# Doppler sonar measurements of internal solitary wave wakes

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## Abstract

*During the spring tides of late November 1992, early January and early February 1993, solitary internal wave packets were observed at 2° S, 156° 15′ E in the western equatorial Pacific. Apparently generated in the Nuguria island group (3° S, 153° E), the waves propagate northeastward at 2.4-2.8 $ms^{-1}$, appearing in fixed phase with the underlying semi-diurnal baroclinic tide. The initial solitary wave crests have downward displacements in excess of 60 m and peak velocities greater than 80 $cms^{-1}$. The solitons displace the ambient equatorial currents, including the Equatorial Undercurrent, both vertically and laterally (1-2 km), with little apparent interaction.*

*A 161 kHz Doppler sonar mounted on the R. V. John Vickers provided ocean velocity measurements with 3 m vertical resolution, 2 minute time resolution in the upper 250 m of the sea. The sonar detected pronounced internal wave "tails" following several solitons. These are apparently triggered disturbances on the pre-existing flow. High frequency shears are oriented nearly orthogonal to the low frequency background, independent of the propagation direction of the soliton.*

## 1. Introduction

In many problems in oceanography, currents are sufficiently strong that measurement arrays are deformed by the passage of the phenomenon under investigation. Such is the case with internal solitary waves, which can not only damage oceanographic moorings, but have been known to damage offshore structures (such as oil platforms) as well. Acoustic Doppler techniques are proving to be very effective in solitary wave studies, suffering minimal distortion from the waves themselves. To illustrate this capability we examine examples of solitary wave propagation through the Equatorial Undercurrent in the western tropical Pacific and the apparent wakes generated by some of these waves.

## 2. Background

Some of the warmest surface waters in the world are found in the western equatorial Pacific. Temperatures in excess of 28°C occur from the date line westward into the Indian Ocean in a band roughly ±10° about the equator. The strong surface heating of the region, with attendant evaporation, provides driving impetus to the large scale atmospheric circulation. Fluctuations in the state of this so-called "Warm Pool" are associated with subsequent oceanic and atmospheric fluctuations eastward along the equator and throughout the Pacific Basin.

To investigate the physics of this region, a multi-national air sea interaction experiment, TOGA COARE, was conducted during 1992-93. The COARE Intensive Observing Period (IOP) was fielded during the Northern winter of 1992-93. Three aircraft, seventeen ships and hundreds of people assembled in the region in an attempt to document the local heat budget precisely.

At the time of COARE, it was not appreciated that the Warm Pool was also significant as a dissipation region for the M2 barotropic tide. Subsequent TOPEX Poseidon measurements indicate that as much as 90 GW of tidal energy is dissipated in the broad region stretching from the Solomon Islands northward over the Ontong-Java Plateau to the equator and eastward through the Central South Pacific (Egbert, his region 6) [1]. Independent modeling studies indicate the region is also a source for baroclinic internal tides (Sjoberg and Stigebrandt [2], Morozov [3]). From a synthesis of direct observations, Feng *et al.* [4] report 538 $Wm^{-1}$ (0.5 gW across a 1000 km wavefront) radiating northeastward in the mode-one baroclinic tide.

Tidal concerns were brought to the attention of COARE investigators with the sighting of numerous large amplitude (~60 m) non-linear waves, propagating towards the northeast through the COARE Intensive Flux Array (centered at 2°S, 156°E, Figure 1). A variety of phenomena, including distortion of baroclinic tidal crests, solitons, and bore-like flows were observed. The solitons are similar to those sighted in the Andaman and Sulu Seas (Osborne and Burch [5], Apel *et. al.* [6]).

