Swell parameters retrieval using ALOS/PALSAR data and its application

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Abstract. We have developed retrieval methods for swell parameters such as wave height, wavelength, and wave propagation direction from images of PALSAR on board ALOS taken over coastal seas around Japan. The retrieval methods for wavelength and wave direction use the PALSAR image spectrum. The SAR image spectrum has an inherent 180° direction ambiguity, which can be solved using the fact that the swells only propagate toward the coast. Using the coupling swell spectra and the PALSAR image spectra, an empirical L-band modulation transfer function was obtained for the wave height retrieval through linear regression analysis. A comparison between SAR-derived and in situ wave parameters showed close agreement. For the wavelength and wave direction, the biases were 10.4 m and 1.3°, the root mean-square errors (RMSE) were 18.3 m and 15.5°, and the correlation coefficients were 0.93 and 0.94, respectively. These results demonstrate that the L-band SAR imaging mechanism for swells is mostly linear. For the wave height, the bias was 0.08 m, the RMSE was 0.30 m, and the correlation coefficient was 0.80. The coastal water depth was calculated from the retrieved wavelength. The comparison shows that the result is better when the water depth is less than 50 meters.

1. Introduction

Synthetic aperture radar (SAR) has proved to be a useful and efficient remote-sensing tool for observing ocean surface wave fields with high spatial resolution (e.g., Alpers et al. [1]; Stewart [2]). SAR images contain vast amounts of information on surface waves, which enables us to retrieve surface wave parameters (e.g., Hasselmann and Hasselmann [3]; Engen and Johnsen [4]; Mastenbroek and Valk [5]; Schulz-Stellenfleth et al. [6]; Sun and Kawamura [7]). Three modulation mechanisms (i.e., tilt modulation, hydrodynamic modulation, and velocity bunching) have been presented so far, which are modeled by three modulation transfer functions (MTFs) in SAR wave imaging (e.g., Alpers et al. [1]; Wright [8]; Monaldo and Beal [9]).

On the basis of MTFs, Hasselmann and Hasselmann (1991, HH91 hereafter) proposed a nonlinear imaging relation for C band SAR data, connecting the SAR image spectrum and the surface wave spectrum, which has been widely used by many researchers (e.g., Brüning et al. [10]; Krogstad et al. [11]; Kerbaol et al. [12]; Mastenbroek and Valk [5]; Sun and Kawamura [7,13]). In addition, data from
other bands have been used to study the wave information retrieval. For example, Li et al. [14] used X-band Terra-SAR data to retrieve the wave parameters with an empirical model because of the lack knowledge of MTFs for X-band SAR.

Swells dominate in coastal seas and can travel long distances across an entire ocean with small energy loss. When propagating into coastal seas, swells interact with the coastal bottom topography and swell refraction, diffraction, and depth-induced breaking occur. Due to their long wavelengths, the swells are easily affected by the bottom topography in coastal seas, and the phenomena are generally considered to be well explained by linear wave theory (e.g., Forget et al. [15]).

Satellite-borne L-band SARs are now observing surface waves, and while L-band surface wind retrieval is well established using accumulated L-band SAR images (e.g., Shimada et al. [16]; Isoguchi and Shimada [17]), retrievals of surface wave parameters have not yet been performed. In this study, we developed methods to retrieve the swell parameters (wavelength, wave direction, and wave height) from L-band SAR images around Japanese coastal seas. The data used and match-up generation method are described in Section 2. The retrieval methods and their validations are presented in Section 3 and 4, respectively. An application to calculate the water depth is included in Section 5. Conclusions are given in Section 6.

2. Data and match-up generation method

2.1 Data

The Phased Array type L-band SAR (PALSAR) on board the Advanced Land Observation Satellite (ALOS) is an active microwave sensor using the L-band frequency to perform cloud-free and all-day earth surface observations. We used its fine resolution mode of horizontal (HH) polarization, whose incidence angle ranges from 20° to 50°. The observation swath is from 40 to 70 km. The PALSAR images used in this study were obtained for May 2006 – December 2008. Their coverage is shown in figure 1.

In-situ surface wave parameters derived from the Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) measurements include the significant wave height, period, and wave propagation direction (hereafter wave direction), used for our study. The NOWPHAS stations in the study area had two data sampling rates: every 20 minutes and every 2 hours. We mainly used the 20-minute interval data for accurate comparison, but if that interval was not available, the 2-hour interval was used instead.

In particular, we used surface wave frequency-directional spectra of the Sendaishinko and Ishinomaki NOWPHAS stations in Sendai Bay to derive a MTF in Section 3. The spectral energy was mapped onto 49 discrete frequencies ranging from 0.0078 to 0.3828 Hz in 88 discrete directions.

Surface wind speeds were retrieved from the PALSAR images using the geophysical model
function proposed by Isoguchi and Shimada [17]. The bottom topography data used here were from the Japan Oceanographic Data Center (JODC) with a spatial resolution of 500 m.

