Retrieval of Ocean Wave Parameters Using Envisat Advanced Synthetic Aperture Radar Data and Its Verification Analysis

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Abstract. Based on MPI iterative retrieve algorithm, we retrieve the 2-D (two-dimensional) ocean wave spectrum by using Envisat ASAR wave mode Single Look Complex (SLC) imageries. The first guess spectrum is a necessary input item to run this MPI algorithm. In this paper, the first guess spectrum was calculated with reanalyzing wind data of ECMWF (European Centre for Medium-Range Weather Forecasts) and NCEP (National Centers for Environmental Prediction) as input wind stress of WAM Model. The Significant Wave Heights (SWHs) retrieved from the first guess spectrum as well as the best fit spectrum corresponding to ECMWF and NCEP wind field respectively are compared with the measurement data from buoys all over the world ocean. The comparison shows that the SWHs retrieved by ECMWF wind are less than field measurement buoy data in general, while the SWHs retrieved by NCEP wind are greater than those buoy data, but the mean SWHs of them fit with the field buoy data are better than whichever pro. However, the MPI algorithm makes the retrieved SWHs more accurate in comparison with the first guess spectrum derived from either ECMWF or NCEP wind field. Moreover, the relative error of the MPI method is improved by ~12 percent with respect to the first guess spectrum.

1. Introduction

As an important phenomenon in ocean, ocean wave has great influence on the coast, ocean engineering and the human activities in the sea and shore [1]. Traditionally, the observation of ocean wave is only for a single point or local small area which have less observation points, high cost, and small observation area and is easily affected by weather. SAR is a kind of active microwave imaging radar which is capable of getting image of ocean wave with all-time, all-weather and high solution. Those characteristics make it possible to extract wave information on a large scale [2-3].

The information of ocean wave is the common ocean phenomena which is reflected on SAR image. By modulating effects (including the tilt modulation, hydrodynamic modulation and nonlinear velocity bunching modulation) of the long wave with respect to short wave (Bragg wave), it changes the distribution of microwave backscatter field in SAR image and forms the texture information with alternating light and dark [3-6]. The texture information is the basis for the retrieval of 2-D wave directional spectrum. The retrieval of wave spectrum by using SAR is actually to solve two problems. One is to compensate the nonlinear effect of SAR imaging. The other is to solve the 180° direction fuzzy problem of wave spectrum which is caused by SAR imaging retrieval and gives the determined direction of wave propagation [7]. The MPI algorithm is proposed by Hasselmanns in 1991. This algorithm takes the third generation wave model—WAM’s result as the first guess spectrum [8-10]. It
not only provides the propagation direction information of ocean wave, eliminates the propagation direction 180° fuzzy of SAR image spectrum but also compensates the wave information that is above the wave spectrum’s cutoff wavenumber [9]. This paper applied the ECMWF wind field [11] and NCEP wind field [12] to drive WAM model for getting the first guess spectrum. Then it used ENVISAT ASAR wave mode SLC products to retrieve 2-D ocean wave spectrum. Meanwhile, by comparing the retrieved significant wave height with the buoy data respectively, we find that there is a better agreement between significant wave height data retrieved from MPI algorithm and the buoy data.

ENVISAT ASAR [10] has once a time of observation every 100km along the satellite path, it can provide approximately 2500 small SAR images of the global ocean every day. From March in 2002 when it was launched to April in 2012 when it lost contact with earth, it has accumulated data for 10 years which creates conditions of studying for distribution of the spatial and temporal characteristics of particular parts of the ocean waves.

2. Data Introduction
Wave mode data of Envisat ASAR can provide continuous information of global wave. Polarization of ASAR wave mode include HH and VV. There are mainly three types of products when the incident angle is between 15~45 degree. Level one data WVI (ASA_WVI_1P) is SLC products and cross spectrum products, and WVS (ASA_WVS_1P) is cross spectrum products of image, level two data WWW (ASA_WWV_2P) is ocean wave spectrum products. In this paper, we used Envisat ASAR wave mode level one data WVI SLC products of China sea from January 2003 to May 2004 and global ocean area from 2009 to 2012.

