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 (Figure 1). It is a deep-water sea with exits to the Indian Ocean (to the west) and the Strait of Malacca (to the south).

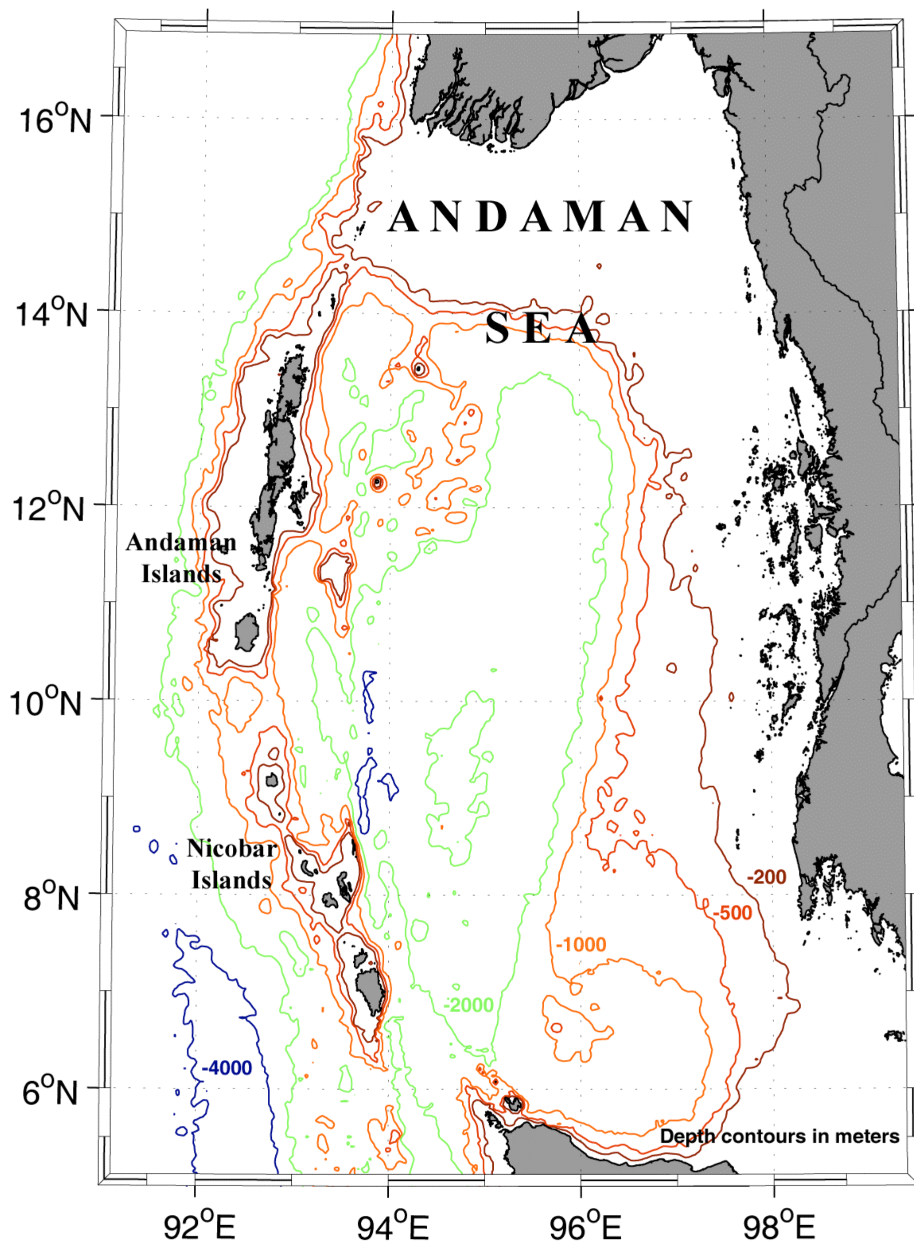


Figure 1. Bathymetry of Andaman Sea [Smith and Sandwell, 1997].

Observations

As far back as the mid-19th century surface manifestations of solitons have been observed consisting of strong bands of sea 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 first scientific reports of internal 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. Internal wave signatures in the Andaman Sea have been observed in a variety synthetic aperture radar and optical imagery including; ERS1/2, DMSP, MODIS, and astronaut photography as well as via in situ measurements. Table 1 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.

Table 1 - Months when internal waves have been observed in the Andaman Sea
(Numbers indicate unique dates in that month when waves have been noted)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
3	4	5	13	4	1		2		3	4	1

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.

Alpers et al. [1997] have examined SAR images from ERS-1/2 acquired by the receiving station in Singapore that became operational in 1995. They report 385 100 km x 100 km SAR scenes collected over the Andaman Sea available for their investigation (e.g. Figure 6). They identified several sources for the internal waves: (1) the shallow ridges between the Nicobar and Andaman islands, and (2) the shallow reefs off the northwest coast of Sumatra, around 6.17°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, (3) submarine banks, like the one located at 12.57°N. 94.67°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, several sources must exist in the eastern part of the Andaman Sea to account for westward propagating internal waves observed in SIR-A (Figure 12) and MODIS (Figure 7) images.

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 [Osborne and Burch, 1980] show the temperature variations of internal waves measured in October 1976. The data in Figure 2 originate from temperature measurements carried out by a thermistor chain during the passage of an internal wave packet. The data clearly delineate the rank ordered signal characteristic for packets of solitary waves. Osborne and Burch [1980] reported that the lead soliton has an 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. Table 2 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. Characteristic Scales for Andaman Sea Solitons

Characteristic	**Scale**
Amplitude Factor	-10 to –80 (m)
Long Wave Speed	> 2.0 (m s^{-1})
Maximum Wavelength	6 to 15 (km)
Wave Period	5 to 95 (min)
Surface Width	600 to 1000 (m)
Packet Length	30 to 75 (km)
Along Crest Length	30 to 150 (km)
Packet Separation	75 to 115 (km)

Figure 4 shows a typical density profile for the area derived from temperature and salinity data collected on 1 February 1972 at 7.00^0 N, 94.97^0 E. The normalized Mode 1 and Mode 2 eigenfunctions have been evaluated for $\lambda = \frac{2\pi}{k_0} = 1100m$, and a water depth of 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 4e and 4f show the phase velocity and dispersion relations for the data. Figure 4 presents the environmental coefficients and KDV parameters evaluated at wavenumber k_0

Figure 5 presents a sequence of photographs of the Andaman Sea surface [Osborne and Burch 1980] showing a rip band as it approached and passed the survey vessel on 27 October 1976. The rip band approached from the west and passed the vessel with a speed of 2.2 m/sec. Figure 7 shows a MODIS (Moderate Resolution Imaging Spectroradiometer) 250-m resolution image acquired over the entire Andaman Basin acquired on 17 April 2003 at 0655 UTC. Solar reflection shows roughness modulation patterns from more than 20 internal wave groups throughout the Andaman Sea. Figure 6 is an ERS SAR image showing an equally ubiquitous number of waves across the basin.