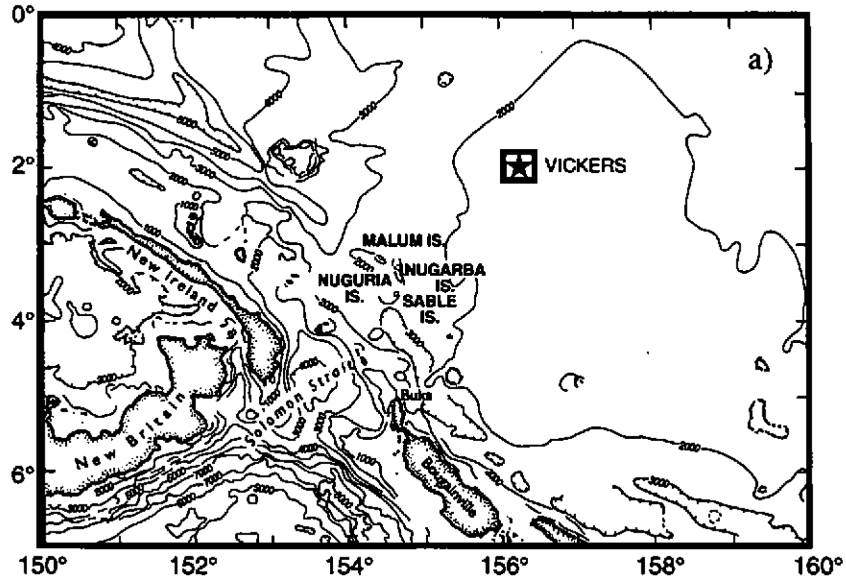


*Figure 1. The bathymetry of the COARE region*

A bore-like aspect of these motions is often seen, as recently emphasized by Henyey and Hoering [7]. However, given the periodic nature of the phenomenon, the bore-like "aftermath" of soliton passage is itself linked to the underlying tide. Indeed, the bore is manifest as an extremely skewed tidal waveform.

The COARE measurements are described briefly below, followed by an examination of several solitons and soliton tails.

## 3. Observations

The COARE Intensive Flux Array (IFA) was centered over the western edge of the Ontong-Java plateau. Water depth at the site is 1800 m. To the west and south, depth is highly variable, with 4 km water interspersed with island chains such as the Solomons, New Guinea, and Indonesia (Figure 1). Non-linear wave activity was seen in the region during the spring tides of January 8 - 12 and February 6 - 11. Ray *et al.* [8], and Schrama and Ray [9], have produced a global model of the semi-diurnal tides based on Topex Poseidon altimetric data. In the IFA, their model shows peak tidal elevations of ± 48 cm and ± 58 cm for these spring tides, in contrast to the ± 42 cm maximum displacements during typical spring tides.

In addition to the tides, the westward flowing S. Equatorial Current (0 ~ 150 m) and the southern flank of the Equatorial Undercurrent (150 - 250 m) occupy the site. The Equatorial Undercurrent is shallow during this period, between 125 and 200 m.

In COARE, the *R. V. Vickers* maintained station at 2°S, 156° 15′ E. The primary function of the ship was to support an on-board meteorological radar which mapped rainfall rates over the IFA. This function was successfully performed in three phases, 11 Nov–12 Dec 1992, 20 Dec–15 Jan, and 20 Jan–18 Feb 1993, separated by port calls in Honiara, Guadalcanal.

A CTD and Doppler sonar on the Vickers provided a view of the upper ocean. The Doppler sonar was constructed at the Marine Physical Laboratory of Scripps Institution of Oceanography. Four transducers, orthogonal in azimuth and 30° off vertical, were mounted on the hull adjacent to the ship's keel. Cylindrically symmetric acoustic beams of width ± 3° (to the 3 dB points) were formed. The sonar transmitted a repeat sequence code (Pinkel and Smith) [10] consisting of 5 repeats of a four bit code, with 0.25 ms/bit. The carrier frequency was 161 kHz. The nominal depth resolution of the sonar was 2.5 m. To realize this resolution, tilt corrections were applied in real time, enabling averages of echo intensity and covariance to be formed at fixed depths, rather than fixed ranges. Two-minute averaged records were stored on magnetic disk.

