A Composite View of Surface Signatures and Interior Properties of Nonlinear Internal Waves: Observations and Applications

MING-HUEI CHANG
Institute of Oceanography, National Taiwan University, Taipei, Taiwan

REN-CHIEH LIEN
Applied Physics Laboratory, University of Washington, Seattle, Washington

YIING JANG YANG
Department of Marine Science, Naval Academy, Kaohsiung, Taiwan

TSWEN YUNG TANG AND JOE WANG
Institute of Oceanography, National Taiwan University, Taipei, Taiwan

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ABSTRACT

Surface signatures and interior properties of large-amplitude nonlinear internal waves (NLIWs) in the South China Sea (SCS) were measured during a period of weak northeast wind ($\sim 2 \text{ m s}^{-1}$) using shipboard marine radar, an acoustic Doppler current profiler (ADCP), a conductivity–temperature–depth (CTD) profiler, and an echo sounder. In the northern SCS, large-amplitude NLIWs propagating principally westward appear at the tidal periodicity, and their magnitudes are modulated at the spring–neap tidal cycle. The surface scattering strength measured by the marine radar is positively correlated with the local wind speed when NLIWs are absent. When NLIWs approach, the surface scattering strength within the convergence zone is enhanced. The sea surface scattering induced by NLIWs is equivalent to that of a $\sim 6 \text{ m s}^{-1}$ surface wind speed (i.e., 3 times greater than the actual surface wind speed). The horizontal spatial structure of the enhanced sea surface scattering strength predicts the horizontal spatial structure of the NLIW. The observed average half-amplitude full width of NLIWs $\lambda_{\text{am}}$ is $1.09 \pm 0.2 \text{ km}$; the average half-amplitude full width of the enhanced scattering strength $\lambda_{\text{am}}$ is $0.57 \\lambda_{\text{am}}$. The average half-amplitude full width of the enhanced horizontal velocity convergence of NLIWs $\lambda_{\text{vcon}}$ is approximately equal to $\lambda_{\text{am}}$. The peak of the enhanced surface scattering leads the center of NLIWs by $-0.46 \lambda_{\text{am}}$. NLIW horizontal velocity convergence is positively correlated with the enhancement of the surface scattering strength. NLIW amplitude is positively correlated with the spatial integration of the enhancement of the surface scattering strength within the convergence zone of NLIWs. Empirical formulas are obtained for estimating the horizontal velocity convergence and the amplitude of NLIWs using radar measurements of surface scattering strength. The enhancement of the scattering strength exhibits strong asymmetry; the scattering strength observed from behind the propagating NLIW is 24% less than that observed ahead, presumably caused by the skewness and the breaking of surface waves induced by NLIWs. Above the center of NLIWs, the surface scattering strength is enhanced slightly, associated with isotropic surface waves presumably induced or modified by NLIWs. This analysis concludes that in low-wind conditions remote sensing measurements may provide useful predictions of horizontal velocity convergences, amplitudes, and spatial structures of NLIWs. Further applications and modification of the presented empirical formulas in different conditions of wind speed, surface waves, and NLIWs or with other remote sensing methods are encouraged.

Corresponding author address: Tswen Yung Tang, Institute of Oceanography, National Taiwan University, Taipei, Taiwan.
E-mail: tyt@ntu.edu.tw

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1. Introduction

Synthetic aperture radar (SAR) has detected nonlinear internal waves (NLIWs) between the Luzon Strait and the continental shelf in the northern South China Sea (SCS; Fig. 1; Zhao et al. 2004). In situ observations (Ramp et al. 2004; Yang et al. 2004; Lien et al. 2005; Chang et al. 2006) of NLIWs have been made at some locations in the SCS. Analyses suggest that NLIWs appear at tidal periodicity with amplitudes modulated at a fortnightly tidal cycle. Strong divergences of energy and energy flux are found along and across their prevailing westward propagation path on the Dongsha Plateau (Chang et al. 2006), suggesting strong and rapid NLIW conversion, interaction, and dissipation.

Satellite observations provide snapshots of NLIWs at a large spatial scale, $O(100 \text{ km})$, but at a poor temporal resolution. In situ measurements of NLIWs from ships or moorings made simultaneously with satellite observations are rare.