Figure 8 is an astronaut photograph (STS51B-53-097) acquired 5 May 1985 showing two internal wave packets near Katchall and Nancowry Island. The first packet shows a continuum

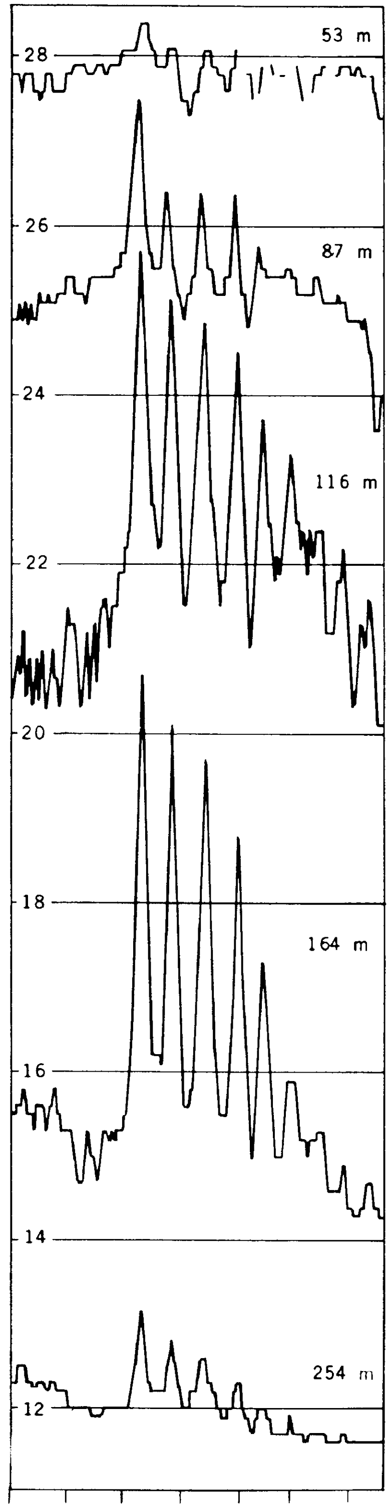


Figure 2. Temperature signals of an internal wave packet recorded by a thermistor chain on 24 October 1976 at 6°53' N. and 97°04' E. [After Osborne and Burch 1980]

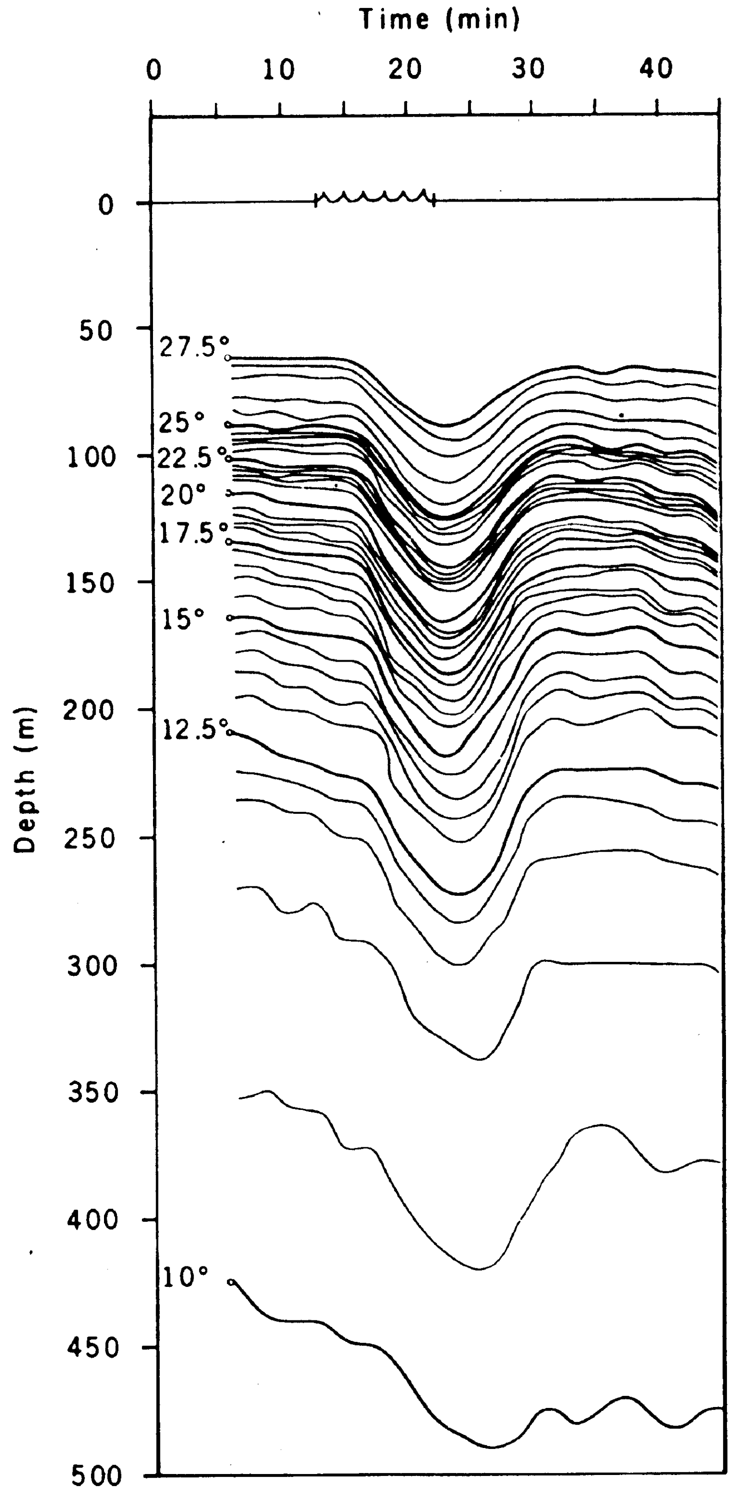
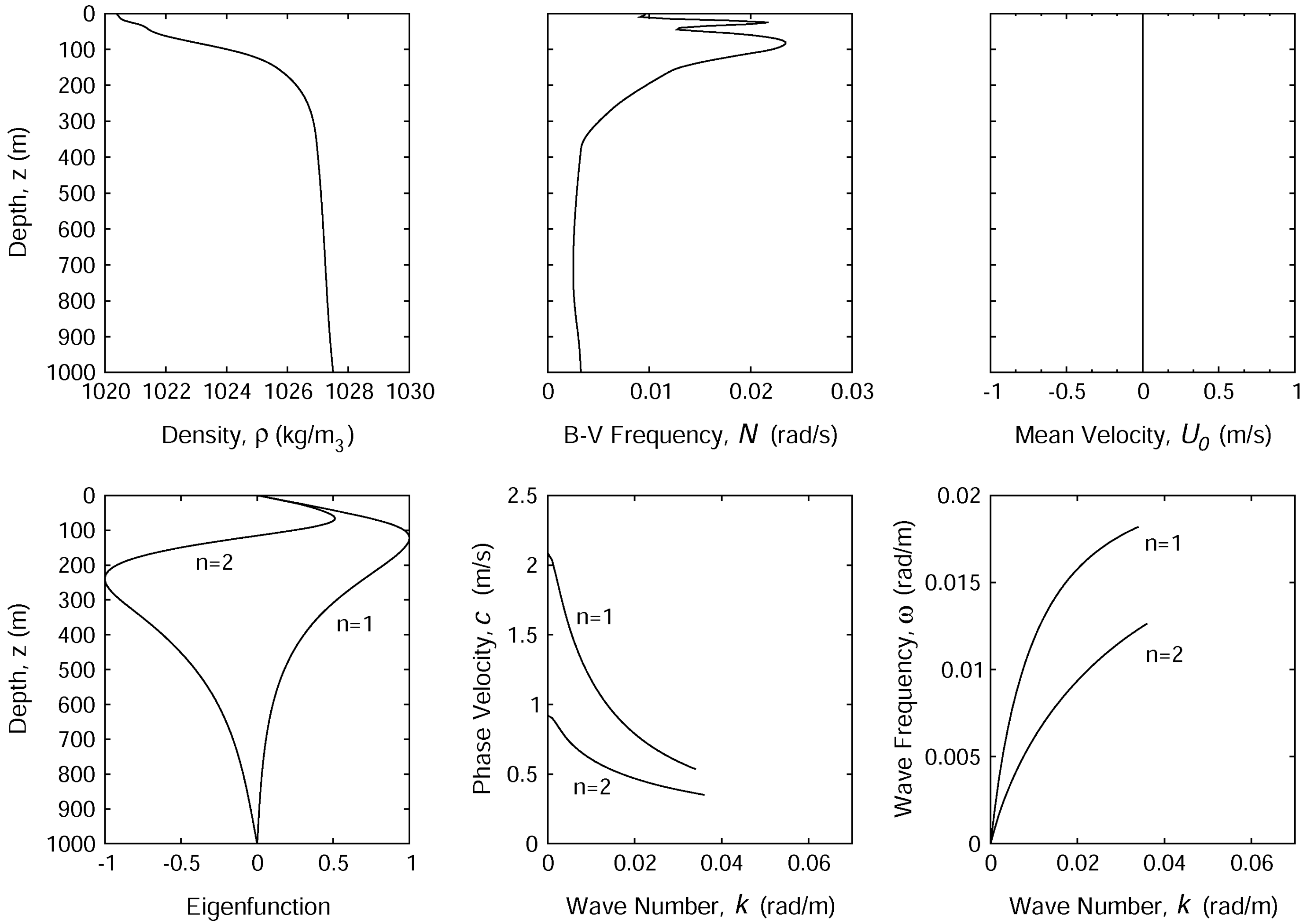


