The Andaman Sea

Overview

The Andaman Sea is located along the eastern side of the Indian Ocean between the Malay Peninsula and the Andaman and Nicobar Islands (between approximately 6^o to 14^o N. latitude and 93^o to 99^o E. longitude). It is a maritime regime containing internal solitary waves of extraordinary amplitude (>60 m), wavelength (6 -15 km), and speed (> 2.0 m/s).

As far back as the mid-19th century surface manifestations of solitons have been observed consisting of strong bands of surface roughness. These bands were referred to as "ripplings", due to their mistaken association with rip tides. A description of such bands can be found in the book of Maury (1861) published in 1861 and which is quoted in Osborne and Burch (1980):

> "In the entrance of the Malacca Straits, near Nicobar and Acheen Islands, and between them and Junkseylon, there are often strong ripplings, particularly in the southwest monsoon; these are alarming to persons unacquainted, for the broken water makes a great noise when the ship is passing through the ripplings at night. In most places ripplings are thought to be produced by strong currents, but here they are frequently seen when there is no perceptible current…so as to produce an error in the course and distance sailed, yet the surface if the water is impelled forward by some undiscovered cause. The ripplings are seen in calm weather approaching from a distance, and in the night their noise is heard a considerable time before they come near. They beat against the sides of the ship with great violence, and pass on, the spray sometimes coming on deck; and a small boat could not always resist the turbulence of these remarkable ripplings."

The Andaman and Nicobar Islands on the western side of the Andaman Sea are volcanic in origin. As a result the water depth in the region changes rapidly from over 3000 m in the Indian Ocean, to approximately 200 m in the areas around the islands, returning to 2000+ m in the Andaman Sea (Figure 1). These bathymetric changes take place over approximately 150-km horizontal distance. The sills between the islands, as well as a number of underwater volcanic seamounts, are all potential sources of internal waves. The result is an area rich in internal wave excitations and complex soliton - soliton interaction.

Space Shuttle photography from May 1985 (figure 5) clearly shows a source of internal waves in or near the Sombreno Channel, at the south end of Nancowry Island. Alpers et al. (1997) has examined SAR images from ERS-1/2 acquired by the receiving station in Singapore that became operational in 1995. He reports 385 100-km x 100 km SAR scenes collected over the Andaman Sea available for his investigation. Using the ERS scene in figure 6, in connection with other images, Alpers estimated three sources for the waves:

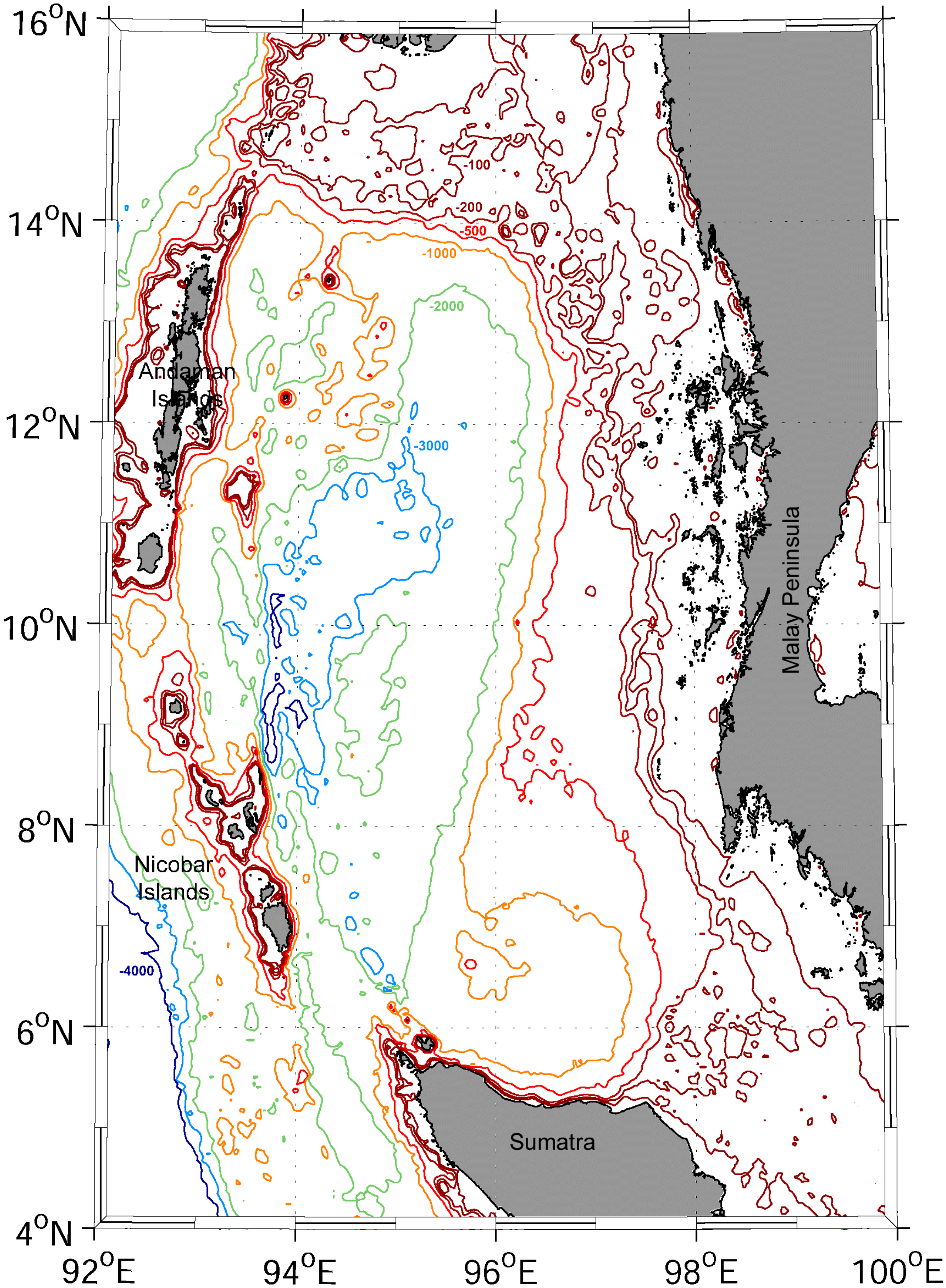

Figure 1: Bathymetry map of the Andaman Sea. (Bathymetry derived from Smith and Sandwell version 8.2)

- the shallow reefs off the northwest coast of Sumatra, around 6°10'N. 95°0'E. (Indonesian name: Alur Pelayaran Bengala), where, near the 1000 m depth line, a coral reef rises up to a depth of 30 m below the sea surface,
- the seamounts at 8°50'N. 94°56'E.; 9°04'N. 94°34'E.; and 8°42'N. 94°30'E., which have depths of 481 m, 671 m, and 680 m, respectively, and which are located in an ambient sea area which has a depth of more than 2500 m, and
- a submarine bank located at 12°34'N. 94°40'E. which rises from a 1800 m to 2500 m deep ocean floor to a depth of 88 m below the sea surface.

