic parameters retrieval from GF-3 SAR data have been documented, indicating the promising operational applications of the GF-3 SAR mission for ocean wind and waves [3][4].

Similar to European SARs, amongst the 12 imaging modes, wave mode is also available on the Chinese GF-3 SAR for wave monitoring over global seas. Additionally, unlike the single-polarized wave mode SARs in Europe, GF-3 is the first satellite acquiring the SAR data in wave mode configuration in the quad-polarization (VV+HH+VH+HV). It has been proven that the significant wave height estimation could be improved by including the quad-polarization information from GF-3 wave mode SAR imagery [4]. Besides, the quad-polarized SAR could also benefit the ocean wave spectra inversion by avoiding the complex hydrodynamic modulation transfer function, which has been theoretically derived and learnt from the experience of RADARSAT-2 data (though not operating in wave mode) [5][6]. So far, very few studies has been reported regarding the quad-polarized ocean spectra retrieval from GF-3 wave mode, and the corresponding validation work rely only on the modelling reanalysis [7]. In this context, the objective of this paper is to assess the ocean wave spectra estimation from quad-polarized GF-3 wave mode against buoy spectral *in situ*.

* wanghe_sio@126.com; phone 86 22 2753-6513; fax 86 22 2753-6516

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2. DATA SETS

2.1 GF-3 SAR data

In this study, the Level-1A GF-3 WM data, single look complex (SLC) images, from January to October 2017 were used. The wave mode is dedicated to observing ocean surface waves over open ocean. In this operating configuration, GF-3 SAR sensor collects small images with an approximate size of 5 km × 5 km every 50 km along the orbit with resolution of about 4 m. Different from the single-polarized wave mode on ERS-1/2 SAR, Envisat ASAR, and Sentinel-1A/B, GF-3 wave mode can acquire imagettes in quad-polarization. More details on the GF-3 wave mode configuration could be found in literatures [3][4].

2.2 Buoy measurements

Reference data used here are *in situ* directional wave measurements from buoy networks of National Data Buoy Centre (NDBC) and Coastal Data Information Program (CDIP). The directional ocean wave spectra were reconstructed from the buoy measurements of frequency spectra and the 4 first directional distribution moments using the Maximum Entropy Method (MEM), which is admitted to be the most accurate estimation method for buoy directional spectra [8].

For the validation purpose, the GF-3 wave mode data and the buoy *in situ* were collocated in time and space. The spatial interval was limited to less than 100 km. And the maximum time difference between SAR and buoy measurements is 30 min. This spatio-temporal criterion yields 87 match-ups as shown in Fig. 1.

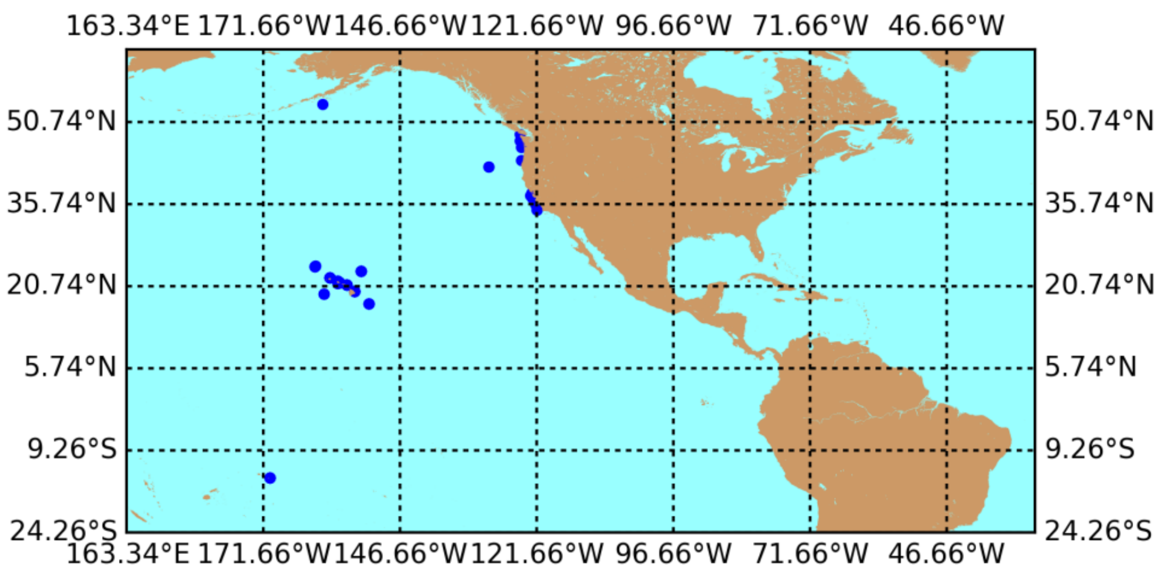

Figure 1. Locations of GF-3 wave mode data co-located with buoys.