The mechanisms and characteristics of the surface scattering modulated by internal waves have been demonstrated by theoretical analysis (Hughes 1978; Alpers 1985; Thompson and Gasparovic 1986; Lyzenga 1998) and observations (Hughes and Grant 1978; Hughes and Gower 1983; Kropfli et al. 1999), mostly based on SAR data. NLIW near-surface currents modulate surface waves, which are the detected surface signature. Most models of wave–current interaction assume a weak hydrodynamic interaction such that the variation of the current is much slower than that of the surface wave. To explain the large changes in X-band marine radar backscatter, Lyzenga (1998) proposes a mechanism that involves the interaction of short Bragg waves with intermediate-scale waves having wavelengths of $O(1 \text{ m})$ and the interaction of both sets of waves with large-scale current gradients associated with the front or internal waves. The model does not predict the interior properties of large-amplitude NLIWs well because the sea state is more complicated than model assumptions and the effect of surface wave breaking caused by NLIWs is not included.

In this study, simultaneous shipboard X-band marine radar remote sensing measurements and shipboard acoustic Doppler current profiler (ADCP), conductivity–temperature–depth (CTD) profiler, and echo sounder measurements are used to study the relationship between surface scattering strength induced by NLIWs and their interior properties. Measurements were taken during an intensive survey of NLIWs in the SCS in April 2005. The marine radar provides 360° two-dimensional surface scattering measurements at a sampling rate of $\sim 1 \text{ min}$. The derived empirical relations are used to interpret remote sensing observations and to extract interior properties of NLIWs.

Section 2 of this paper describes the experiment and instruments. In section 3, we discuss the effects of wind and NLIWs on surface scattering. In section 4, a com-
posite view of the surface signature and the interior structure of NLIWs is presented. The relation between the near-surface horizontal velocity convergence \( \partial_v u \) induced by NLIWs and the surface scattering strength is discussed, as is the relation between the amplitude of NLIWs and the surface scattering strength. Empirical formulas are obtained to predict properties of NLIWs using remote sensing measurements. A discussion and summary of this analysis are given in section 5.

2. Experiment and measurements

The experiment was performed in two successive \(~5\)-day legs in April 2005 on the Taiwanese Research Vessel (R/V) Ocean Researcher III (OR3). The first leg was during the neap tide and the second leg during the spring tide. Our observations were primarily taken along 21°05′N, perpendicular to the prevailing NLIW propagation direction (Fig. 1a). The experiment strategy was to wait for the approaching large-amplitude NLIW at 21°05′N, 117°30′E and make intensive shipboard and marine radar measurements while tracking the NLIW propagating westward until \(~116°30′E\).

Shipboard measurements were taken by a 38-kHz echo sounder, a 150-kHz ADCP, and the CTD (Fig. 1b). Meteorological sensors measured the surface wind speed and direction at \(~5\) m above the sea surface. The echo sounder sampled at 0.2 Hz. The ADCP bin size was 4 m with a pulse length of 4 m; it recorded 1-min ensembles averaged over \(~20\) pings. The shipboard CTD was profiled vertically most of time, except when yo-yo CTD profiles were taken coincident with passing NLIWs.

The shipboard X-band marine radar measured the sea surface scattering strength with a 6-ft antenna by rotating at a rate of \(~6\) cycles per minute. The polarization is horizontal (HH). The emitted X-band frequency was 9.41 GHz, corresponding to a 3.2-cm wavelength in the regime of capillary waves. The radar sampling rate was 10 MHz. The range resolution was 15 m, and the azimuth resolution was 1°. Radar measurements were taken every 5 min in the first leg and every 1 min in the second leg. During each sampling period, the antenna rotated four successive cycles and all four cycles of measurements were recorded.