2.2 Match-up generation method

To validate the retrieved wave parameters from PALSAR, match-ups were generated by coupling the PALSAR images and the corresponding NOWPHAS wave gauge data. PALSAR slant-range images covering the NOWPHAS stations were selected in the study area. For a PALSAR image with wave patterns, an area of 640×640 pixels (approximately 5.0 km×10.0 km in range and azimuth direction, respectively) was extracted with a NOWPHAS station in the center. Then the area was divided into 5×5 sub-images, containing 128×128 pixels as a candidate. For match-up generation, we selected one sub-image by the procedure described below:

1. Image spectra of the sub-images were calculated, and those with a ratio of spectral peak and background level (referred to as the S/N ratio) less than 7 were excluded from the match-up candidates.

2. Among the candidate sub-images, the sub-image closest to the NOWPHAS station was selected as the match-up sub-image.

3. The time difference between the PALSAR image and the NOWPHAS measurements was less than 10 minutes or less than 1 hour as described above. If one of the three in situ wave parameters was not available, we did not make a match-up.

Through the above-mentioned procedure, we obtained 23 match-ups, among which 17 were swell cases and 6 were wind wave cases. The swell and wind wave cases were separated by a wind speed of 6 m/s, which was retrieved from the match-up image using the formulas of Isoguchi and Shimada [17]. A physical justification for the separation was given by Sun and Kawamura [7]. Besides, seven surface wave spectra matched with the 17 swell cases.

3. Wave parameter retrieval methods

3.1 Retrieval of wavelength and wave direction

Previous studies have noted that in a long-wavelength swell situation, the nonlinear imaging mechanism (velocity bunching) can be considered to be a linear process (Alpers et al. [1]; HH91 [3]; Vachon et al. [18]). Therefore, it is possible to retrieve the spectral peak wavelength and wave direction from the SAR image spectrum after some image process procedure. However, its nonlinearity is enhanced in the case of short wind waves, which is one of the reasons we did not deal with wind waves in this study, although we consider wind wave research using the L-band SAR to be an important subject for future study.

The flowchart of wavelength and wave direction retrieval is described below. We first applied a Gaussian high-pass filter to the swell match-up image to remove noise components with low wavenumbers. Then we applied a two-dimensional fast Fourier transform (2-D FFT) to compute the coarse SAR image spectrum which was smoothed by a low-pass filter, conserving the spectral energy. The background clutter noise is removed from the spectrum using the method of Sun and Kawamura [7]. After these noise reduction processes, we obtained the high-quality SAR image spectrum (called the “SAR spectrum” hereafter).

The spectral peak wavelength and wave direction can be directly retrieved from the SAR spectrum. For the swell case, the inherent 180° direction ambiguity was solved by considering that swells only propagate toward the coast. The direction was measured counterclockwise, with 0° in the east.

In order to obtain better comparison, we first needed to convert the significant wave period to that of the spectral peak wave and then calculate the wavelength using the following relations (e.g., Wen and Yu [19]):

$$T_{\text{seg}}=0.937T_{\text{peak}} \quad \text{and} \quad \omega^2=g\tanh(kd).$$

(1)
3.2 Retrieval of the wave spectrum and wave height

Using the seven SAR / in situ wave spectrum pairs (see Section 2), we derived an empirical MTF (hereafter $MTF_{L\text{-band}}$) for L-band PALSAR. To establish the L-band MTF, the following linear relationship between the SAR spectrum $S_{\text{SAR}}(k, \phi)$ and the surface wave spectrum $S_{\text{wave}}(k, \phi)$ was adopted according to Wang and Jansen [20]:

$$S_{\text{SAR}}(k, \phi) = (MTF) S_{\text{wave}}(k, \phi) = m_\text{h} + m_\text{t} + m_\text{v} |k^2 f(k_x) S_{\text{wave}}(k_x, k_y)|,$$

where $m_\text{h}$, $m_\text{t}$, and $m_\text{v}$ are the hydrodynamic, tilt, and velocity bunching MTFs and $f(k_x)$ is the azimuth cut-off function, which models the smearing effect caused by the random motions of the ocean waves. The specific forms of L-band MTFs are not known. Therefore, we determined the $MTF_{L\text{-band}}$ by integrating all the effects through a regression analysis (described below). Equation (2) is simplified to

$$S_{\text{SAR}}(k_x, k_y) = |MTF_{L\text{-band}}| k^2 f(k_x) S_{\text{wave}}(k_x, k_y),$$

where $f(k_x)$ has the same form as given by Wang and Jansen [20].