3. METHODOLOGY OF OCEAN WAVE SPECTRA RETRIEVAL

The ocean wave spectra inversion method applied to the GF-3 wave mode is as follows.

(1) Linearly polarized radar cross section computation.

Firstly, the normalized radar cross-sections (NRCS) of GF-3 wave mode data are obtained in co-polarization (HH, VV) and cross-polarization (HV) channels using the calibration formula provided by the official GF-3 data manual. Note that the GF-3 radiometric calibration constants are from the ocean-based re-calibration [9], instead of the officially released. After speckle denoising by the refined Lee filtering, the co (σ_{hh} and σ_{vv}) and cross (σ_{vv}) -polarized NRCS are then used to compute the linearly polarized backscatter cross section (σ_p), using the following expression proposed by [6]:

$$\sigma_p = \frac{1}{4}(\sigma_{hh} + \sigma_{vv}) \cdot [1 + \cos^2(2\varphi)] + \frac{1}{2}(\sigma_{hh} - \sigma_{vv}) \cos(2\varphi) + \sigma_{hv} + \frac{1}{2}\Re(\sigma_{hhvv})\sin^2(2\varphi) \tag{1}$$

where $\Re(\sigma_{hhvv})$ denotes the correlation between NRCS at horizontal and vertical polarizations, and the polarization orientation angle φ is set to be 45° here.

(2) Ocean wave slopes inversion.

In the azimuth direction, the vertically and linearly polarized NRCSs are used to estimate the azimuthal wave slope image $\frac{\partial \xi}{\partial x}$:

$$\frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} - \frac{\Delta\sigma_{hh}}{\bar{\sigma}_{hh}} = -\frac{8\tan\theta}{1+tan^2\theta}\frac{\partial \xi}{\partial x} \tag{2}$$

where θ represents the radar incident angle.

In the range direction, the corresponding wave slopes $\frac{\partial \xi}{\partial y}$ are obtained from the horizontally and vertically polarized NRCS and azimuthal wave slopes obtained, according to the derivations from [6]:

$$\frac{\Delta\sigma_{\varphi\varphi}}{\bar{\sigma}_{\varphi\varphi}} - \frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} = A\frac{\partial \xi}{\partial x} + B\frac{\partial \xi}{\partial y} \tag{3}$$

where A and B are coefficients derived from the modulation transfer functions as given by [5]. Both ocean surface slopes in each direction are smoothed using 3×3 Gaussian filter.

(3) Ocean wave slope spectra estimation.

Fast Fourier transform is performed to convert the ocean wave slopes to the ocean wave slope spectra in azimuth and range directions respectively, which are finally combined in azimuth and range directions to generate the ocean wave slope spectra as a whole. Additionally, we make use of cross spectral technique to resolve the 180° ambiguities in the wave propagation direction[10].

(4) Ocean wave integral parameters calculation.

The peak wavelength λ and wave propagating direction ϑ are estimation from the peak of the ambiguity-free ocean wave slopes. In terms of significant wave height H_s, the following relationship with the root mean square slopes S_{rms} is used:

$$\tan(S_{rms}) = H_s/(\lambda/2) \tag{4}$$

And the root mean square slopes is obtained from wave slopes by

$$S_{rms} = [(S_a \sin\vartheta)^2 + (S_r \cos\vartheta)^2]^{1/2} \tag{5}$$

where S_a and S_r are the wave slopes in the azimuth and range directions, respectively.

4. VALIDATONS AGAINST BUOYS

4.1 Case studies

We first present two representative cases selected from the GF-3 SAR and directional wave buoy co-locations.