3. Sea surface scattering

The strength of the sea surface scattering reflects the sea surface roughness. Winds, surface gravity waves, ocean fronts, internal waves, rains, oils, foams, and other air–sea processes may produce or modulate the sea surface roughness. Leaving out the effects of oceanic processes, the radar scattering strength may be represented as \( f(r) = (Ar^n) \), where \( r \) is the distance with unit meter from the target to the radar and \( n \) and \( A \) are constants reflecting the grazing angle effect. The values of \( A \) and \( n \) are 350 ± 55 and 1.11 ± 0.03, respectively. In our observations, the variation of surface scattering strength is modulated primarily by NLIWs. Therefore, we estimate \( f(r) \) by averaging all radar scattering measurements when the NLIW is absent. In the following analysis, we divide radar scattering measurements by \( f(r) \) to minimize the grazing angle effect and other possible instrument effects and noises. Two radar images of normalized scattering strength, taken 6 min apart, show measurements ahead of the east to west propagating NLIW (Fig. 2a) and behind (Fig. 2b) as it passed the ship (in the center of the images). Both reveal two main features: (i) a uniform background scattering with a normalized strength of \(~1\), and (ii) a strong scattering band with a normalized strength of \(~10\). The uniform scattering is induced by the wind and the strong scattering band is induced by NLIWs.

a. Surface scattering induced by wind waves

The uniform background scattering with a normalized strength \(~1\) covers the greater part of the radar image (Fig. 2). The magnitude of \(~1\) is expected as a result of our normalization. Wind–wave-induced scattering is the likely cause for the uniform background scattering, which is of \(~8\)-km scale, consistent with the general scale of the sea surface wind [\(>O(10\) km); Cushman-Roisin (1994)]. The strong scattering band appears only on radar images taken late in the first leg and during most of the second leg.

Radar surface scattering strength depends on the wind speed and the wind direction (Lee et al. 1995; Trizna and Carlson 1996; Dankert 2003; Dankert et al. 2005). Following Dankert (2003), the relation could be expressed as \( I_a = aS(1 + b \cos \Delta \Phi) \), where \( I_a \) is the normalized scattering strength (azimuthally averaged over a 1-km radius and over all directions of radar measurements), \( \Delta \Phi \) is the difference between the looking direction of the antenna and the wind direction, and \( S \) is the wind speed. The coefficients \( a \), \( b \), and \( r \) depend on the radar frequency, the polarization, and the incidence angle, respectively. For our measurements, the shipmeasured wind speed is computed following Smith et al. (1999). Instrument towers on the R/V OR3 are taller than the wind sensor and distort the wind blowing from the stern. The distortion is less severe for the wind speed than for direction. The distortion forms data spikes in wind speed measurements. A 2-h low-pass filter is applied to minimize the influence of the disturbances.
Time series of the normalized scattering strength averaged over the 1-km radius of radar measurements $I_a$ and the wind speed $S$ are shown in Fig. 3a. A strong correlation, 0.84, is found. During the first leg, the average $S$ is $2.17 \pm 0.74$ m s$^{-1}$ and the average $I_a$ is $\sim 1$.

The two time series fluctuate in unison. The clear correlation is further illustrated by the scatterplot between the 2-h averages of $I_a$ and $S$. A power-law model $I_a = kS^r$ fits their relation (thick curve in Fig. 3b). Within the 95% confidence interval, $k = 0.24 \pm 0.1$ and $r = 1.70 \pm 0.4$. Compared to the model (Dankert 2003), the uncertainty of $k$ is presumably due to the effect of $\Delta \Phi$, that is, $\epsilon_k = \langle ab \cos \Delta \Phi \rangle$, where $\langle \rangle$ is the ensemble average. Alternatively, a linear regression fit is obtained (gray dotted line, Fig. 3b), that is, $I_a = 0.67S - 0.49$. The aptness of the power-law fit or the linear fit are indistinguishable. The strong correlation between $I_a$ and $S$ suggests that the primary surface scattering in the first leg is caused by wind waves.

