

# **Nonlinear Internal Waves in the South China Sea**

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Award #: N0001402IP20008  
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## **LONG-TERM GOAL**

To study nonlinear ocean internal wave processes in the South China Sea (SCS) by using satellite synthetic aperture radar (SAR) imagery, in-situ data, and numerical models to understand the environmental effects (e.g. bottom topography, shoaling, mixing, and current/shear) on nonlinear internal wave generation, evolution, and dissipation.

## **OBJECTIVES**

The objective of this study is focused on nonlinear internal wave and mesoscale feature (e. g. eddies, fronts) observations in the shelf-break region of the SCS. The effort is to support the Asian Seas International Acoustics Experiment (ASIAEX) for the ocean modeling and remote sensing. The task is concentrated on the collection, processing and analysis of RADARSAT SAR and mooring data in the SCS from ASIAEX-2001. Of particular interest is the generation of huge internal waves caused by the branch out of Kuroshio through Luzon Strait and its evolution and dissipation on the shelf break.

## **APPROACH**

The approach is to use the SAR data in conjunction with the in-situ measurements from field experiments to calibrate and validate SAR imaging mechanism of internal waves, and to integrate all data sets by nonlinear wave model for data assimilation. A validated and calibrated algorithm and model can be very useful for understanding of shelf processes and for the applications of the internal wave effects on acoustic propagation. A parametric study for various environmental conditions to assess the nonlinear effects such as bottom topography (across critical depth), shoaling, stratification, and dissipation has been conducted. The generation and evolution of nonlinear internal waves (elevation versus depression, and mode-one versus mode-two), and wave-wave interaction have been studied using satellite data in conjunction with in-situ data from the field experiments.

The ASIAEX has been conducted in SCS in May 2001 and this joint experiment from US, Singapore, and Taiwan used three ships from Taiwan (R/V OR-1, OR-3, and Fisheries Researcher-1). The mooring deployments were done by the end of April, and SEASOAR surveys was carried out from April 29 to May 14. The intensive period of measurements was from May 3 to May 18. Four RADARSAT ScanSAR images (500\*500 km) from May 2, May 9, May 18, and May 11 (replaced by June 4), 2001 during ASIAEX have been collected and processed through RADARSAT International. More RADARSAT standard high-resolution SAR images (100\*100 km) from April 17, 18, 24 and May 1, 4, 5, 19, 26, 28 during ASIAEX have been collected through NRL. All data have been

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2002</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2002 to 00-00-2002</b>	
4. TITLE AND SUBTITLE <b>Nonlinear Internal Waves in the South China Sea</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Oceans and Ice Branch, NASA/GSFC Code 971,,Greenbelt,,MD, 20771</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>To study nonlinear ocean internal wave processes in the South China Sea (SCS) by using satellite synthetic aperture radar (SAR) imagery, in-situ data, and numerical models to understand the environmental effects (e.g. bottom topography, shoaling, mixing, and current/shear) on nonlinear internal wave generation, evolution, and dissipation.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

analyzed and are being synthesized/integrated by using numerical models (Liu et al., 1986; Liu, 1988; Liu et al., 1998).

## **WORK COMPLETED**

Besides it provides synoptic information, satellite remote sensing is critical to several aspects of ASIAEX, including tracking the internal waves, and locating surface fronts and mesoscale features. All SAR data have been processed and analyzed to compare with mooring data. During ASIAEX-2001, many marine radar images from R/V OR-1 have been recorded from May 3 to May 10. The ship track was focused on the shelf break area in shallow water with a serpentine pattern for internal wave evolution. These marine radar, EK500 echo sounder, ship-board ADCP, and SEASOAR data are very useful to combine with SAR and mooring data for internal wave evolution study in the shelf break area. These data sets have been compiled with special focus on internal wave study, especially for internal soliton tracking in conjunction with SAR and mooring data. The CTD castings are used for the calculation of wave dispersion relation.