In addition, at least one source must exist in the northeastern part of the Andaman to account for westward propagating internal waves observed in SIR-A (figure 8) and DMSP (figure 9) images.

Table 1 presents a summary of internal wave characteristics from the Andaman Sea. The values have been reported in the literature and derived from both in-situ and remote sensing data sources. Table 2 shows the months of the year during when internal waves have been observed in the Andaman Sea. It is believed that the waves occur year round and that the August and September gap would be eliminated with the examination of more imagery.

Table 1. Characteristic Scales for Andaman Sea Solitons

Packet Length L (km)	Along Crest Length C_r (km)	Maximum Wavelength λ_{MAX} (km)	Internal Packet Distance D (km)
30-75	75-150	6 - 15	75-115
Amplitude $2h_0$ (m)	Long Wave Speed c_0 (m/s)	Wave Period (min)	Surface Width l_1(m)
-60 to -70	> 2.0	5 - 95	600 - 1000

Table 2 - Months when Internal Waves have been observed In the Andaman Sea.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
X	X	X	X	X	X	X			X	X	X

Observations

The first scientific reports of such large waves in the Andaman appear to have come from Perry and Schimke (1965) who, in 1964, made bathythermograph observations of an 80-meter-amplitude internal wave that had audible, breaking surface waves accompanying it.

In late 1975 and early 1976 Osborne et al. (1978) and Osborne and Burch (1980) carried out current-meter measurements on several packets of internal waves that had amplitudes of up to 70 meters and current speeds in excess of 2 meter per second and established their soliton like character. Figures 2 and 3 (from Osborne and Burch (1980)) show the temperature variations of internal waves measured in October 1976. The data in figure 2 show a thermistor chain temperature measurement taken during the passage of an internal wave packet and show the packets characteristic rank ordered signal. Osborne and Burch (1980) reported the lead

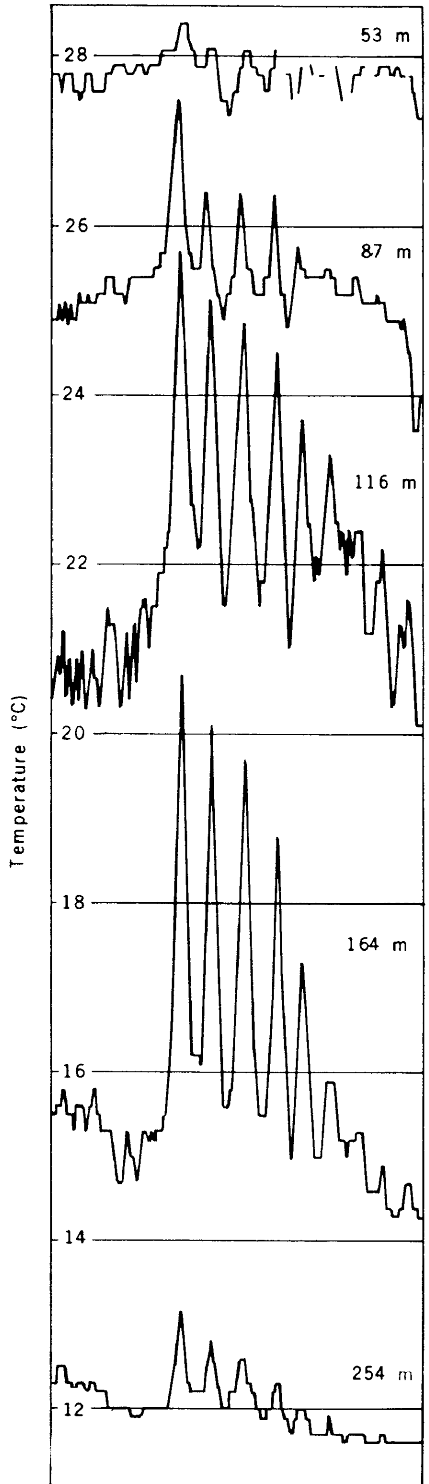

Figure 2. Temperature signals of an internal wave packet recorded by thermistor chain on 24 October 1976 at 6°53' N. and 97°04' E. (From Osborne and Burch 1980)