Figure 3. Isotherms of an internal solitary wave having an amplitude of 60-m. The data were obtained by XBT casts carried out on 25 October 1976 at 6°53' N. and 97°04' E. [After Osborne and Burch 1980]



KDV Parameters
Mode 1

Wave Speed (k = 0) c_0 (m/s) 2.09
Nonlinear coefficient $1/\alpha$ (m) -79.27
Dispersion Factor $\gamma^{1/2}$ (m) 90.65
Amplitude (KDV theory) η_0 (m) -31.88
Non-Linear Phase Velocity V (m/s) for (s^2=1) 2.65

Figure 4. a) Density profile derived from SD2 data collected on 1 February 1972 at 7.00^{0}N, 94.97^{0}E , 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 $2\pi/k_0$ = 1100 m, H = 1000 m for density and velocity profiles shown e) phase velocity f) dispersion relations.

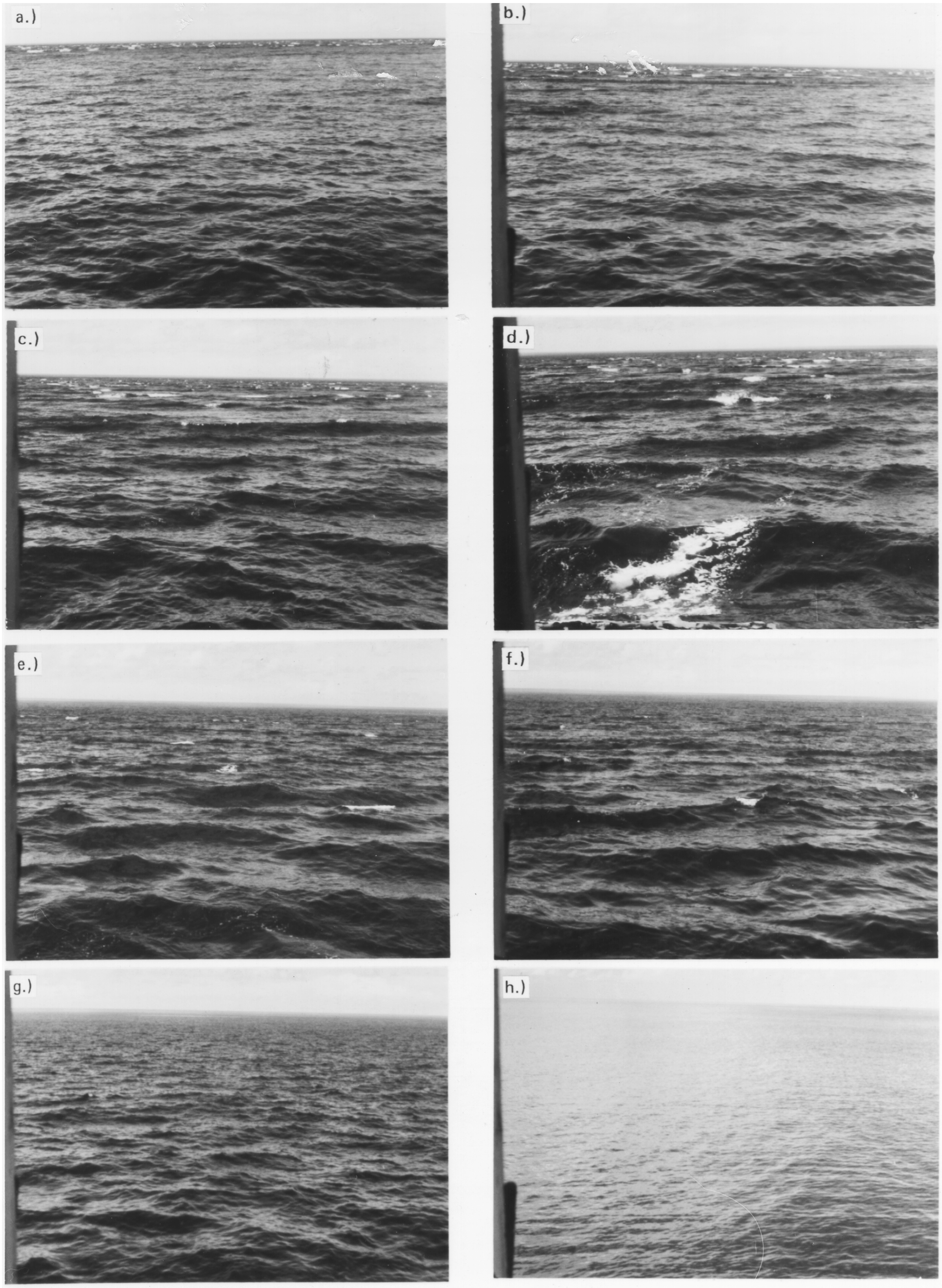
of internal waves for over 32 km as the packet propagates northeast into the Andaman Sea. The second packet, with just a few waves, breaks away from the lower end of Nancowry Island. This suggests that the waves originate on the shelf area just south of Katchall and Nancowry Island in the Sombreno Channel. 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) in the northerly direction. The variation in separation of the wavefronts in the packets could be due to advection by currents.