Most of oceanography data collected have been processed. The SAR data are used to compare with mooring data at several stations. Based on the SAR image, two large internal wave packets in the ASIAEX area can be identified on May 9 which is close to the spring tidal cycle (May 10). Based on the separation distance between packets and semi-diurnal tidal theory, the wave speed and direction in deep basin can be estimated to be 1.7 m/s and 28 degree from west. Based on this radar backscatter data, three solitons are observed in a wave packet, and their wavelengths (or separation distances) can be estimated as summarized in Table 1. The soliton widths in two packets can also be estimated to be 1.4 and 2.5 km from KdV type model as discussed by Zhang et al. (2001) using SAR transect data. A numerical model of nonlinear internal wave evolution has been used to assimilate these data sets.

## **RESULTS**

Mooring data from S2, S4, S5, S6, S7, and S8 are used for this internal wave study. The water depths of each mooring and the separation distances between them are summarized in Table 1. There are two wave packets can be clearly observed in the SAR image on May 9. First the soliton packets are identified from ADCP data based on SAR image information, so the shift/lagging time between moorings can be estimated from the arriving time of each identified packet. Then ADCP velocity components have been re-combined or rotated to find the direction of maximum current induced by internal waves which is the internal wave propagation direction. The mooring horizontal line is about 16 degree from the North (or 74 degree from the West). So, the shift distances between moorings along wave propagation can be calculated as listed in Table 1. Using the shift distance and time, the internal wave speed between moorings for each packets have been computed to compare with SAR data result.

In general, the internal solitons observed in the SAR images are consistent with those mooring data as summarized in Table 1. Based on the preliminary study of internal wave evolution in the ASIAEX area from SAR and mooring data, the typical internal wave characteristics in SCS on May 9, 2001 can be summarized as follows:

- Water Depth : 800 m to 70 m
- Internal Wave Direction: 25° to 75°
- Internal Wave Speed: 1.7 m/s to 0.72 m/s

- Soliton Width: 2.5 km to 0.7 km
- Soliton Number: 5 to 3 to wave train
- Soliton Separation: 9.7 km and 2.4 km to wavelength of 1.2 km
- Wave Amplitude: 90 m to 40 m

These observations have provided a calibration on SAR data and inputs for the numerical simulation of nonlinear wave evolution on the continental shelf.

It is clear that these internal wave observations in the South China Seas provide a unique resource for addressing a wide range of processes. Among these the following may be included: the generation of elevation internal waves by upwelling due to the Kuroshio intrusion across the continental shelf, the generation of internal waves by current-island interaction, the evolution of nonlinear depression waves through the critical depth, the disintegration of solitons into internal wave packets, internal wave breaking and turbulent mixing on wave propagation, the shoaling effects of variable bottom topography on wave evolution, generation of mode-two waves, and internal wave-wave interaction. Numerical simulations for data assimilation have been performed by using internal wave field in the deep water region observed from SAR images as an initial condition to produce the wave evolution and to compare with the mooring observations downstream in the ASIAEX test site (e.g. S4, S5) in SCS.

However, the internal wave field in ASIAEX area sometimes can be quite complicated. As shown in SAR image on May 18, besides the regular nonlinear internal wave packet propagating in the west direction, there are second packets refracted and generated by Dongsha Island propagating to the north in ASIAEX area. These two wave systems were merged as a circle by the nonlinear wave-wave interaction. Two-dimensional wave pattern of this two-wave field is crucial for the interpretation of acoustic measurement since the time spread and bias depend critically on soliton number and location. Consistent results from May 4 and 5 SAR data have also been analyzed and show good agreement with mooring data.

The mesoscale variability, mean horizontal and vertical shears and varying stratification near the shelf-break are highly transient in April/May during the spring transition from winter monsoon to summer typhoon season. Therefore, the evolution of internal solitons in the ASIAEX test area at shelf-break is complicate in April/May with many interested features such as mode-two solitons. For the internal wave study, it is hoped that issues on generation, evolution, and dissipation in SCS can be addressed based on the data analysis of ASIAEX project. An ONR ASIAEX analysis workshop will be held from October 14 to 18, 2002 in China to present progress towards completed manuscripts for submission to the IEEE Journal of oceanic Engineering special issue on ASIAEX results. Dr. Antony Liu has been invited to be a guest editor of this IEEE/JOE special issue.