b. Surface waves and surface scattering modulated by NLIWs

A band of strong scattering appears frequently on radar images in the second leg (Fig. 2). Time series of $I_a$ and $S$ in the second leg show that the average of $S$ is $2.12 \pm 0.77$ m s$^{-1}$, similar to that during the first leg, and the averaged $I_a$ is also $\sim 1$ (Fig. 4). However, bands of strong surface scattering cause enhancement peaks of $I_a$ (Fig. 4a), which create outliers against the correlation between $I_a$ and $S$ (Fig. 4b). The linear correlation coefficient between $I_a$ and $S$ is 0.62. There are two groups of measurements that depart from the power-law relation yields of the first leg, labeled 1 and 2 in Figs. 4a and 4b, respectively. Group 2 departures exhibit a high $S$ but low $I_a$. The exact causes are unknown, but are possibly due to surface foams, oil spill, or contaminated wind speed measurements. Group 1 departures exhibit a high $I_a$ associated with NLIWs.
Simultaneous measurements by CTD, echo sounder, and shipboard ADCP captured the vertical displacement and velocity variations of NLIWs during the surface scattering spike events captured by radar. Figure 5 illustrates an NLIW event on 30 April 2005. The maximum vertical displacement of the isopycnal surface, \( \sigma_0 = 24 \text{ kg m}^{-3} \), is \( \sim 110 \text{ m} \). The maximum westward current in the upper layer is \( 1.2 \text{ m s}^{-1} \), and the maximum eastward current in the lower layer is \( 0.8 \text{ m s}^{-1} \). The water depth is about 600 m. Note that velocity fluctuations in the upper 10 m and below 200 m are not measured by the shipboard ADCP. The vertical velocity shows a clear structure of a first-mode depression wave, with the maximum speed at middepth, and a downwelling followed by an upwelling. The characteristics of the observed NLIW agree well with those described by Yang et al. (2004) and Lien et al. (2005).

Variations of surface signatures modulated by passing NLIWs are illustrated in Fig. 6. Before the NLIW arrives, the sea surface is relatively smooth (picture 1). In the convergence regime of NLIW, rows of large-amplitude surface gravity waves propagate in nearly the same direction as the NLIW. Plunging wave breaking occurs, similar to beach shoaling (picture 2). At the sea surface above the NLIW trough and behind the convergence region, small-amplitude surface gravity waves of no specific propagation direction prevail (picture 3). At the sea surface above the NLIW divergence region, boils that suggest strong upwelling appear. In the NLIW convergence zone, a bump of enhanced \( I_a \) (maximum \( I_a \sim 3.5 \)) coexists with the increase of the horizontal velocity maximum convergence \( \partial_z u \approx -0.002 \text{ s}^{-1} \) (Figs. 6b and 6c).

4. Comparing remote and in situ observations of NLIWs

a. Remote sensing of NLIW spatial structure and position

The propagation speed of NLIWs and the ship speed are used to convert the coordinates of radar surface scattering measurements into the coordinates of NLIWs (see appendix). Two NLIW events measured on 29 and 28 April 2005 are illustrated in Figs. 7a–c and 7d–f, respectively. On 29 April, the NLIW vertical displacement was \( \sim 150 \text{ m} \) from the initial depths of 100 and 150 m. The maximum westward velocity was \( \sim 1.8 \text{ m s}^{-1} \). The full width of half amplitude \( \lambda_{1/2} \) (i.e., the horizontal distance between the consecutive locations of the vertical displacement and half of the maximum amplitude of the NLIW labeled in Fig. 4b) was 854 m. In the convergence zone (\( \partial_z u < 0 \)), the surface scatter-
The complexity of NLIWs prompted us to average $I_\mu$, horizontal convergence, and vertical displacement initially at 100- and 150-m depth over all seven large-amplitude NLIW events observed during 27–30 April (Fig. 8). One event on 29 April is excluded because the ship steamed against the NLIW, passing the wave too fast to measure it properly.

The spatial structure of the enhanced surface scattering strength is related closely to the spatial structure of NLIWs. The average full width of the half amplitude $\lambda_{\mu,2}$ of NLIWs is $1.09 \pm 0.2$ km (Fig. 8c), with a 95% confidence interval computed with the bootstrap method. The average full width of the half amplitude of the horizontal convergence $\lambda_{u,2}$, defined similarly as $\lambda_{\mu,2}$, is $0.57 \pm 0.12 \lambda_{\mu,2}$ (Fig. 8a). The average full width of the half amplitude of the horizontal convergence $\lambda_{\mu,2}$ is $0.46 \pm 0.06 \lambda_{\mu,2}$ (Fig. 8b); $\lambda_{u,2}$ is nearly equal to $\lambda_{\mu,2}$. The peak of the enhanced surface scattering strength leads the trough of NLIWs by $0.46 \pm 0.11 \lambda_{\mu,2}$.

