Study on Surface Waves in Sendai Bay Using PALSAR on board ALOS

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論 文 内 容 要 旨

Surface waves are one of the most important factors that influence human's activities in coastal seas. Since a large portion of human population is located in the coastal zones, it is a social requirement to enhance understanding characteristics of the coastal surface waves. Because of the coastal complex bottom topography,

the surface wave field becomes complicated there and is needed to be analyzed with fine resolutions. Synthetic Aperture Radar (SAR) has been proven to be a useful and efficient remote sensing tool for observing the ocean surface wave fields with high resolutions. SAR images contain vast amounts of information on the surface waves, which enables us to retrieve the surface wave parameters from them.

Using C-band SAR images, retrieval algorithms for the surface wave parameters have been proposed in both open oceans and coastal seas. In contrast, there is no such a study using L-band SAR images. Nowadays, satellite carrying the L-band SARs was and is in the space, and has been observing the surface waves. Although the L-band surface wind retrieval is well established using the accumulated L-band SAR images, studies on retrieval of the surface wave parameters are not conducted till present.

This study is motivated by the above-mentioned needs in the coastal wave study and the availability of the L-band SAR images around the Japanese coasts. The surface wave imaging mechanisms of microwave radars were studied by using the C-band SARs. Though the mechanisms may be referred to understanding the L-band imaging mechanisms, no study is conducted in this direction. Swells are a typical feature of the surface waves, and they dominate in the coastal seas. Because, from the C-band SAR studies, the swell imaging mechanisms of L-band SAR are expected to be linear, we decide to investigate swells captured by the L-band SAR images as a first step. In Section 1, we introduce the backgrounds, the purpose of this study and the thesis structure.

In Section 2, the study area, the used datasets and the match-up generation method are described in details. Coastal seas facing to north-eastern coasts of the Honshu Island and Sendai Bay are chosen as the study areas. Images of Phased Array type L-band Synthetic Aperture Radar (PALSAR) on board Advanced Land Observing Satellite (ALOS) are used for this study. In-situ wave parameters observed by the Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) wave gauges are used for the retrieval algorithm development, validation of the retrieved wave parameters and the analyses of swell fields. In particular, we have used the surface wave spectral data in Sendai Bay. The match-ups are generated combining the PALSAR scenes and the corresponding NOWPHAS in-situ wave parameters. We separate the wind wave cases and the swell cases by using the threshold of 6 m/s of PALSAR-derived wind speed following Sun and Kawamura [2009a].

In Section 3, retrieval algorithms of the swell parameters, i.e., the wavelength, the wave height and the wave propagation direction (wave direction, hereafter), are studied and developed using the match-ups generated in Section 2. The retrieval method for wavelength and wave direction utilizes the spectral peak of the smoothed PALSAR wavenumber spectrum. The SAR image spectrum has the inherent 180° direction ambiguity, which can be solved by the common-sense view that the swells only propagate toward the coast. The derived wavelength and wave direction are validated with the NOWPHAS in-situ wave parameters. The in-situ wavelength is calculated by using the dispersion relation in the limited depth water together with the wave period and water depth at the wave gauge point. The SAR-derived and the in-situ wavelengths and the wave directions show good agreements with each other. For the wavelength, the bias is 10.4 m, the root mean square error (RMSE) is 18.3 m, and the correlation coefficient is 0.93. For the wave direction, the bias is 1.3°, the RMSE is 15.5°, and the correlation coefficient is 0.94. These results demonstrate that the L-band SAR imaging mechanism for the swells is considered mostly to be linear.

The C-band Modulation Transfer Functions (MTFs) have been established and used for retrievals of the surface wave spectra and wave heights. In this study, we try to develop a MTF for retrievals of the surface wave spectrum and the wave height using the L-band PALSAR. Fortunately, we have time series of in-situ two-dimensional wave spectra at two stations in Sendai Bay. Using the seven pairs of the swell spectra and the corresponding PALSAR image spectra, we obtain an empirical MTF for the L-band SAR (MTF_{L-band}, hereafter) through the linear regression analysis. Using the MTF_{L-band}, the SAR image spectra are converted to the surface wave spectra, which are integrated to estimate significant wave heights. Their validation against the in-situ significant wave height shows a good agreement; the bias is 0.08 m with the RMSE of 0.30 m and their correlation coefficient is 0.80.

In Section 4, high-resolution two-dimensional (2-D) maps of the swell parameters are retrieved from a PALSAR scene on 2006/09/24 in Sendai Bay using the retrieval methods studied and developed in Section 3. The characteristics of coastal wave field (i.e., wave refraction, shoaling effect) can be clearly seen in the map. Features of the wavelength map are investigated by comparing with a wavelength map calculated through the linear wave theory with the wave period obtained from a wave gauge in Sendai Bay. They correspond well in most areas though large differences appear in the near-shore area and the complicated bottom topography area.