MPI iterative algorithms require the input of SAR image spectrum. Wave mode data of ERS-1/2 SAR directly provides image spectrum products UWA and MPI can be directly input. But wave mode data of Envisat ASAR no longer provides UWA products, so it is necessary to generate SAR image spectrum from SLC products. Azimuth resolution and range resolution of Envisat ASAR wave mode SLC are 4.00m and 21.24m respectively. Firstly, it is necessary to generate an intensity image with equivalent resolution in azimuth and range when it is used. In this paper, we took the average in azimuth and did difference operation in range, then obtained intensity image with its resolution resampled to 12.5m. After that, the Fourier transform was applied to obtain the complex spectrum. The value of the real spectrum is square of absolute value of the complex spectrum, the spectrum obtained is under Cartesian coordinates. To get image under the polar coordinates, the polar coordinates transformation should be carried out.

In this paper two groups of wind field data were used to run WAM model:
One group of wind field data is ERA40 Reanalysis data which is obtained from ECMWF. The spatial resolution is 1x1 degree and the time interval is 6 hours.
Another group is NCEP/DOE AMIP-II Reanalysis-2 reanalysis data which is obtained from NCEP. The spatial resolution is 1.875x1.875 degree and the time interval is 6 hours.

Because WAM mode supports wind field data with 0.5 degree x 0.5 degree of spatial resolution, time series for 1 hours. Hence it is necessary to have time and spatial interpolation for the downloaded wind field data.
Terrain data required to run WAM is global terrain data-Terrain Base Global Land Elevation and Ocean Depth (tbase), its spatial resolution is 5°.
The buoy data used to the verification analysis obtained from National Data Buoy Center (NDBC) of American National Oceanic and Atmospheric Administration (NOAA) which is observed every hour.

3. MPI Method
SAR is not to image the ocean wave directly, it can only be interacted with the surface gravity waves or capillary waves. The modulation of surface short gravity wave by ocean wave is responsible for measuring wave information by SAR. This modulation effect shows wave information like patterns of
light and dark in SAR image. Directional wave spectrum can be retrieved from SAR images. In 1991, Hasselmanns derived the nonlinear transformation relationship from the directional wave spectrum to SAR image spectrum, and proposed the MPI retrieval algorithm to obtain the best fit wave spectrum by iterative method at the same time. MPI retrieval method flow chart is shown in figure 1.

The core framework of the MPI algorithm is the iterative process which needs SAR image spectrum and the first spectrum as the input items. Then to modify the wave spectrum during the iterative process to make the simulated SAR image spectrum form the first guess spectrum by nonlinear transform as far as possible close to the observed SAR image spectrum. Defines the value function $J(\hat{F})$, the best fit directional wave spectrum will be obtained when taking the minimum $J$.

$$J = \int |P(k) - \hat{P}(k)|^2 dk + \mu \int \frac{|F(k) - \hat{F}(k)|^2}{[B + \hat{F}(k)]} dk$$

(1)

$\hat{P}(k)$ is the observed SAR spectrum. $P(k)$ is the best simulated SAR image spectrum. $\hat{F}(k)$ is the first guess spectrum obtained from WAM. $F(k)$ is the retrieved best fit spectrum.

![Figure 1. MPI retrieval method.](image)

4. Results and Analysis

4.1. Retrieval Results

Figure 2 shows an example of retrieved results corresponding to ECMWF wind field. Figure 3 is the retrieved results under the same conditions (the same ASAR image, same time and space) except the wind field was supported by NCEP compared with figure 2. Left-upper is SAR image, right-upper is SAR image spectrum, left-bottom is the first guess spectrum of WAM, right-bottom is the retrieved best fit wave directional spectrum. All these are expressed in two-dimensional wave number spectrum in polar coordinates.

We can find that the guess spectrum obtained from different wind fields from WAM mode have obviously differences. The MPI retrieval method depends deeply on the first guess spectrum by comparing figure 2 with figure 3. And SAR image also plays an important role in inversion.

4.2. Analysis of Verification

In order to determine the errors between first guess spectrum that got from WAM model driven by different wind field and buoy data, and the error between wave direction spectrum retrieved using ASAR data and buoy data. We used the significant wave height data measured by field buoys to confirm and analyze them respectively. The data matching principle is space distance less than 100 km, and the time gap is less than half an hour. Then 54 groups of space-time matched data are found. Figure 4 gives the position relationship between the buoy data and the ASAR data.
Figure 2. The retrieval result corresponding to ECMWF wind field.

Figure 3. The retrieval result corresponding to NCEP wind field.

Figure 4. The contrast figure of ASAR data point and buoy data point.

Figure 5 is the comparison of two groups wind field corresponding to guess spectrum and retrieval of optimal wave directional spectrum significant wave height with the field wave data respectively. We can find that retrieved results corresponding to ECMWF wind field are small, retrieved results corresponding to NCEP wind field are large. If so, compare the average value of these two groups’ retrieved results with the field wave height data, as shown in figure 6, both the deviation (-0.03) and the mean variance (0.71) compared with figures 5b and 5d are obviously improved.