### b. Remote sensing of the magnitude of NLIW horizontal convergence

In the divergence zone, the NLIW rear portion, the surface scattering strength is not significantly different from the background (Figs. 7 and 8). In the convergence zone, the NLIW front portion, the surface scattering strength is positively proportional to the magnitude of the NLIW horizontal convergence.

The relation between the horizontal convergence and the radar scattering intensity is shown in Fig. 9. A linear regression line fits reasonably well in the weak convergence region, $-1.8 \times 10^{-3}$ s$^{-1} < \partial_\mu u < 0$ s$^{-1}$, with a correlation coefficient of $-0.93$ (red curves in Fig. 9). In the strong convergence region, the enhancement rate of the surface scattering strength reduces, and the linear relation does not apply. An empirical arctangent fits with all observations of surface scattering strength and horizontal convergence (blue curves). The empirical arctangent fits for observations from ahead (forward looking) of the propagating NLIWs and from behind the propagating NLIWs (backward looking) are

\[
I_\mu = 2\pi^{-1} I^\mu_\mu \tan^{-1} (|\partial_\mu u(H_f) + I^\mu_f|) \quad \text{and} \quad I^\mu_\mu = 2\pi^{-1} I^\mu_\mu \tan^{-1} (|\partial_\mu u(H_h) + I^\mu_h|) \quad (1)
\]

### Figure 6

(a) Pictures (1–4) taken during the experiment illustrating the surface signatures accompanying the passing NLIW. (b) graphs of the radar scattering strength, and (c) the horizontal divergence computed from shipboard ADCP measurements in 8.4–12.4-m depth. The double-arrow lines in (a) illustrate the approximate horizontal scale. The numbers in (b) and (c) correspond to the picture numbers in (a).

The NLIW event on 28 April illustrates the complexity of NLIWs in our observations. The zonal velocity profile shows two maximum velocity cores in the vertical. The center of the shallow core is not fully resolved. A close examination of the time sequence of marine radar images reveals that a small NLIW (associated with the shallow core) was caught up by a much larger NLIW (associated with the deeper core). The shallower vertical displacement was $\sim 150$ m from the initial depth of 100 m, and the deeper vertical displacement was $\sim 180$ m from the initial depth of 150 m. The horizontal convergence is only one-half of that observed on 29 April, although the surface scattering strength is comparable. Presumably, the specific combination of two waves on 28 April reduced the horizontal velocity convergence.
where the subscripts $f$ and $b$ indicate forward and backward looking, respectively, $I_f^0$ is the forward-looking radar scattering strength, $I_b^0$ the backward-looking radar scattering strength, and $\partial_x u$ the horizontal convergence computed from shipboard ADCP measurements in the shallowest depth bin (8.4–12.4 m).

The values of $I_f^0$ and $I_b^0$ exhibit a similar behavior, namely a linear increase at small convergence ($-1.8 \times 10^{-3} \, \text{s}^{-1} < \partial_x u < 0$) and a slower than linear increase at large convergence ($\partial_x u < -1.8 \times 10^{-3} \, \text{s}^{-1}$). Fitted values for $I_f^0$ and $I_b^0$ are 1.0 and 1.1, respectively. They represent the background scattering strengths without the effect of horizontal convergence, and the fitted values of ~1 are expected as a result of the normalization of our radar measurements. The parameters $H_f = 0.0014 \, \text{s}^{-1}$ and $H_b = 0.0012 \, \text{s}^{-1}$ scale the magnitude of surface scattering strength enhancement induced by $\partial_x u$. The maximum enhancements of surface scattering strength induced by the horizontal convergence are $I_f^m = 4.05$ and $I_b^m = 2.70$. The maximum enhancements

![Fig. 7](image-url) **Fig. 7.** Two NLIW events on (left) 29 and (right) 28 Apr. (a), (d) The forward-looking surface scattering intensity (i.e., observed from ahead of the propagating NLIW; red curves) and the backward-looking surface scattering intensity (i.e., observed from behind the propagating NLIW; blue curves). Gray shadings represent the 95% confidence intervals. The wave speed $C$ and wave width of the half of the maximum amplitude $\lambda_{\eta/2}$ are labeled. (b), (e) Horizontal convergence averaged from ADCP measurements in 8.4–12.4-m depth. (c), (f) Contours of zonal velocity and vertical displacements of isopycnal surface initially at 100 and 150 m.