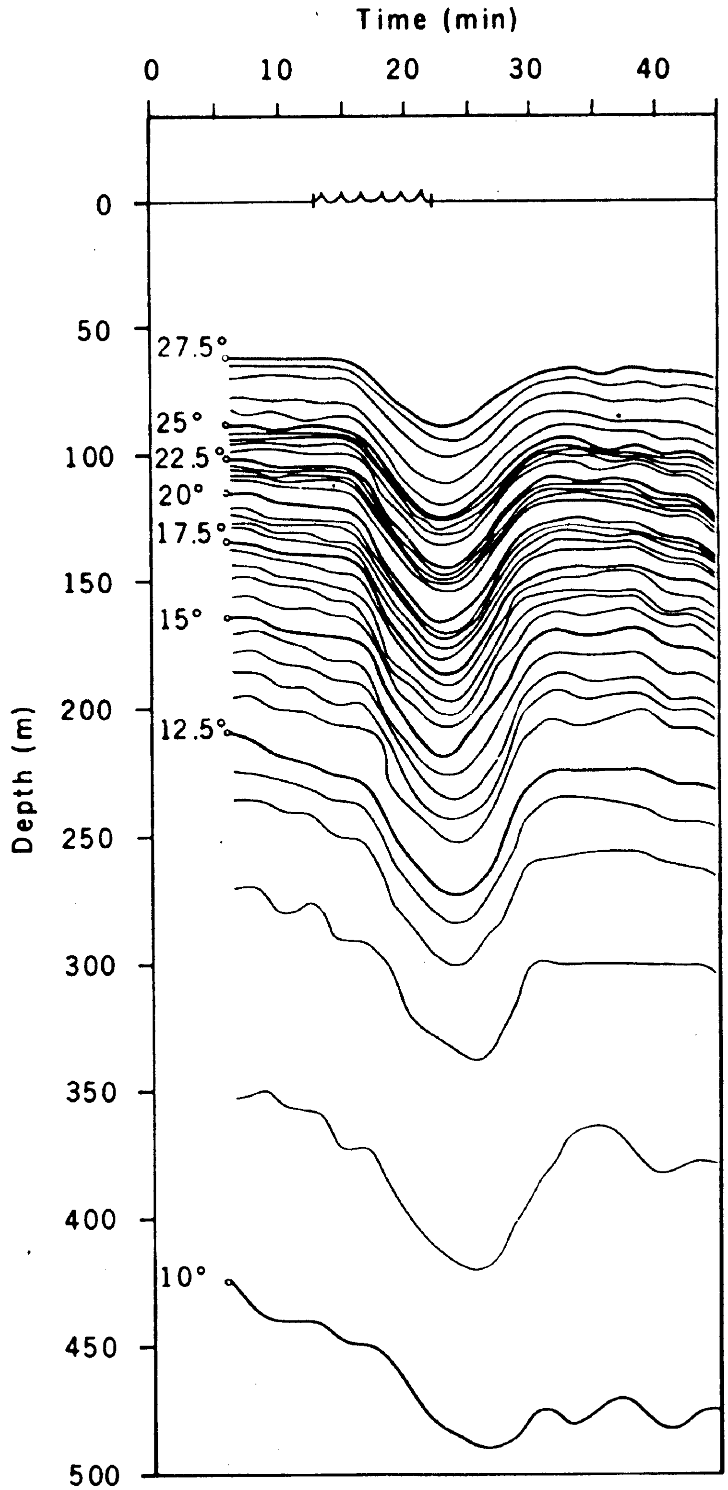

Figure 3. Isotherms of a 60-m internal wave recorded XBT casts on 25 October 1976 at 6°53' N. and 97°04' E. (From Osborne and Burch 1980)

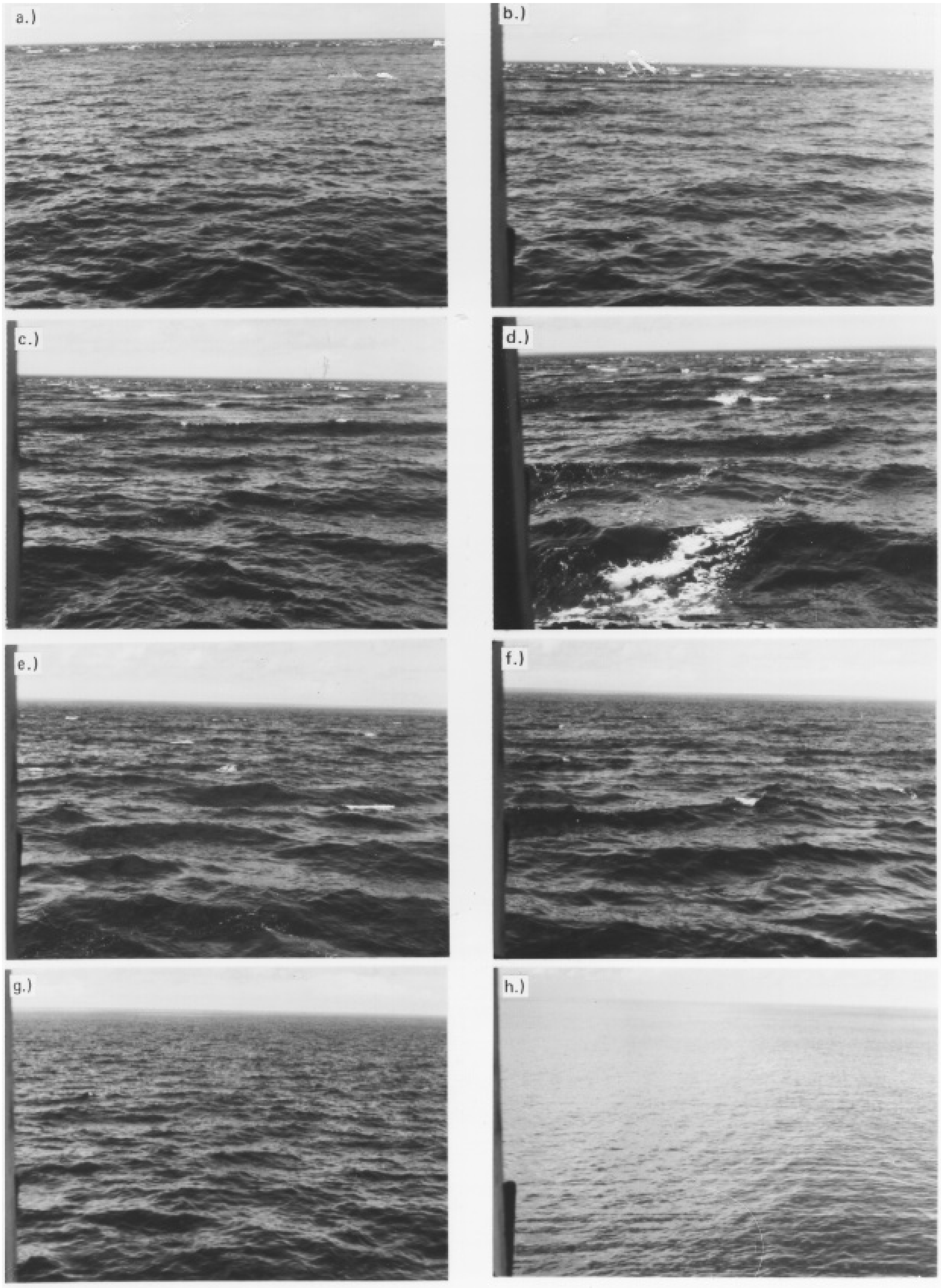
a.)
b.)
c.)
d.)
e.)
f.)
g.)
h.)