The sonar profiled to depths of 300 m while the ship was stationary. Propeller cavitation noise limited the range to 200-250 m when the ship traveled faster than 7 kts. Typically, the Vickers was in motion once or twice a day, repositioning to the anticipated up-drift edge of the watch circle.

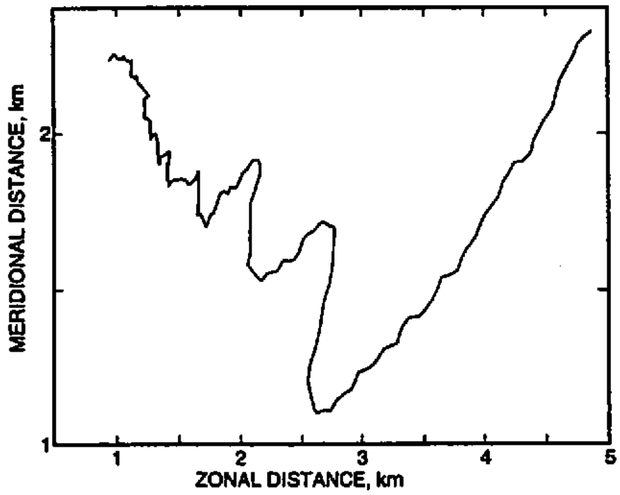


*Figure 2. Drift track of the R.V. Vickers over the five hour period 8:50-13:50 UTC, 11 January 1993, during passage of a non-linear wave train. The ship is initially at the upper right, drifting southwest.*

## 4. Event Passage

Internal solitary waves were observed in COARE in conjunction with the spring tides of late November, 1992, early January and early February, 1993. The underlying baroclinic tide appeared strongly non-sinusoidal over the few cycles preceding and following solitary wave sightings. The most consistent indicator of solitary wave activity was the ship's navigation record. The record for 11 January (Figure 2) shows the *Vickers* initial southwestward drift interrupted by a series of three abrupt offsets toward the north-northeast, each corresponding to the passage of a soliton crest. The aggregate displacement of the ship (as well as local surface drifters, biota, and the upper ocean itself) exceeds 1.5 km. Following passage of the packet, the southward component of drift is reversed while the westward component remains, resulting in the observed net flow to the northwest.

The final solitons of the February group were associated with distinct internal wave "tails". Acoustic intensity records are presented for the events of 10 February, 08:00 and 12 February, 23:30 UTC. The 10 February passage consists of two pronounced crests, the first perhaps exceeding 100 m in amplitude (Figure 3a). A third crest, following closely after the second, is apparent at depths of 200 m but not near the surface. Shortly thereafter the upper thermocline breaks into oscillations of ~5 m half-amplitude and 12 minute period. The wave-like disturbances spread to 200 m depth in the 5 hours after soliton passage and subsequently decay.

The soliton of 12-13 February, the last observed in COARE, consists of a single ~50 m downward crest (Figure 3b) followed almost immediately by an upper ocean (<150m) high frequency response (>7.5cph) and a lower frequency (~2cph) response at very high mode. The high mode waves have a vertical half-wavelength of ~80 m with amplitudes of ~±20 m. The downward crests at depths below 150 m have significantly greater amplitude than the upward crests at ~100 m. They appear extremely non-sinusoidal, with the upward displacement a mirror reflection of the downward. It is suggested that these high mode waves are interfacial solitons of the type investigated by Davis and Acrivos [11]. The COARE observations might represent a first sighting of these waves in the deep sea. [Qualification is necessary, in that we have no evidence that these are, in fact, of stable form.]