It is found that the spatial resolution of the retrieval method is not enough to investigate the surface waves in the near-shore area. Then, we introduce wavelet transform, which is used to decompose a signal into those with arbitrary scales. The high-resolution profiles of wavelength are obtained along wave rays by the wavelet transform. The new wavelength map is derived, which clearly shows that the large difference in the near-shore area disappears.

For the area over the complicated bottom topography, we have investigated the bottom slope effect referring the work of Chen et al. [2004]. They have studied the bottom slope effect on the surface wave propagating from the deep water to the coastal seas by using an advanced perturbation theory. It is concluded that the large wavelength difference in the area is well reduced by using the 2nd order solution of the perturbation equation.

The wave height map is also generated from the same PALSAR scene using the MTF_{L-band}. The map shows the typical feature of the coastal wave field that the wave height first decreases from the deep water to shallow water and then increases again to the coast. The SAR-derived wave height variation agrees well with the variation estimated from the theory including the bottom slope effect.

In Section 5, discussions are focused on the MTF_{L-band}. No L-band surface wave retrieval methods were presented until this study, which, however, has left many research subjects for future studies. For example, 1) the MTF_{L-band} combines all the effects of SAR surface wave imaging mechanisms, which should be separated and clarified theoretically. 2) The developed MTF_{L-band} cannot be applied to surface wave conditions under moderate and strong winds. Further examination/validation of the MTF_{L-band} should be done for the full surface wave and wind conditions in future.

Section 6 provides the conclusions and the future plans of this thesis. Throughout this study, the retrieval methods of swell parameters have been established, and the advanced analyses of 2-D swell field in the coastal sea are first conducted using the L-band PALSAR images. The successful achievements in these subjects imply that the L-band SAR images have a quite high potential for monitoring the coastal surface wave fields around Japan.

論文審査の結果の要旨

海洋表面波は、沿岸海域における人間活動に大きな影響を与える。海岸や海底の地形が複雑な沿岸海域に進入する表面波は、そこで様々な変形を受けるが、これまでその詳細を観測する手法がなかった。合成開口レーダー(SAR)は非常に高い空間解像度を有し、その海面画像は波浪をよく映し出す。我が国のALOS衛星に搭載されたPhased Array L-band SAR(PALSAR)は、波長23.5cmの電磁波を用いているが、これまで海洋波浪の研究にほとんど利用されたことがない。本研究の目的は、PALSARを用いてうねりに関する研究を行い、表面波パラメータの導出手法を開発し、それを用いて沿岸域におけるうねりの特性に関する研究を実施することであった。

PALSAR画像のスペクトル解析を行うことにより、うねりの波長と伝搬方向（波向）を導出する手法を開発した。衛星観測と同期した沿岸波浪計観測データを用いて検証したところ、波長の推定誤差(RMSE)は18.3m、波向のそれは15.5度であることが判った。PALSAR画像から波高を推定するため、SAR画像・沿岸波浪計の7組の同期観測2次元スペクトルを解析し、両者を関係づける新しい変調伝達関数(MTF)を導くことに成功した。これを用いてPALSAR画像からうねりの2次元スペクトルを求め、それを積分して有義波高に変換し、沿岸波高計観測有義波高と比較したところ、RMSEは0.3mであった。

新しく開発した導出手法を用いて、2006年9月24日のPALSAR画像から高空間解像度（1km x 2km）のうねりパラメータ分布図を作成し、仙台湾におけるうねりの特性を調べた。SAR導出波長分布を調べたところ、微少振幅波理論から予想される波長分布とほぼ全海域で良い一致を見たが、うねりが到達する沿岸域付近と海岸・海底地形が複雑な海域で、両者に大きな差異が生じていた。前者では波長が急速に短くなるので、スペクトル解析導出手法の空間解像度に問題があることが予想された。そこで、それを改善するため、ウェーブレット解析による導出手法を導入した。その結果、沿岸域付近の差異は無くなった。

Chen et al. (2004)は、特異摂動法により、海底地形の微小変化効果を定式化した。その新しい理論の適用により、海岸・海底地形が複雑な海域におけるSARうねりパラメータの動向がよく説明できることがわかった。

本研究は、L-band SARによる表面波パラメータ導出手法を確立し、SAR高解像度特性を活用した沿岸波浪解析研究に道を開いた。これは、魏永亮が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、魏永亮提出の博士論文は、博士（理学）の学位論文として合格と認める。