Figure 4 (Previous page): Sequence of Photographs of the Andaman Sea surface taken as a rip band approached from the west at a speed of 2.2 m/sec and passed the survey vessel on 27 October 1976 at 10:15 local time (Greenwich mean time +7 hours). The air temperature was 30^{o}C and the winds were calm during the sequence. (a) 10:15, the rip was seen in the distance stretching from one horizon to the other, as a well-defined line of breaking waves. The background sea state preceding the rip was ~0.6 m and approached from the west; (b) 10:16, the rip continued to approach in the background waves of ~0.6m; (c) 10:17, the rip had just arrived at the vessel with wave heights of ~1.8m; (d) 10:19 the survey vessel was tossed about in the 1.8-m waves of the rip band; (e) 10:22, the rearward edge of the rip was visible in 1.8-m waves; (f) 10:23, the rearward edge of the rip receded as the waves dropped to 1.3 m; (g) 10:25, the wave amplitude dropped to 0.6 m; (h) 10:32, the rip had completely passed as the waves dropped to ripples of ~0.1m. (From Osborne and Burch 1980)

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soliton amplitude of 60 meters. Figure 3 shows the isotherm displacement from a 60-meter internal wave obtained from XBT casts at 90-second intervals. A rip surface was observed on the leading edge. Figure 4 is a sequence of photographs published in Osborne and Burch (1980) and taken from the survey vessel during the passage of a rip band associated with an internal soliton.

Imagery

Internal wave signatures in the Andaman wave have been observed in astronaut photographs, DMSP, and Landsat optical images, as well as synthetic aperture radars SIR-A, ERS 1/2 and Radarsat-1.

Osborne and Burch (1980) reported the detection of internal waves in over 40 LandSat images. Five of those images containing waves with crests as long as 150 km and wavelengths as great as 15 km. The joint US-USSR space mission Apollo-Soyuz (July 22, 1975), returned color photographs that showed narrow strips of rough water in the sun glint region; one such photograph (AST-7-426) [Apel, 1979; Osborne and Burch, 1980; Apel at al., 1985] shows four packets of narrow, elongated strips near the region of Puket. Apel (1979) interpreted these as surface signatures of large internal waves presumably produced by the semi-diurnal tidal flow over underwater topography; the inferred group speeds were approximately 2.5 m/sec as derived from their interpacket separation. Astronauts on the Space Shuttle (STS075-709-53, 54,55) photographed a very similar scene in the sunglint region on February 27, 1996 (Fig 5). Three groups of internal waves are clearly visible, two propagating to the southeast, one to the northeast. Interpacket separation of the southeast packet is approximately 88 km with an inferred group speed of 2 m/s. The longest wave visible in the northeast group has an along crest length of around 150 km.

A Space Shuttle photograph (STS51B-53-097) taken on 5 May 1985 (Fig 6) shows two internal wave packets near Katchall and Nancowry Island. The first packet shows a continuum of waves for over 32 km as the packet propagates northeast into the Andaman Sea. The second packet, with just a few waves is seen breaking away from the lower end of Nancowry Island. This suggests that the waves originate on the shelf area just south of Katchall and Nancowry Island in the Sombreno Channel (Fig 7). The interpacket separation varies from approximately 35 km (0.78 m/s group speed) in the northeasterly direction to almost 48 km (1.1 m/s group speed) almost directly north. The variation in separation of the wavefronts could be due to advection by currents.