Is the energy for the wake coming from the soliton or the background shear? If the background shear is the energy source, one might expect a preferential relationship between shear direction and wake orientation. In turn, if the solitons generate the "wake", a relation between the direction of soliton propagation and that of the wake might be presumed. To investigate, "background" records of velocity and shear are formed by applying a one-hour running mean filter to the velocity data. The "high frequency wake" is defined as the difference between the instantaneous and "background" fields. In Figure 4a,b,c, the background and perturbation velocity vectors are plotted. Axes are oriented such that a velocity in the direction of soliton propagation appears as an upward pointing vector. Mean velocity vectors are plotted at 10 minute intervals. The difference between the mean and instantaneous velocity is plotted at 2 min intervals. Successive vectors are offset to the right to indicate the passage of time.

In the velocity records, the soliton arrival appears as a vertical pulse in the high frequency signal. Subsequently, there is little relation between the high frequency motions and the background. In contrast, high frequency shear (Figure 4d-f), taken as the velocity difference between 70 and 130 m, shows a marked preference in direction, being nearly orthogonal to the low frequency shear background. Neither shear nor velocity signals appear to exhibit a preferred direction relative to the soliton propagation path.

If the event passage could be viewed in plan, the "wake" pattern might appear as a "herringbone", with the long axis of the pattern oriented parallel to the mean shear, independent of soliton direction. In spite of their rapid onset, the wake waves are oriented so as to minimally exchange energy with the mean shear. The ultimate size of the fastest growing waves, oriented more nearly parallel to the shear, is presumably limited by instability.

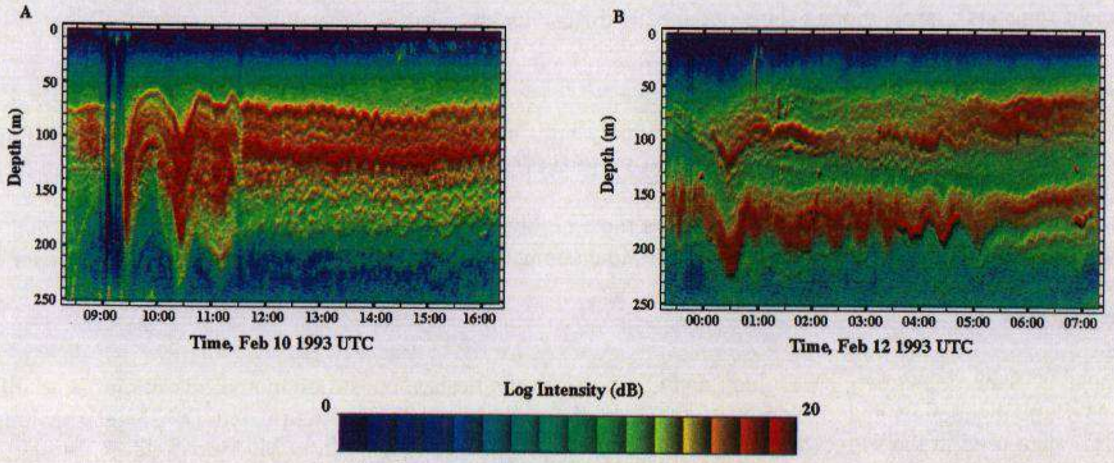


*Figure 3. Acoustic scattering strength for the February 10 and 12 solitons. There is a marked increase in high-frequency low-mode internal wave activity in the hours following passage of the February 10 packet. In addition to the enhanced low mode activity, high mode "interfacial" waves are seen in the hours following passage of the 12 February event.*