Figure 9 is an astronaut photograph (STS075-709-53, 54,55) in the sunglint region acquired 27 February 1996. Four groups of internal waves are clearly visible: three are propagating to the north-northwest and one is propagating to the west. Interpacket separation of the southeast wave group is approximately 88 km with an inferred group speed of 2 m/s. The longest wave visible in the northeast group has a crest length of around 150 km. A similar image of this area was acquired during the joint US-USSR space mission Apollo-Soyuz (22 July 1975), (AST-7-426) [Apel, 1979; Osborne and Burch, 1980; Apel at al., 1985].

Figures 10 and 11 show shoaling effects as the large eastward propagating solitons encounter the continental shelf and dissipate. The distance between the solitons within a packet and their width decrease as the solitons approach the coast . Further north, where the shelf break is sharper, Figure 11 shows the generation of secondary internal waves as the large solitons impinge on the shelf.

Most satellite images of the Andaman Sea show internal waves propagating eastwards towards the coast of the Malay Peninsula, but some images also show westward propagating internal waves. Apel et al. [1985] analyzed synthetic aperture radar images from the Shuttle Imaging Radar-A (SIR-A) flight on November 1981 which contained signatures of several internal wave packets in the vicinity of the Andaman and Nicobar Islands [Cimino and Elachi, 1982; Ford et al., 1983]. Figure 12 shows a section of the SIR-A radar image of 11 November 1981, having dimensions of 51.2 by 51.2 kilometers, with the white marks along the lower boarder being time ticks of one second (or distance ticks of 7.14 kilometers). 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 yielded an estimate of the amplitude of the leading soliton in the packet of 60 meters and a speed of 1.1 m/sec.

Figure 5 (Following 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 band 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. [After Osborne and Burch 1980]


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

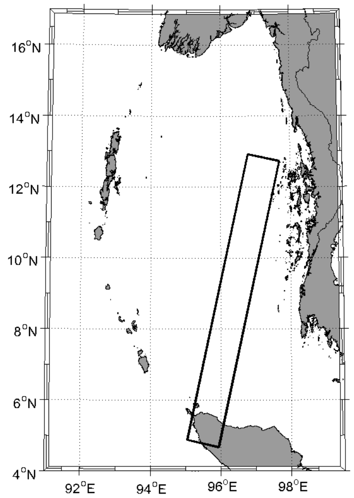
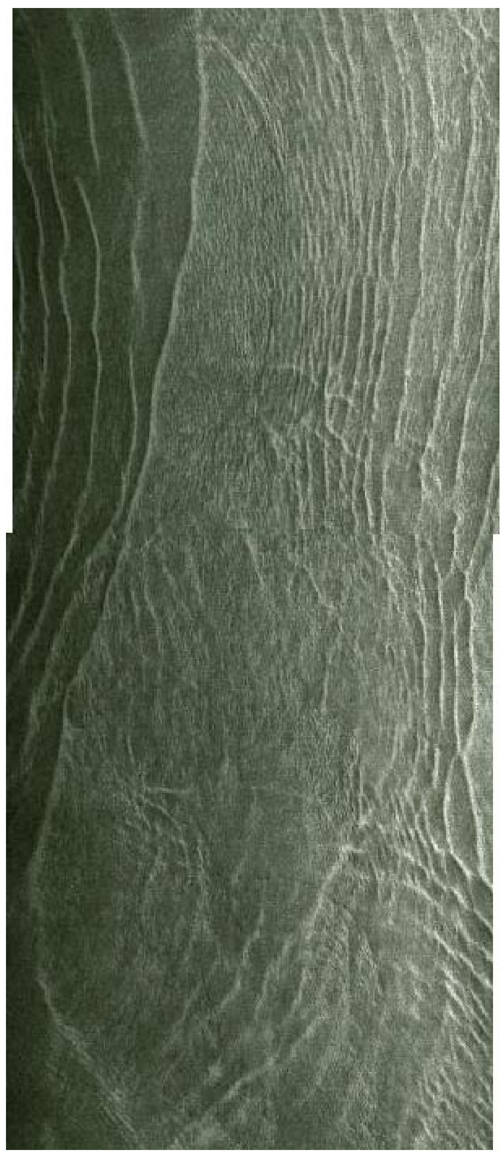


Figure 6. (Right) ERS-2 (C-band, VV) SAR image of the Andaman acquired on 11 February 1997 at 0359 UTC (orbit 9477, frames 3357, 3375, 3393, 3341, 3429, 3447, 3465, 3483, and 3501.). The image shows a large number internal wave packets and associated soliton-soliton interaction. Imaged area is 100 km x 900 km. (Below) An enlargement highlighting a middle portion of the image. Imaged area 235 km x 100 km ©ESA 1997.