![Fig. 8](image-url) **Fig. 8.** (a) The surface scattering strength, (b) horizontal convergence, and (c) vertical displacement of NLIWs averaged over seven NLIW events. (d)–(f) Same as (a)–(c), but the $x$ axis is scaled by the wave width of the half maximum amplitude. In (a) and (d), red (blue) curves represent the surface scattering strength observed from ahead of (behind) the propagating NLIW. In (c) and (f), the upper and lower blue curves represent vertical displacements of the isopycnal surface initially at 100 and 150 m, respectively. The light gray and heavy gray shadings represent 95% confidence intervals.
are regarded as the saturation of the surface scattering strength induced by horizontal convergence due to NLIWs. As the horizontal convergence increases, surface waves break, capillary waves are generated, and the surface scattering strength reaches its maximum value. At \( |\partial_x u| = H_f \) and \( |\partial_x u| = H_b \), the enhancement of the forward-looking surface scattering intensity and the enhancement of the backward-looking surface scattering intensity reach their respective half-maxima, 0.5 \( I^m_f \) and 0.5 \( I^m_b \).

Following Eqs. (1) and (2), the horizontal convergence of NLIW could be predicted using measurements of surface scattering strength expressed as

\[
\partial_x u = H_d \tan \left[ \frac{\pi (I^m_f - I^0_f)}{2 I^m_f} \right] = F(I^d_f, I^0_f, I^m_f, H_d),
\]

where \( d = f \) or \( b \), representing forward- or backward-looking radar measurements.

The maximum observed scattering strength produced by NLIWs was \( I^m_f = 4.05 \). Following the power law and the linear fits between the scattering strength and the local wind speed, the maximum surface scattering enhancement by NLIWs is equivalent to that caused by a wind of \( \sim 6 \) m s\(^{-1}\) with surface waves of \( \sim 1.5 \) m, according to the Beaufort wind scale.

c. Remote sensing of NLIW amplitudes

The observed positive correlation between \( \partial_x u \) and \( F \) in (3) implies that the velocity fluctuation of NLIWs, represented as \( \delta u \), is proportional to \( \int F \) dx. Accordingly, we expect that the vertical displacement of NLIWs \( \eta \) is also proportional to \( \int F \) dx. This relation is examined by comparing \( \int_{x_0}^{x_0 + \delta x} F dx \) with \( A_{\delta \eta} \) for \( \delta x \). Where \( x_0 \) is the horizontal position before the NLIW arrives (Fig. 10). Two initial vertical positions, \( z_0 = 100 \) m and \( z_0 = 150 \) m, are examined, and \( I^0_f \) measured from ahead of the propagating NLIW, is used. The maximum value of \( A_{\delta \eta} \) occurs at the NLIW trough. Empirical linear fits between \( \int_{x_0}^{x_0 + \delta x} F(I^0_f) \) dx and \( A_{\delta \eta} \) for \( z_0 = 100 \) m and \( z_0 = 150 \) m are obtained as

\[
A_{100} = (0.13 \pm 0.01) \left[ \int_{x_0}^{x_0 + \delta x} \tan \left( \frac{I^d_f - I^0_f}{I^m_f} \right) \right] dx \tag{4}
\]

and

\[
A_{150} = (0.16 \pm 0.01) \left[ \int_{x_0}^{x_0 + \delta x} \tan \left( \frac{I^d_f - I^0_f}{I^m_f} \right) \right] dx \tag{5}
\]

The maximum values of \( A_{100} (= \eta_{100}) \) and \( A_{150} (= \eta_{150}) \) of observed NLIW events are roughly proportional to maximum values of \( \int_{x_0}^{x_0 + \delta x} \tan [(I^d_f - I^0_f)/I^m_f] \) dx induced
by NLIWs. A better correlation might be achieved if there were a larger dynamic range of $\eta_{100}$ and $\eta_{150}$. Our analysis concludes that a positive correlation exists between the spatially integrated surface scattering strength anomaly and the NLIW amplitude. The above empirical formula should be useful to predict the amplitude of NLIWs from remote sensing measurements of surface scattering strength, at least for low-wind conditions.