Quick-look images in the channels of VV, HH and 45° linearly polarization (see equation 1) of the first example for the GF-3 wave mode data acquired in the west coast of North America at 02:15:52 UTC on 1 February 2017 are shown in Fig. 2 (a), (b) and (c), respectively. From the inverted ocean wave slope images in azimuth direction and range direction using equations 2 and 3 as shown in Fig. 2(d) and (e), respectively, the wave slope spectrum estimate is given in Fig. 2(f), representing swells with wavelength of 277.80 m (or wave period of 13.33 s) and significant wave height of 2.96 m propagating towards southeast (125.15°). As reference, the nearby buoy station (#46239) reported the consistent swells *in* *situ* (significant wave height: 3.55 m, peak wavelength : 277.57 m, wave period: 13.35 s, and wave propagating direction: 117°) at 02:25 UTC on the same day, with the two-dimensional ocean wave spectrum in line with the SAR retrieval shown in Fig. 2(g).

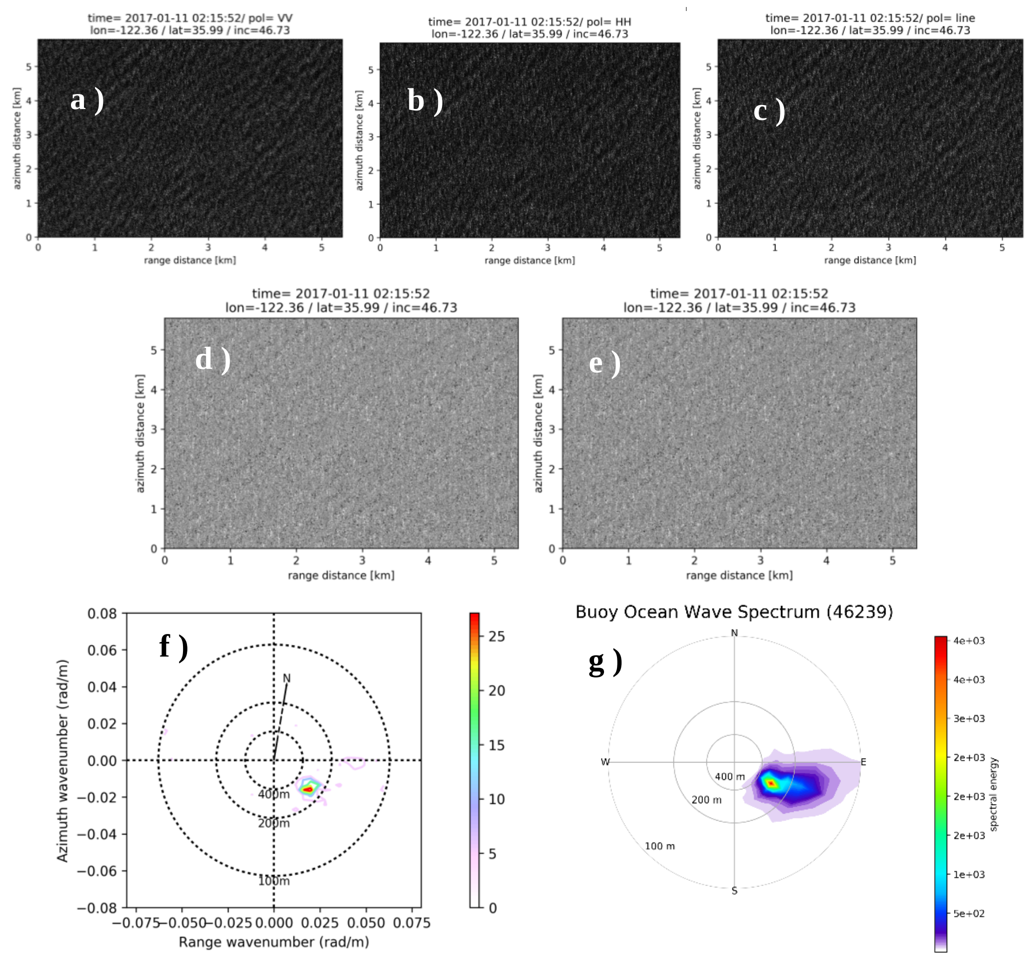

Figure 2. Case of GF-3 wave mode data acquired in the west coast of North America at 02:15:52 UTC on 1 February 2017 co-located with the buoy # 46239, showing (a) VV , (b) HH and (c) 45° linearly polarized GF-3 SAR image, ocean wave slope images in azimuth direction(d) and range direction(e), wave slope spectrum retrieval (f) and buoy directional ocean wave spectrum observation (g).