**Table 1. Summary of SAR and Mooring Data Comparison (May 9-10, 2001)**

SENSOR (ADCP)	S2	S4	S5	S6	S7	S8	SAR
DEPTH (m)	71	120	184	275	350	800	---
DISTANCE (km)	34.1	8.5	12.9	12.0	88.1		
SHIFT TIME (min)	762	162	134	91	415		744
	---	160	132	91	468		
IW DIR (deg)	75/85	45	45	25/5	25	---	28
MOOR DIR	16	16	16	16	16		
SHIFT DIST (km)	33.1	7.4	10.0	6.2	44.1		76
IW SPEED (m/s)	0.72	0.76	1.24	1.14	1.77		1.70
	(0.51)	0.77	1.26 (1.14)	1.14	1.57 (1.47)		
IW WIDTH (km)	---	0.7	1.5	0.9	1.4	---	1.4
			1.6	1.5	1.4		2.5
SOLITON #	---	---	3	3	3	5	3
IW LENGTH (km)	---	1.2	2.4-1.6	4.2-1.6	4.4-2.1	9.7-2.4	3.2-2.0
CURRENT (m/s)	0.3	0.5	0.8	0.6	1.1	---	---
	---	0.4	1.2	1.2	1.3	---	---
AMPLITUDE (m)	---	---	55	(32/63)	75	---	---

## IMPACT/APPLICATIONS

It is clear that these internal wave observations in the South China Seas provide a unique resource for addressing a wide range of processes (Liang et al., 1995; Liu et al., 1996, 1998; Hsu and Liu, 2000). These processes are listed as follows: the generation of elevation internal waves by upwelling, the evolution of nonlinear depression waves through the critical depth, the disintegration of solitons into internal wave packets, internal wave breaking induced by solitons, the generation of mode-two internal waves, and internal wave-wave interaction. The inclusion of these physical processes is essential to improve quantitative understanding of the coastal dynamics. The ASIAEX has been conducted in the East and South China Seas in May 2001. One of the major tasks is to study the effects of large-amplitude internal wave packets on the propagation, scattering, and volume interaction of low frequency sound propagating up the continental slop and shelf.

## TRANSITIONS

The internal wave evolution model developed by Dr. Antony Liu has been used in a NRL study of internal wave effect on acoustic propagation. Recently, the internal wave distribution maps from more than three hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images in the East and South China Seas from 1993 to 2000 have been compiled for ASIAEX field test planning and operation (Hsu et al., 2000). These internal wave distribution maps are the most recent and important information for future planning of internal wave related field tests in these areas. Near real-time processed SAR images can be very helpful for scientists on research ship to coordinate the survey strategy. Dr. Liu has written an article on satellite remote sensing: SAR in the Encyclopedia of Ocean Sciences (2001). He is actively participated in the field test and coordinates the joint efforts between participants from the US, China, Singapore, and Taiwan. A validated and calibrated internal wave model can be very useful for understanding of shelf processes and for the applications of the internal wave effect on oil drilling platform, nutrient pump, sediment transport, and acoustic propagation.

## RELATED PROJECTS

This study is jointly funded by ONR Physical Oceanography and Ocean Acoustics Programs for ASIAEX support. Dr. Antony Liu has participated in the field test stationed at Taiwan during the ASIAEX-2001. He has also established an internal wave project with the National Taiwan University as a part of Kuroshio Upstream Dynamics Experiment (KUDEX) funded by Taiwan's National Science Council. Hydrographic surveys by Taiwan's research ships with CTD casts, thermistor chains, acoustic echo sounder, marine radar, and ADCP have been conducted during ASIAEX-2001 by Prof. David Tang and Joe Wang of the Institute of Oceanography of the National Taiwan University and Prof. Ming-Kuang Hsu of the National Taiwan Ocean University. The SPOT images have been collected and processed in near real-time at the Taiwan ground station. RADARSAT SAR images were collected and processed through RADARSAT International as an approved research project and through NRL. These in-situ measurements have provided a calibration on SAR observations and inputs for the numerical simulation of nonlinear wave evolution on the continental shelf.

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### **PATENTS**

Distinguished Science Award from Pan Ocean Remote Sensing Conference (PORSEC) Association