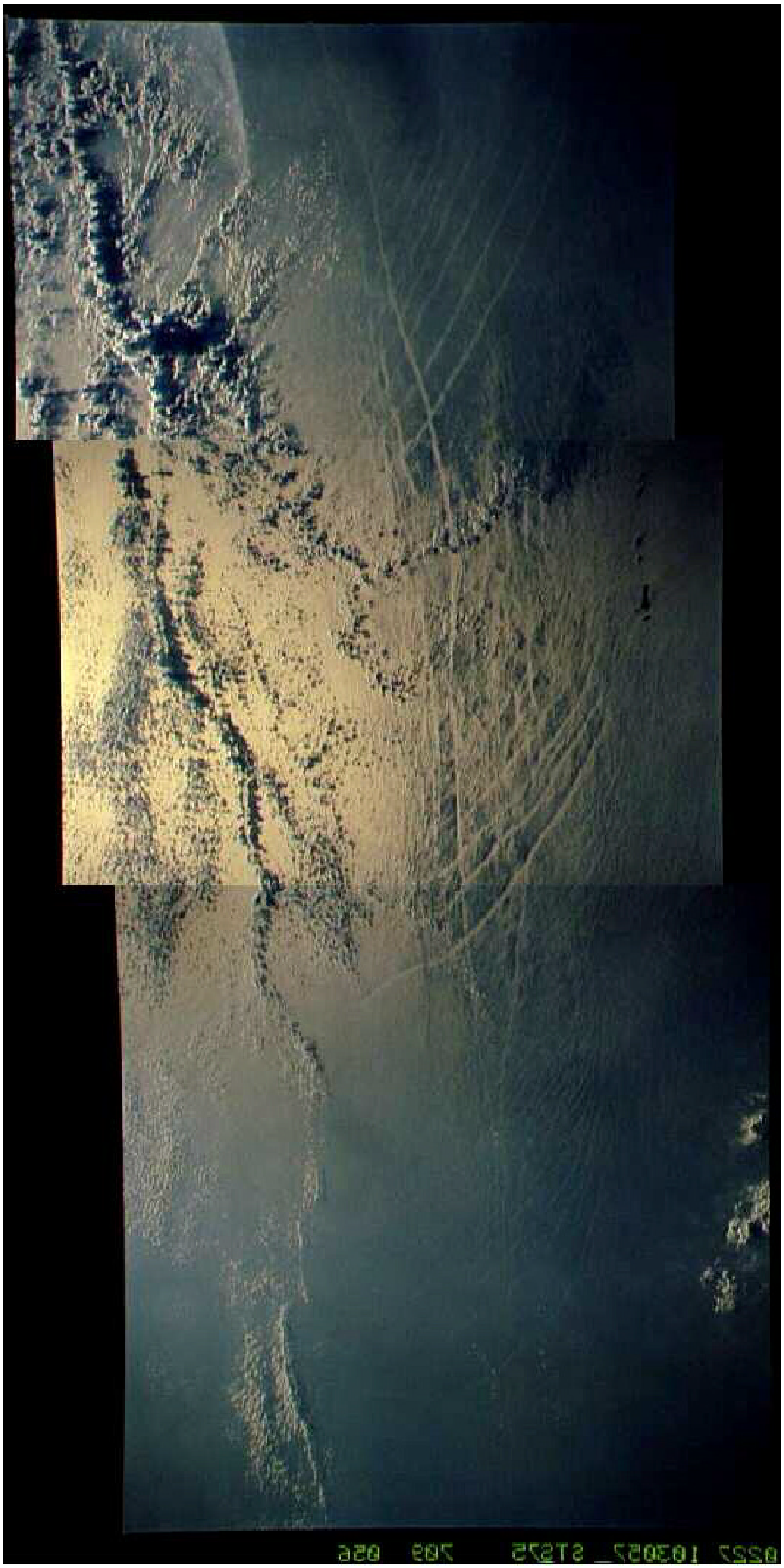

Figure 5. Space Shuttle Photograph (STS075-709-54, 55, 56) acquired February 27, 1996, 10:30 GMT. The image dimensions are approximatly 100 x 235 kms centered near 8^o N. 97.5^o E. Image Courtsey of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov)

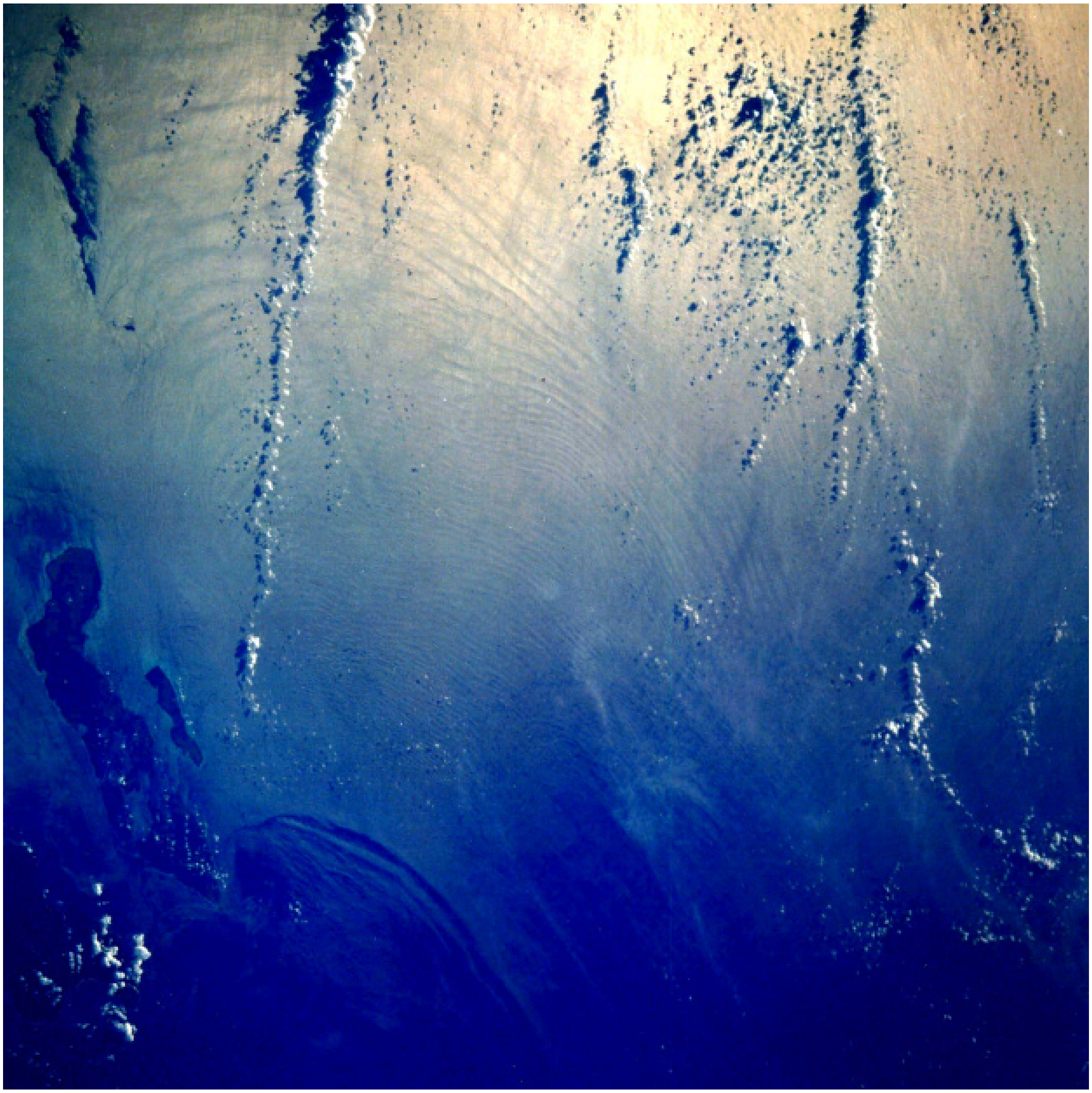

Figure 6. Space Shuttle Photograph (STS51B-53-97) acquired May 5, 1985, 01:42 GMT. Image dimensions are approximately 68 x 68 km centered near 8° N. 94° E. Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov).