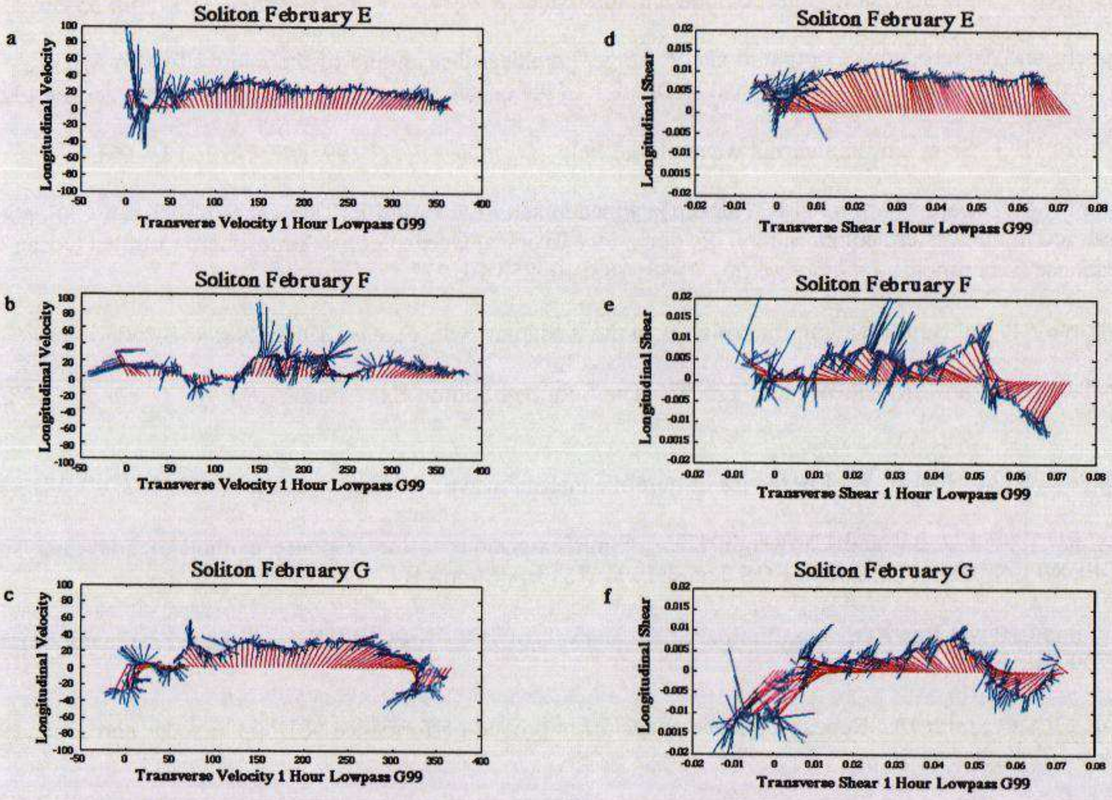


*Figure 4. Velocity (a,b,c 10-40 m average) and shear (d,e,f 70-130 m difference) during the passage of the February 10-12 events. Fields are presented in plan view as a sum of low frequency (<1cph) and residual (>1cph) components. Successive observations are offset to the right. Following the events, there is a clear preference for high frequency shear fluctuations to orient normal to the low frequency shear.*

## 5. Summary

During the spring tides of late November 1992, early January and early February, 1993, groups of internal solitary waves were observed propagating through the COARE domain. They travel northeastward at approximately 2.5 $ms^{-1}$ (as verified by radar, Pinkel *et. al.*) [12], closely coupled with the semi-diurnal tide. The Doppler Sonar on the R.V. Vickers was one of the few instruments in COARE which detected their passage.

The solitons of February 10-12 are associated with pronounced internal wave tails, which develop in the hours following soliton passage. The waves appear to be oriented normal to the dominant background shear, independent of the direction of soliton travel. The suggestion is that the solitons trigger instability of the background shear. The observed rate of wave development suggests a large, though short lived, eddy diffusivity, $K_v$, of:

$$K_v = 10^{-2} - 10^{-3} m^2 s^{-1} \quad (1)$$

acting to reduce the shear.

In the aftermath of the 12 February event, several extremely high mode (vertical half- wavelength 80 m) non-linear waves are observed. These are reminiscent of the interfacial solitons of Davis and Acrivos [11], and represent a rare deep-sea sighting of this phenomenon.

The long-term climatology of deep ocean solitary waves must be highly variable, changing with sea level fluctuations over thousands of years, and with ocean basin geography and tidal strength variations over hundreds of millions of years.

## 6. Acknowledgments

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