5. Discussion and summary

Simultaneous remote and in situ measurements of NLIWs in low-wind conditions provide an opportunity to study the modulation of sea surface scattering induced by NLIWs. Based on direct observations, we construct a complete spatial view of NLIWs from their surface scattering signatures.

In the NLIW convergence region, the surface scattering strength is enhanced. The spatial structure of the enhancement is correlated with the spatial structure of the NLIW. The magnitude of the enhanced surface scattering strength is proportional to the horizontal convergence of the NLIW. The NLIW amplitude is proportional to the horizontal integration of the surface scattering strength anomaly. The maximum enhancement of surface scattering intensity produced by typical NLIWs in the SCS is equivalent to that made by a wind of $\sim 6$ m s$^{-1}$ and surface waves of $\sim 1.5$ m. For winds $>6$ m s$^{-1}$, the surface scattering intensity caused by the wind is stronger than that caused by NLIWs, and the surface signature due to NLIWs cannot be identified on radar images.

Empirical formulas are derived describing the relation between the spatial structure of NLIWs and the spatial structure of surface scattering, the relation between the horizontal convergence of NLIWs and the surface scattering strength, and the relation between the amplitude of NLIWs and the integrated surface scattering strength anomaly. These empirical formulas provide a powerful tool to extract properties of NLIWs from remote sensing measurements in low-wind conditions. The application of these results concerning satellite derived NLIW surface signatures is encouraged. Further studies with simultaneous remote sensing and in situ measurements of NLIWs under different sea conditions are needed to improve the applicability of these results.

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APPENDIX

Construction of the Spatial Structure of NLIWs

We rotate the coordinate system so that the NLIW propagation path is the $x$ axis and the axis perpendicular to the propagation path is the $y$ axis. The normalized
surface scattering strength \( I(x, y, t) \) is averaged perpendicular to the propagating path (i.e., along the wave crest) as

\[
I(x, t) = \frac{1}{y} \int I(x, y, t) \, dy.
\]

We define a new coordinate \( x_w(t) \) moving with the NLIW, that is, \( x_w(t) = x(t) - R(t) \), where \( R(t) \) is the position of the NLIW center relative to the ship, \( x(t) \) is the position of the radar measurement relative to the ship, and \( x_w(t) \) is the position of the radar measurement relative to the NLIW center. The NLIW center is defined as the point where the maximum zonal velocity is captured by the shipboard ADCP.

During each NLIW event, all measurements of \( I(x_w, t) \) taken ahead of the propagating NLIW \( [I^a(x_w, t)] \) and those taken behind the propagating NLIW \( [I^b(x_w, t)] \) were averaged separately, yielding two representative spatial distributions of the surface scattering strength \( I^a_w \) and \( I^b_w \), that is,

\[
I^a_w = \frac{1}{m} \sum_{t=1}^{m} I^a(x_w, t), \quad (A2)
\]

\[
I^b_w = \frac{1}{n} \sum_{t=1}^{n} I^b(x_w, t), \quad (A3)
\]

where \( m \) and \( n \) are the number of radar images taken ahead of and behind the propagating NLIW, respectively.

Measurements of the shipboard ADCP and the echo sounder are also converted to the coordinate following the NLIW, expressed as

\[
x_w(t) = \int_{t_0}^{t} [U_s(\tau) - C(\tau)] \, d\tau - R(t_0), \quad (A4)
\]

where \( U_s \) is the ship speed computed from the ship GPS fixes and \( C \) is the speed of the NLIW estimated from the propagating speed of the band of enhanced surface scattering strength induced by the NLIW.

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