As noted in the previous subsection, the imaging mechanism for swells is considered to be linear. We therefore used a linear analysis to derive the $MTF_{L\text{-band}}$. Here the dependent variables were $S_{\text{SAR}}(k_x, k_y)$ and the independent variables were $S_{\text{wave}}(k_x, k_y)$. The relationship between the dependent and independent variables was given by the regression function:

$$S_{\text{SAR}}(k_x, k_y) = (MTF_{L\text{-band}}) S_{\text{wave}}(k_x, k_y).$$

For each pair of the seven match-ups, linear regression was applied to each point in wavenumber space. Then, an optimal discrete $MTF_{L\text{-band}}$ was derived that had 128 points each in the azimuth and range wavenumber directions. The SAR surface wave spectrum $S_{\text{wave}}^{\text{in situ}}(k_x, k_y)$ could then be derived using the $MTF_{L\text{-band}}$ and the SAR spectrum through equation (3). The significant wave height $H_s$ was calculated from this spectrum using the relation

$$H_s = 4.0 \sqrt{\int \int S_{\text{wave}}^{\text{in situ}}(k_x, k_y) dk_x dk_y},$$

4. Validation results

Figure 2a shows the comparison between the wavelengths retrieved from the PALSAR spectra and those derived from the NOWPHAS wave gauge observations. Their bias and root mean-square error (RMSE) were 10.4 m and 18.3 m, respectively, and the correlation coefficient between them was 0.93. These values show close agreement between the retrieved and in situ cases.

Because of the nonlinear imaging mechanism of surface waves, SAR could not image azimuthal wave components with wavelengths less than the azimuthal cut-off wavelength, which depended on the sea state and the range-to-velocity ratio (R/V) of the SAR platform (Vachon et al. [18]). Generally, this value is around 100–200 m. However, in our result, several wavelengths retrieved from the PALSAR images were less than 100 m, which was also less than the general azimuthal cut-off wavelength. When the waves propagated nearly parallel to the range direction, the nonlinear velocity bunching mechanism was considered to be linear. For cases less than 100 m, we have confirmed that the waves were mainly range-travelling.

The validation results of the wave direction are shown in figure 2b. The bias and RMSE were 1.3° and 15.5°, respectively. The correlation coefficient between the SAR-derived and in situ wave directions was 0.94. The retrieved wave direction ranged from 100° to 250°, implying that the swells propagated from the east because of the characteristics of the study area. It can be concluded that the wave directions were not distorted too much by the nonlinear imaging mechanism in the swell case, which suggests that the mechanism for imaging these swells is linear.

The significant wave heights derived from the PALSAR images and the NOWPHAS wave gauges are compared and shown in figure 2c. The wave heights retrieved from the seven match-ups used for the derivation of $MTF_{L\text{-band}}$ are indicated by black triangles. The bias was 0.08 m, the RMSE was 0.30 m, and the correlation coefficient was 0.80. Our result is comparable with that of a retrieval using the
C-band SAR by Sun and Kawamura [7].

**Figure 2.** a) Validation of the wavelengths retrieved from PALSAR; b) Validation of the wave directions retrieved from PALSAR; c) Validation of the significant wave heights retrieved from PALSAR. The black triangles were used for the MTF derivation. The white triangles were the independent match-ups.

### 5. Application: water depth calculation

A case study of swell propagating into Sendai Bay and its interaction with bottom topography was studied by Wei and Kawamura [21] using the abovementioned retrieval method for wavelength and wave direction. A high-resolution, two-dimensional distribution map of swell wavelength was derived (see Fig. 4a of Wei and Kawamura [21]). In this paper, we will continue their work to calculate the coastal water depth through the swell wavelength map and the dispersion relationship.

We assume that the swells (in PALSAR data imaged on 2006/09/24) propagating into Sendai Bay obey the wave number conservation law, which was already proved by the work of Wei and Kawamura [21]. Therefore, a wave period of 14.3 s is derived from Sendai-shinko wave gauge to calculate the water depth.

Figure 3 shows the comparison between the calculated water depth and the depth provided by JODC. The latter is interpolated to the corresponding locations of the former. The comparison shows a result far away from good agreement with the correlation coefficient of 0.79, bias of -6.9 m and RMSE of 21.2 m. However, one can see from the figure that the points are congregate in water depth less than 50 m. This implies a qualitative conclusion that the retrieval behavior performs relatively better in shallower water where the swells “feel” the bottom completely. In other words, waves propagating from ocean to coastal seas are not seriously affected by the bottom at the beginning when they become shallow water waves.

**Figure 3.** Comparison between calculated water depth and JODC data.

### 6. Conclusions

In this study, the swell parameters, i.e., the wavelength, the wave direction, and the wave height were
retrieved from L-band SAR images taken over Japanese coastal seas. The retrieved parameters were validated by NOWPHAS in situ wave data. The retrieved wavelength is used to calculate the water depth and compared with measured depth. The main conclusions are listed below:

Seventeen match-ups were generated to retrieve swell parameters. The wavelength and wave direction were retrieved from the spectral peak of the SAR spectrum because the imaging mechanism of swells is mostly linear. To estimate the wave height, the $MTF_{L\text{-band}}$ was derived through linear regression analysis using seven pairs of in situ surface wave spectra and the corresponding SAR spectra. The validations showed close agreement between the SAR-retrieved and NOWPHAS wave parameters.

The comparison between the calculated water depth and JODC water depth shows a result that is far away from good agreement. However, the result shows that coastal waves and bottom interact more complete when they propagate in shallower water.

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