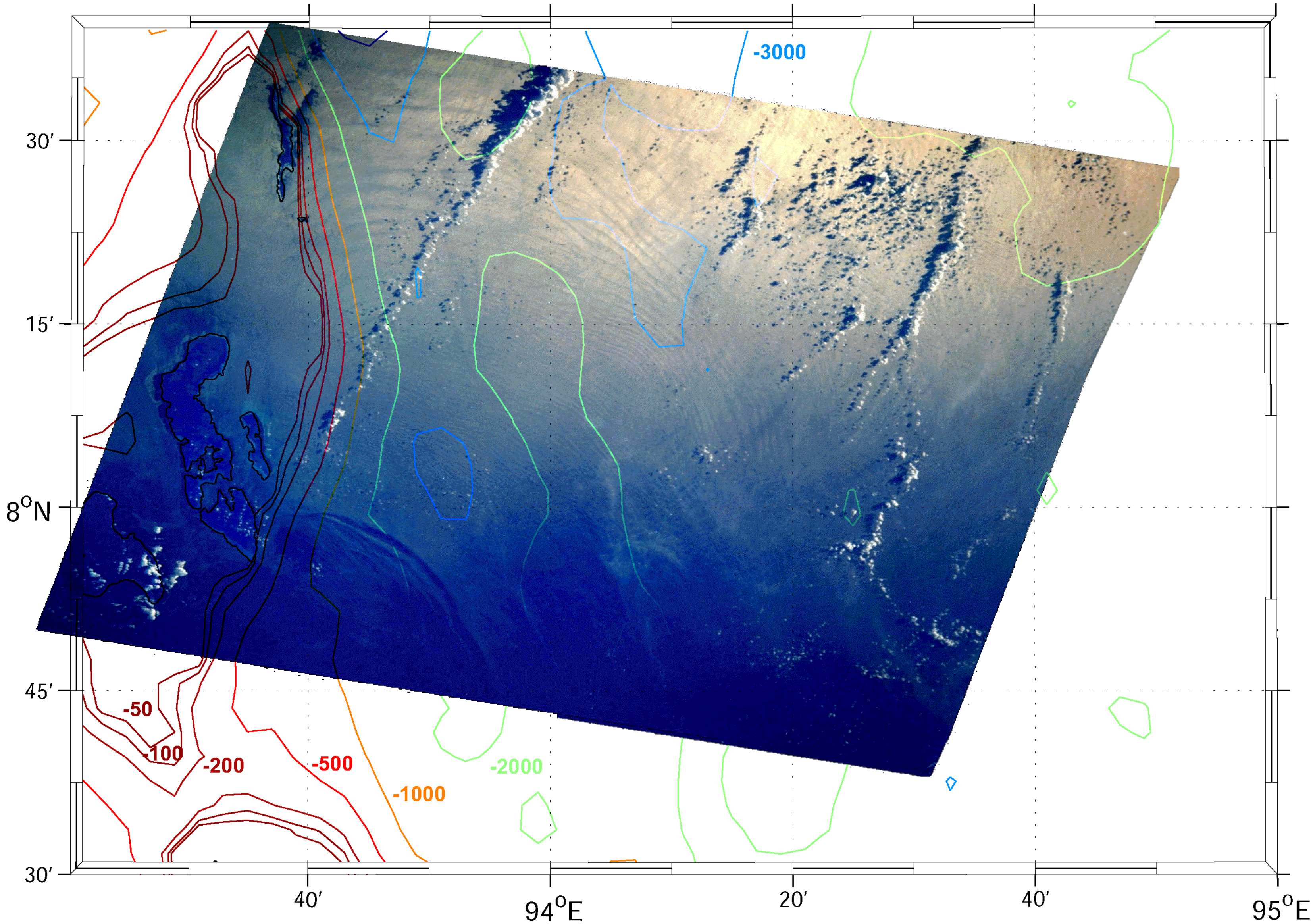

Figure 7. Space Shuttle Photograph (STS51B-53-97) shown with local bathymetry

One of the most spectacular images from the Andaman Sea was acquired by ERS-2 on February 11, 1997 (figure 8). The image, a composite of 9 ERS SAR frames (3357, 3375, 3393, 3411, 3429, 3447, 3465, 3483, and 3501) and covers an ocean area of approximately 900 km x 100 km extending from the northwestern coast of Sumatra (Indonesia) towards the NNE into the Andaman Sea. The image shows an exceptional wealth of strong sea surface manifestations of internal solitary wave packets.

While most internal waves observed in the Andaman Sea propagate westward towards the coast of the Maylay Peninsula, imagery has also shown westward propagating waves east of the Andaman Islands. Apel et al. (1985) analyzed synthetic aperture radar images from the Shuttle Imaging Radar-A (SIR-A) flight on November 1981 which contained several internal wave packets in the vicinity of the Andaman and Nicobar Islands [Cimino and Elachi, 1982; Ford et al., 1983]. Figure 9 is a section of the SIR-A radar image of November 11, 1981, having dimensions of 51.2 by 51.2 kilometers, with the white marks along the lower boarder being one second time ticks (or a distance of 7.14 kilometers). North is along the direction shown, at an angle of approximately 38 degrees from the lower edge. The internal solitons are revealed by the mostly dark (smooth) regions, with the associated rough regions not clearly visible, probably due to the large 43-degree earth incidence angle of the synthetic aperture radar. The SIR-A analysis produced an amplitude estimate of 60 meters and a current speed of 1.1 m/sec.

Figure 10 is a visible Defense Meteorological Satellite Program (DMSP) image of the Andaman Sea from 1979 (exact acquisition date unknown). The image shows two internal wave packets east of the Andaman Islands propagating to the west southwest. The interpacket separation is approximately 110 km with giving an implied group speed of 2.4 m/sec.

KDV Parameters

Figure 11 shows a typical density profile for the area derived from temperature and salinity data collected on February 1, 1972 at 7.00^0 N. latitude, 94.97^0 E. longitude. The normalized Mode 1 and Mode 2 eignefunctions have been evaluated for $l = \frac{2}{pk_0} = 1100m$, with H = 1000 m. For long waves ($k \to 0$) the maximum first mode wave speed (c_0) is computed to be 2.09 m/s without the effect of current shear. Figures 11e and 11f show the phase velocity and dispersion relations for the data. Table 2 presents the environmental coefficients and KDV parameters evaluated at k_0

Table 2. Environmental Coefficients and KDV parameters (λ_0=1100) Andaman Sea Solitons

Long Wave Speed c_0 (m/s)	Nonlinear coefficient $1/\alpha$ (m)	Dispersion Factor $\gamma^{1/2}$ (m)	Amplitude (KDV theory) h_0 (m)	Non-Linear Phase Velocity V (m/s) for (s^2=1)
2.09	-79.27	90.65	-31.88	2.65