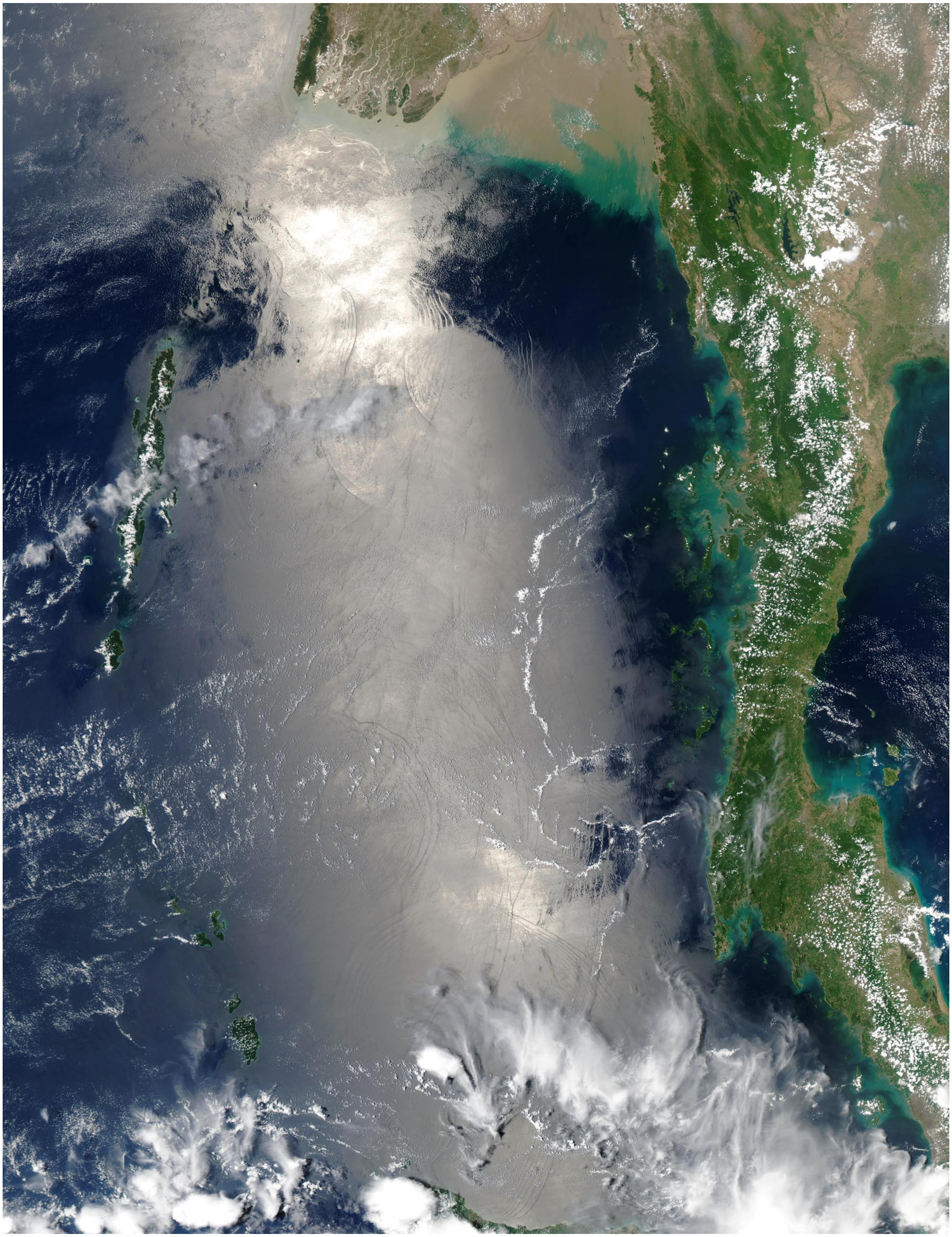


Figure 7. MODIS (Bands 1,3,4) 250-m resolution visible image of the Andaman Sea acquired 17 April 2003 at 0655 UTC. The sunglint allows more than 20 internal wave packets to be seen throughout the basin. The variety of propagation directions signatures highlight the multiple internal wave sources.. Imaged area is 1000 km x 1300 km.

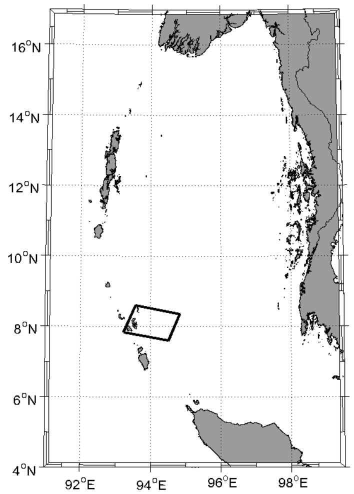
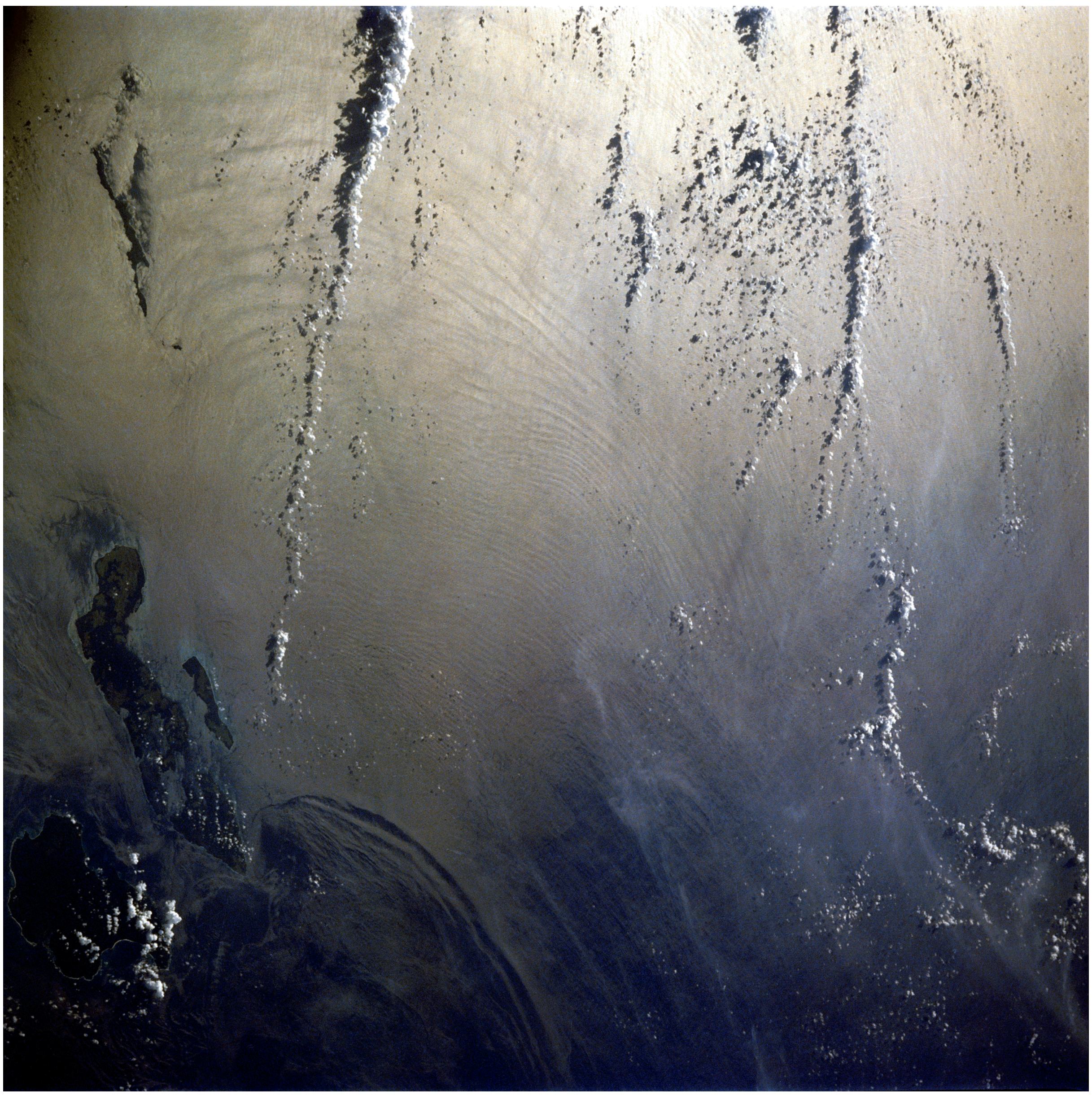
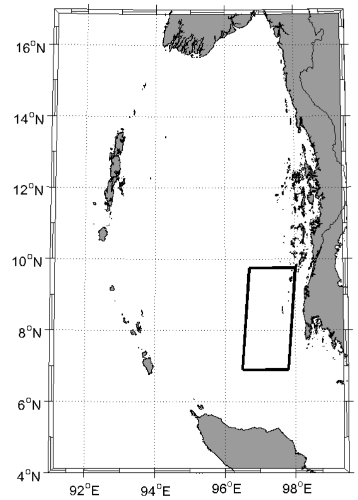