The conclusion can be obtained by analyzing the parameters value of figures 5a-5d and 6 (see table 1) respectively:

1. Retrieved results are influenced obviously by the first guess spectrum. For the ECMWF wind field: the SWHs of first guess spectrum (figure 5a) are smaller than the buoy data (bias=-0.09) overall, then the retrieved results (figure 5b) are also smaller (bias=-0.07). For the NCEP wind field: the SWHs of first guess spectrum (figure 5c) are larger than the buoy data (bias=0.07), then the retrieved results (figure 5d) are also larger (bias=0.06).

2. The retrieved results’ bias and mean square error (RMSE) are smaller than the bias and mean square error of the first guess spectrum. The retrieved results were significantly improved compared with guess spectrum. Overall, the retrieved results of using ECMWF wind data were better than that using NCEP wind data.

3. To compare the mean data of the retrieved results obtained by using ECMWF and NCEP wind data with the buoy data. There is bias value 0.03<0.07, 0.03<0.06, and mean variance value 0.71<0.86, 0.71<0.95. Therefore, the average of the two retrieved results will be closer to the buoy data than the retrieved results of any single wind field. This result can be used as a reference in application.
Figure 5. (a) The scatterplots between the significant wave height of the first guess spectrum based on ECMWF wind field and buoy data; (b) the scatter plots between the significant wave height of the best fit wave spectrum based on ECMWF wind field and buoy data; (c) the scatter plots between the significant wave height of the first guess spectrum based on NCEP wind field and buoy data; (f) the scatter plots between the significant wave height of the best fit wave spectrum based on NCEP wind field and buoy data.

Figure 6. The scatter plots between the mean of the retrieved results based on different wind field and buoy data.

Table 1. The parameters of each scatterplots.

| Figure | Corrcoef | Bias (/m) | RMSE |
|--------|----------|-----------|------|
| Figure 5a | 0.93 | -0.09 | 0.98 |
| Figure 5b | 0.94 | -0.07 | 0.86 |
| Figure 5d | 0.89 | 0.07 | 1.03 |
| Figure 5d | 0.91 | 0.06 | 0.95 |
| Figure 6 | 0.94 | -0.03 | 0.71 |
For 54 pairs of paired data, corresponding to the ECMWF wind field: the relative error between the SWH data of the first guess spectrum and the buoy data value, the relative error between the SWH data of the retrieved wave spectrum and the buoy data value, and corresponding to the NCEP wind field: the relative error between the SWH data of the first guess spectrum and buoy data value, the relative error between the SWH data of the retrieved wave spectrum and the buoy data value, are respectively obtained. And the relative error between the mean SWH data of the two retrieved spectrum and the buoy data value are also obtained. All the results are shown in table 2.

Table 2. The relative errors of every results with buoy data.

|        | Guess spectrum—buoy data | MPI—buoy data | Average value—buoy data |
|--------|--------------------------|---------------|--------------------------|
| ECMWF  | 10.6%                    | 9.4%          |                          |
| NCEP   | 11.7%                    | 10.3%         | 8.7%                     |

From each value in table 2, it is indicated that the relative error between the SWH data of MPI inversion and the buoy data is improved by about 12% compared with that of the guess spectrum. Compared with the retrieved results of each group, the mean value of the SWH data of the two groups improved significantly in terms of relative errors relative to buoy data, which increased by 7% compared with the result that used ECMWF wind field to driven WAM model and increased by 15.5% relative to NCEP wind field.

5. Conclusion
To analyze the retrieved SWH results based on the MPI method with the buoy data. We find the retrieved SWH data are smaller than the buoy data generally when we use the ECMWF wind field to driven the WAM to get the first guess spectrum. The retrieved SWH data are larger than the buoy data generally when we use the NCEP wind field to driven the WAM to get the first guess spectrum. But the mean data of those two retrieved SWH data are in better agreement with the buoy data than any of them. The reason for this result may be due to the spatial resolution of ECMWF wind field is 1 degree and the spatial resolution of NCEP wind field is 1.875 degrees. Moreover, the comparation between retrieved results with respect to wind fields and results of guess spectrum shows that retrieved wave parameters of MPI method depends partly on the accuracy of the first guess spectrum. Next we can try to integrate these two wind fields and then drive WAM again to obtain the needed first guess spectrum. Then compare the retrieved results based on MPI method under this new guess spectrum with buoy data.

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