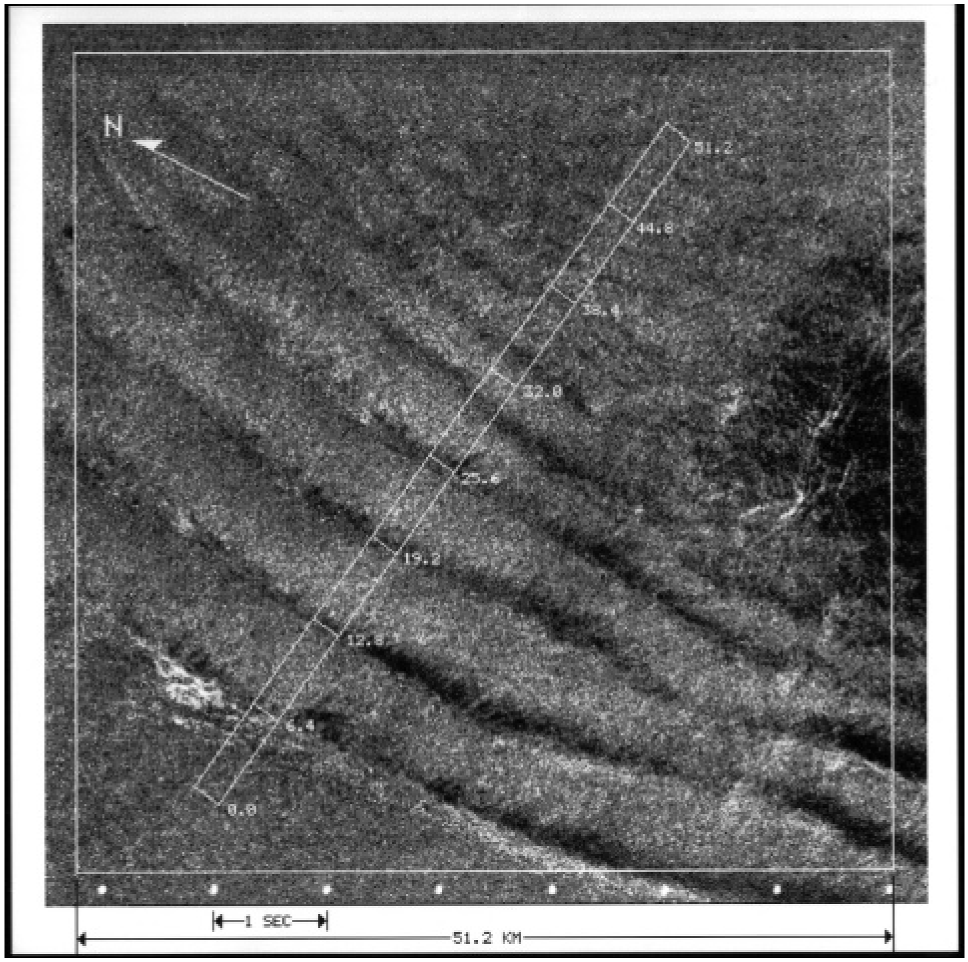

Figure 9 (Above) L-Band HH SAR image from SIR-A taken November 11, 1981, near the Andaman Islands, showing a packet of 6 km long solitons and what is thought to be a rain squall. Image dimensions are 51.2 x 51.2 kilometers. Image is located near 12.5° N 94° E. (Photograph courtesy of the Jet Propulsion Laboratory)

Figure 8 (Left). C-Band VV SAR image from ERS-2 taken February 11, 1997. Image dimensions are 100 x 900 km. The composite is made from ERS frames: 3357, 3375, 3393, 3341, 3429, 3447, 3465, 3483, and 3501. ©1997 ESA.