Figure 8. Astronaut photograph (STS51B-53-97) acquired on 5 May 1985 at 0142 UTC. The image shows a near continuum of wave signatures back to the generation region south of Nancowey Island. Imaged area is approximately 68 km x 68 km. [Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov).]





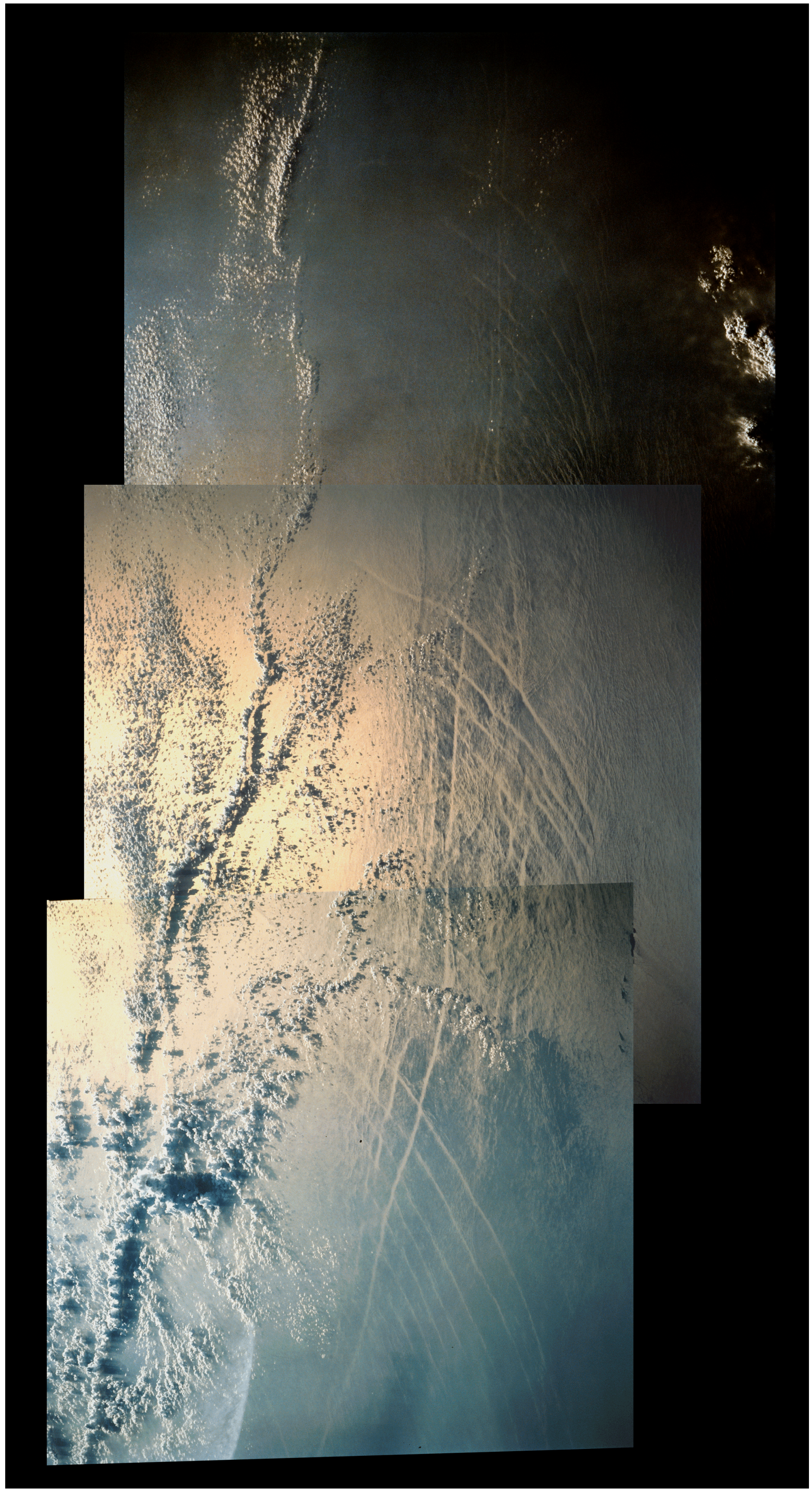
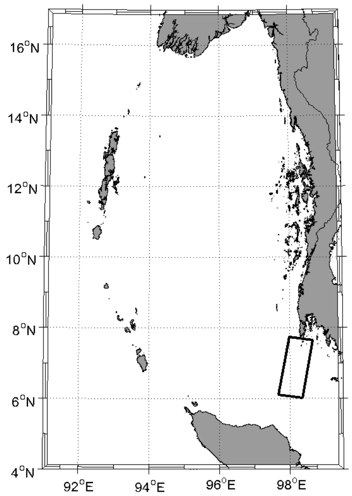