Another demonstration could be found in Fig. 3 for the ocean wave spectral retrievals from GF-3 SAR data and co-located *in situ* from buoy #51206 acquired near Hawaiian Islands on 1 February 2017. The comparison shows good agreement in terms of significant wave height (SAR: 2.86 m versus buoy: 3.32 m), peak wavelength (SAR: 321 m versus buoy: 318 m) and wave direction (SAR: 184.66° versus buoy: 174°). Note that although the azimuthal cut-off effect could be slightly found in the SAR inverted ocean wave slope spectrum presenting in Fig. 3 (f), the underestimation of SAR derived wave height is only 0.46 m or 13 % relative to *in situ*.

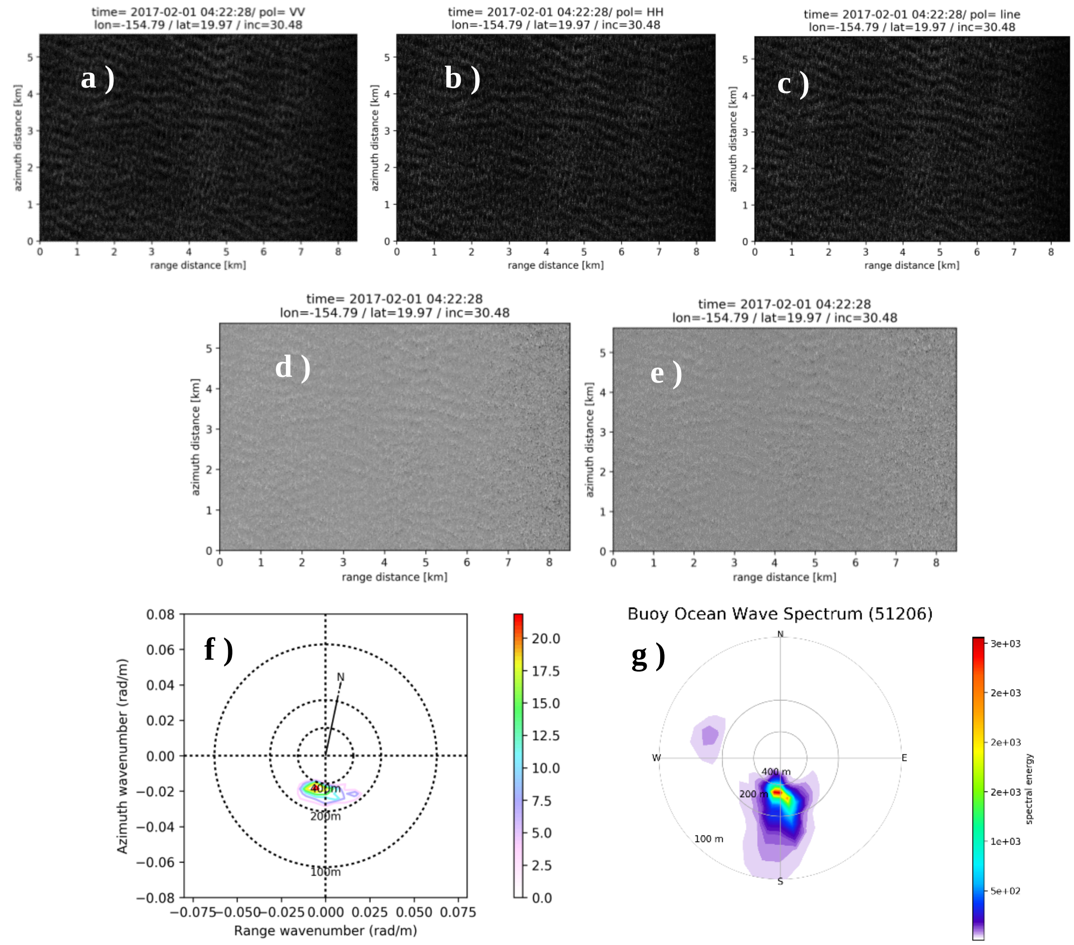

Figure 3. As in Fig. 2, but for the case of GF-3 wave mode SAR image acquired near Hawaiian Islands at 04:22:28 on 1 February 2017 co-located with the buoy # 51206.