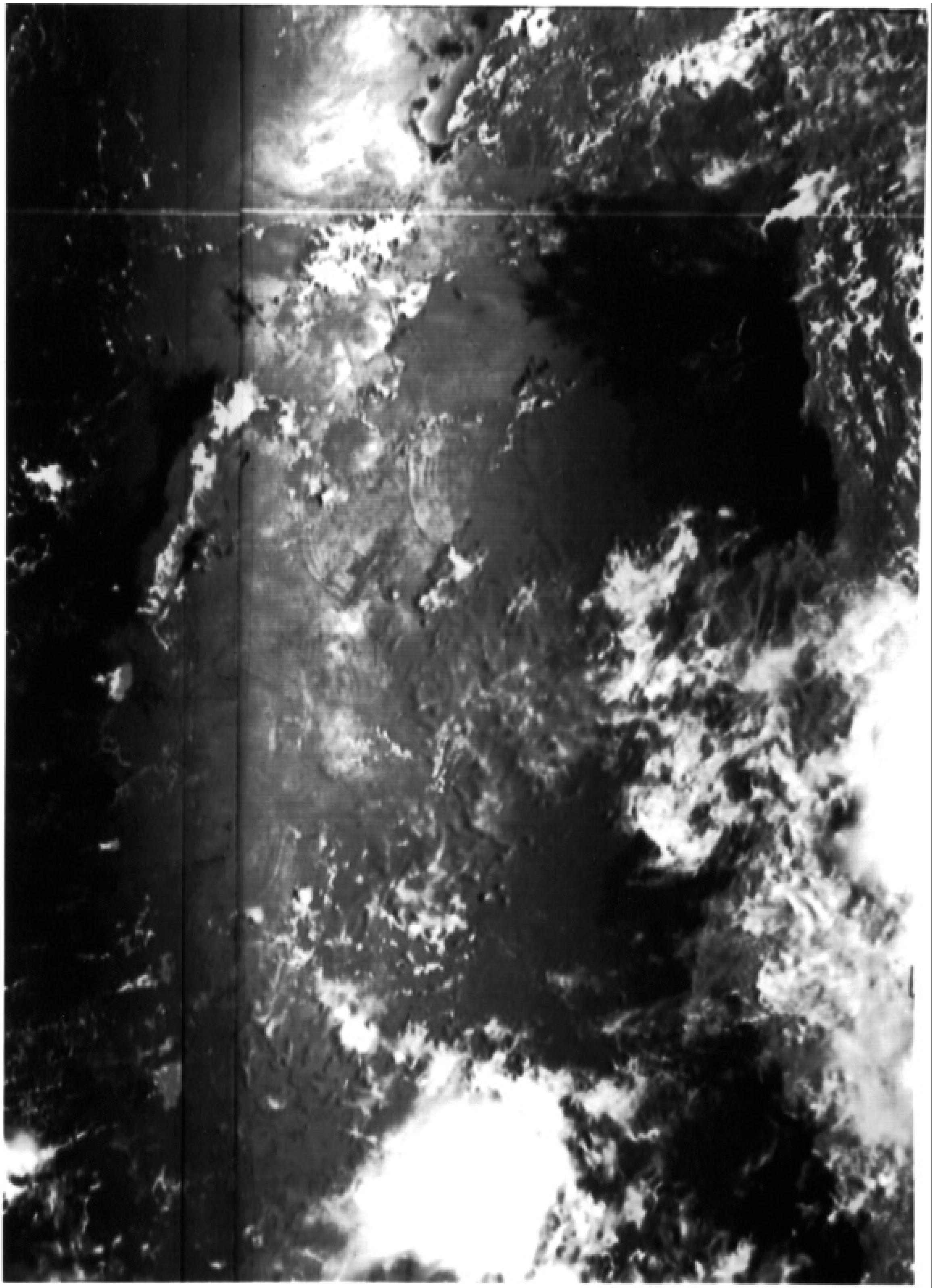

Figure 10. DMSP image of the Andaman Sea (1979) showing both eastward and westward propagating internal wave packets. The image is approximately 1200 x 870 km

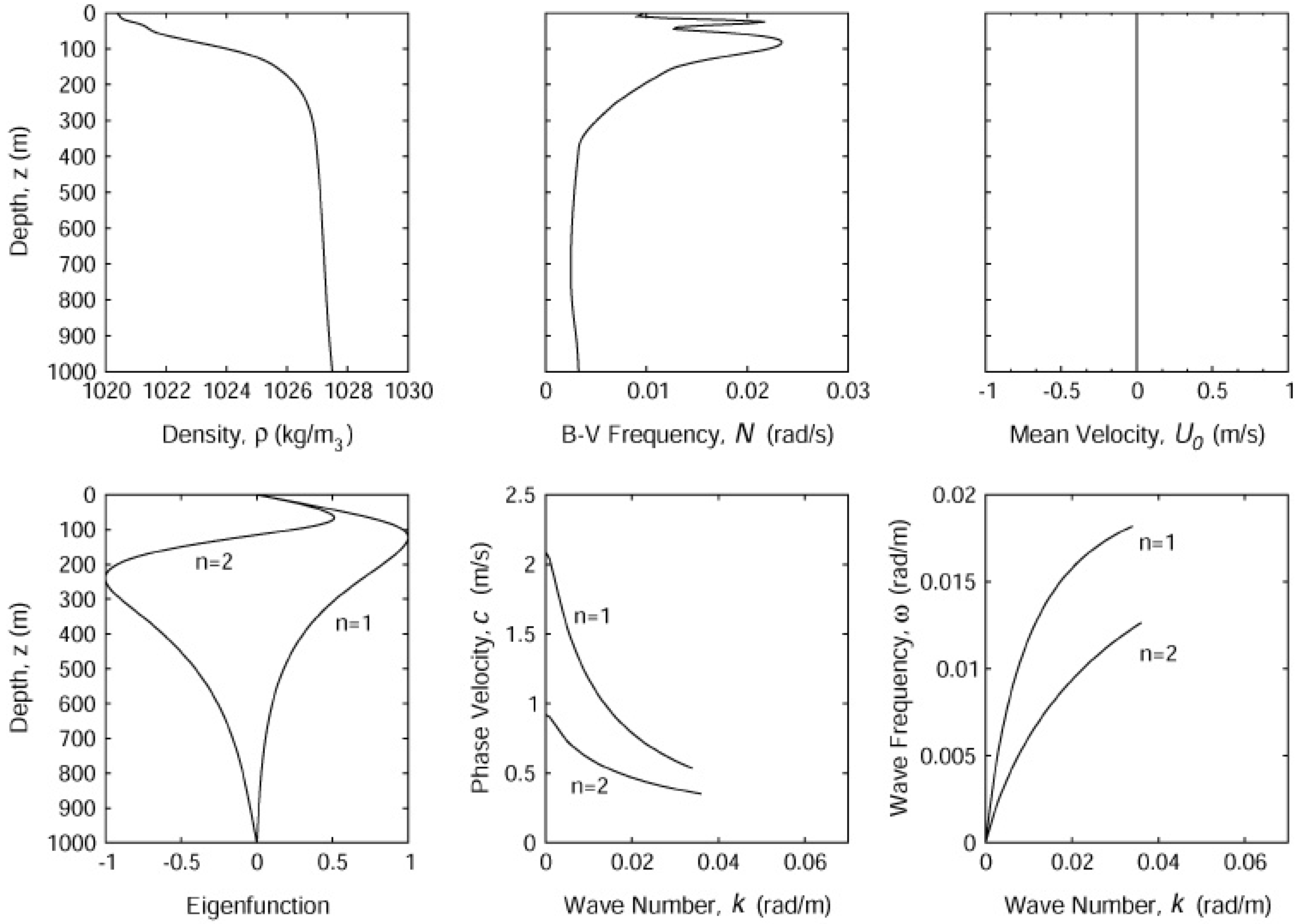

Figure 11. a) Density Profile derived from SD2 data collected on February 1, 1972 at 7.00^0 N. latitude, 94.97^0 E. longitude, depth = 1000 m (Source NODC Global Ocean Temperature and Salinity Profiles (Jun 1991) b) derived Brunt-Väisälä frequency *N*(z). c) zero flow current profile d) Normalized vertical eigenfunctions (mode 1 & 2) for $2\pi/k_1$ = 1100m, H = 1000 m for density and velocity profiles shown e) Phase Velocity f) Dispersion relations.

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Perry, R. B. G. R. Schmike, "Large Amplitude Internal Waves Observed Off the Northwest Coast of Sumatra," *J. Geophys. Res.* 70, 2319-2324 (1965).

Related Publications

Centre for Remote Imaging, Sensing and Processing, The National University of Singapore, Internal Waves in the Andaman Sea:
http://www.crisp.nus.edu.sg/~research/research/ocean/intWaves/index.html

The Tropical And Subtropical Ocean Viewed By ERS SAR, Werner Alpers, Leonid Mitnik, Lim Hock, http://www.ifm.uni-hamburg.de/ers-sar/

Oceanography from the Space Shuttle
http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/OCDST/shuttle_oceanography_web/oss_82.html