Figure 9. Astronaut photograph (STS075-709-54, 55, 56) acquired on 27 February 1996 at 1030 UTC. The image shows the signature of internal wave packets along the Malay Peninsula. Imaged area is approximately 100 km x 235 km [Image courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov)]



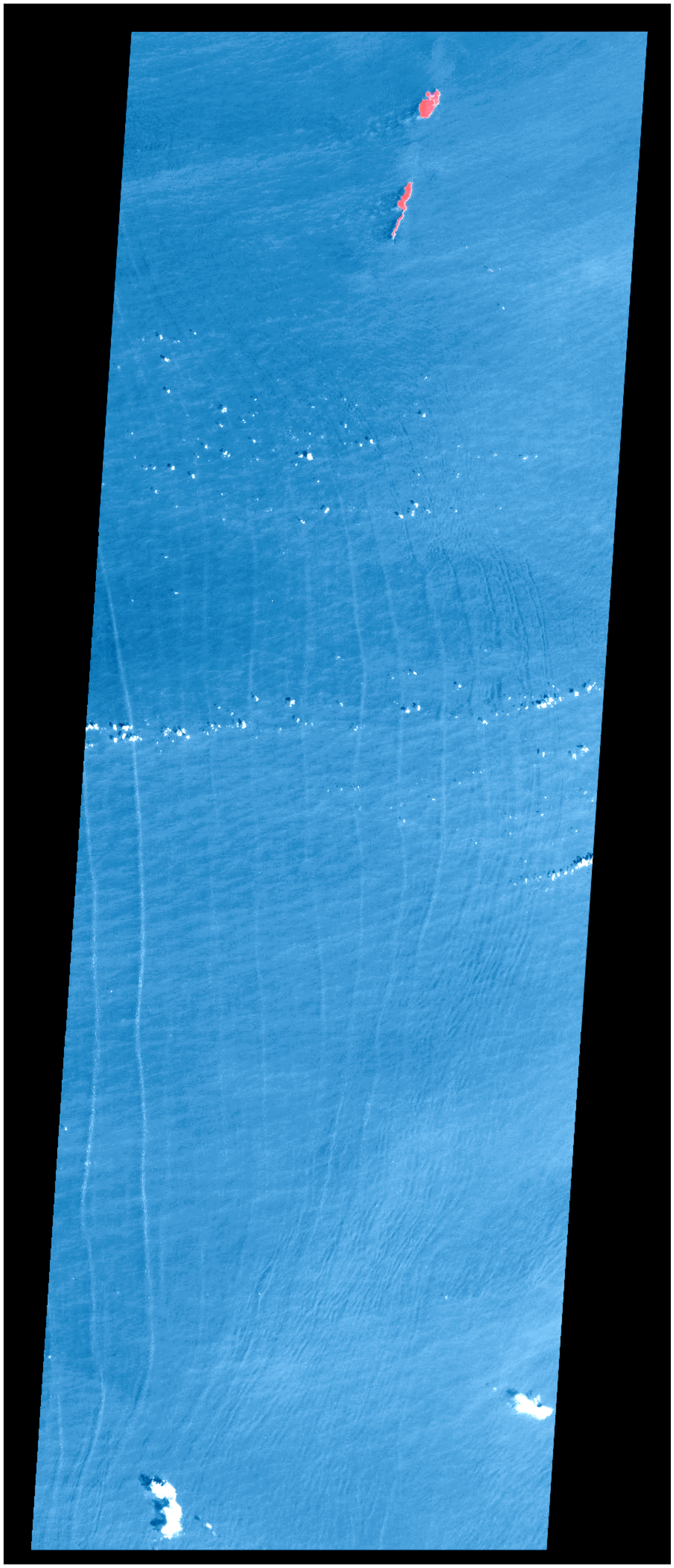
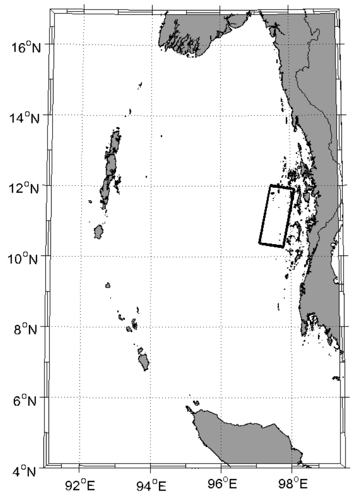


Figure 10. ASTER false-color VNIR image over the area between the Andaman Sea and the Strait of Malacca acquired on 31 January 2002 at 0406 UTC. The image shows the shoaling of large solitons at the shelf break near the 200-meter isobath. Imaged area is 60 km x 180 km.