4.2 Statistical analysis

Fig. 4 shows the general statistics for the comparison of GF-3 SAR quad-polarized retrievals against buoy *in situ* regarding the integral ocean wave parameters. The assessment for all the 87 match-ups provides the root mean square error (RMSE) of 0.35 m, 19.52 m and 24.89 ° in terms of the significant wave height, peak wavelength and peak wave direction derived from the ocean wave spectra, respectively. Results indicate that the quad-polarized algorithm is suitable for spectral ocean wave estimation from GF-3 wave mode, and encouraging for operational implementation.

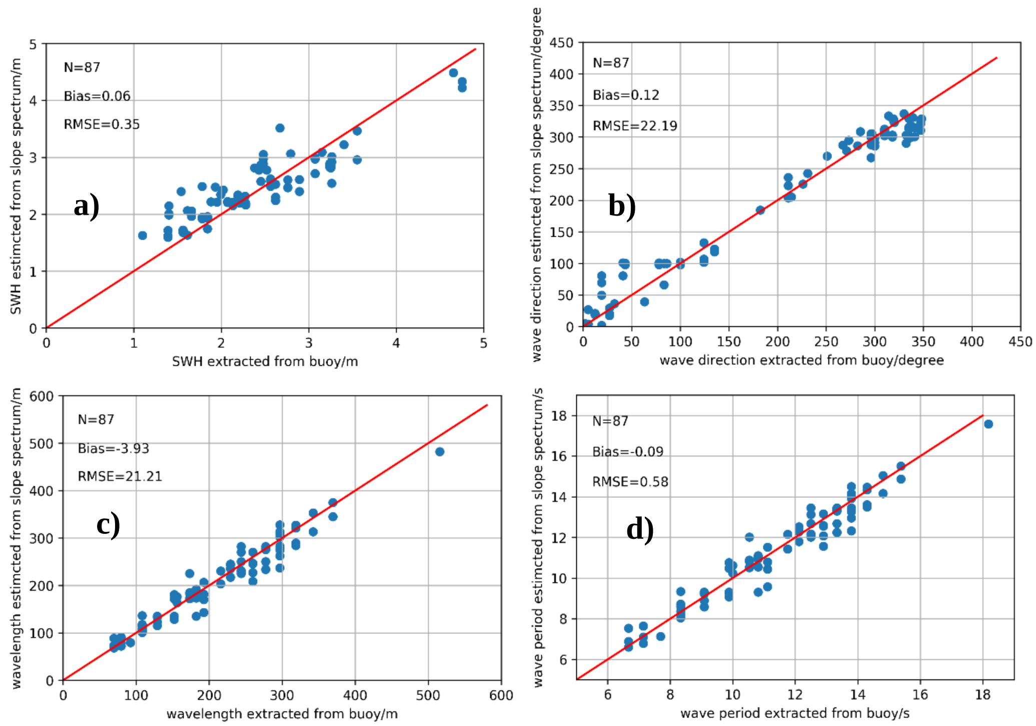

Figure 4. The scatter plots of wave height (a), wave propagating direction (b), wavelength (c) and wave period (d) retrieved from the quad-polarized GF-3 SAR wave mode images against the co-located buoy measurements.

5. CONCLUSIONS

The C-band Chinese GF-3 SAR equipped with wave mode configuration can provide information on ocean waves in open ocean at a global scale. In this paper, we applied a strategy of combination of quad-polarized retrieval algorithm and cross-spectral technique to estimate the ocean wave spectra from the GF-3 SAR images in wave mode, taking advantage of the quad-polarization capability of the Chinese SAR sensor. The assessment of the ocean wave spectral retrieval is carried out through the comparison between GF-3 wave mode SAR and directional buoy *in situ* within the spatio-temporal criteria of 100 km and 0.5 h. Two cases illustrate the good agreement between the GF-3 SAR ocean wave spectra and buoy observations. Statistical analysis also provides the RMSE of 0.35 m, 19.52 m and 24.89 ° regarding the significant wave height, peak wavelength and wave direction, respectively. The preliminary results in this study demonstrate that the quad-polarized ocean wave spectral inversion scheme proposed here is suitable for GF-3 wave mode SAR images for operational implementation in the future.

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