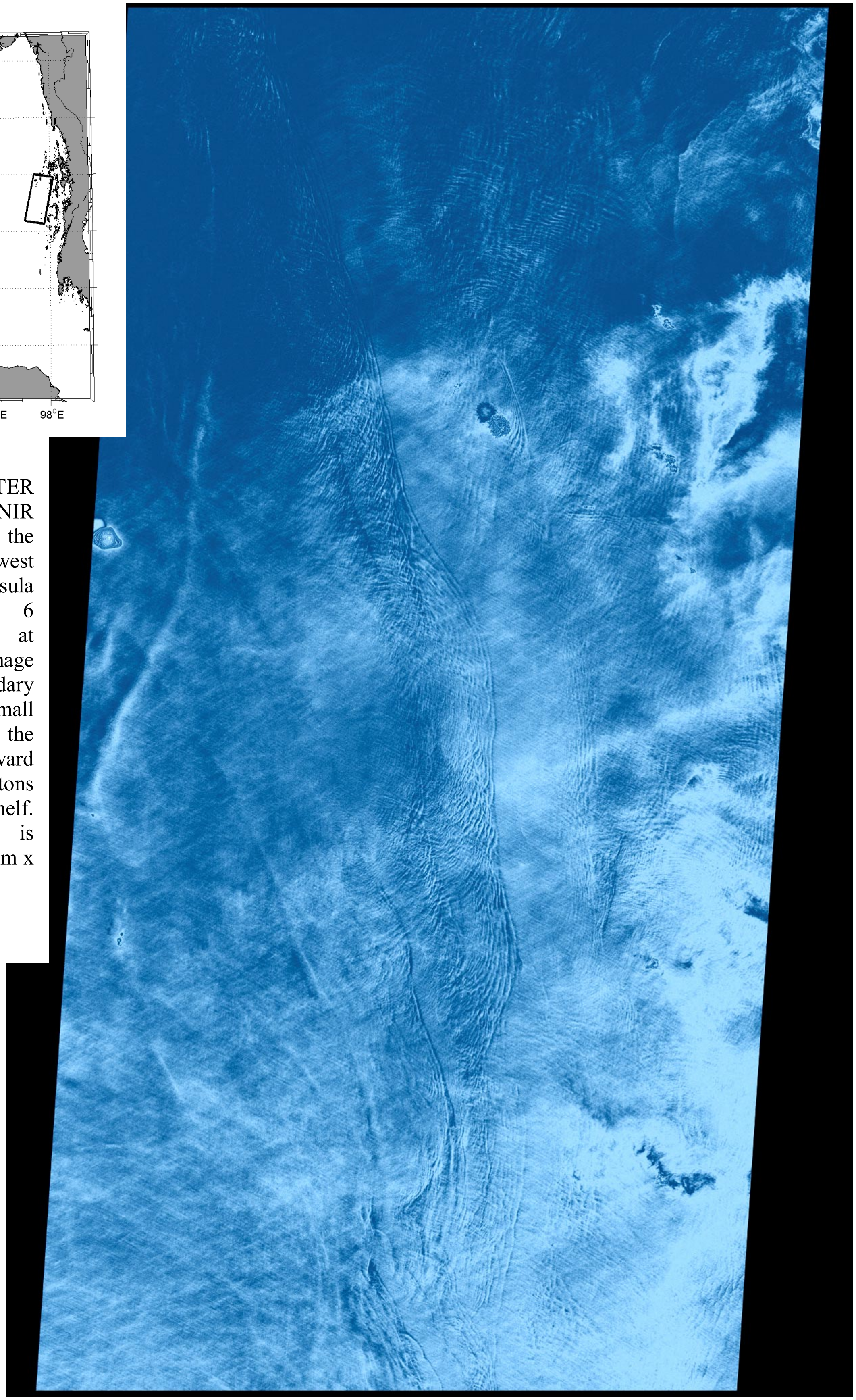


Figure 11. ASTER false-color VNIR image over the continental shelf west of the Malay Peninsula acquired on 6 November 2002 at 0410 UTC. The image shows the secondary generation of small internal waves as the large westward propagating solitons reach the shelf. Imaged area is approximately 60 km x 120 km.

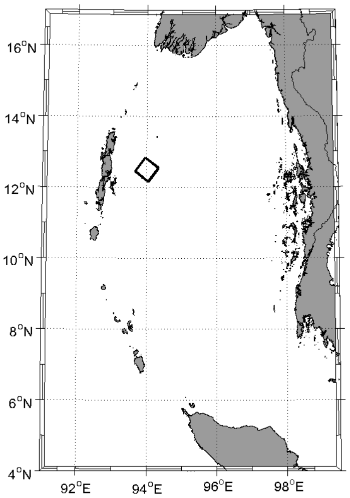
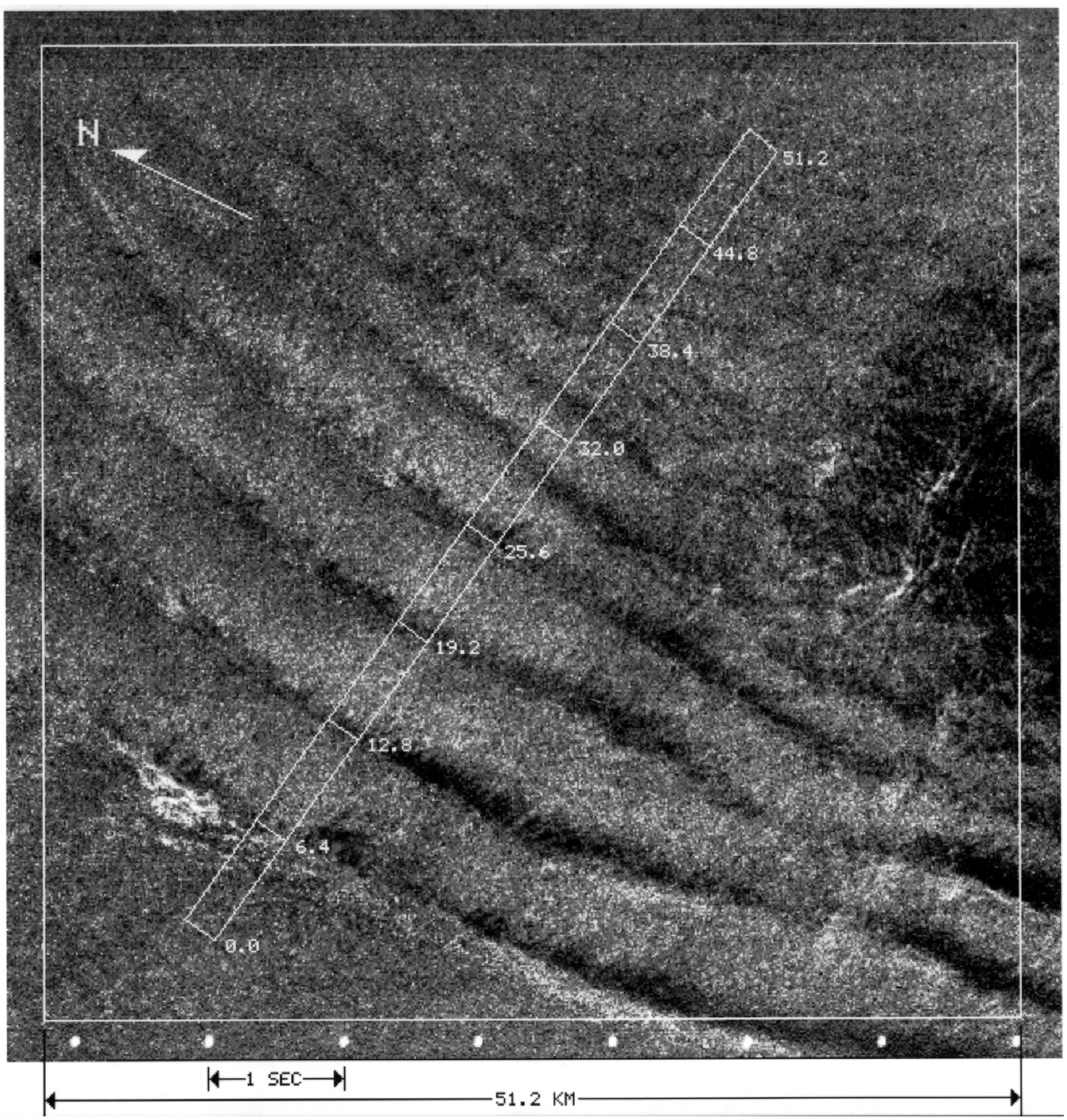


Figure 12. SIR-A (L-band, HH) SAR image near the Andaman Islands acquired on 11 November 1981. The image shows a packet of westward propagating solitons and what is thought to be a rain squall (dark patch at right center). Imaged area is 51.2 km x 51.2 km. [Image courtesy of the Jet Propulsion Laboratory][After Apel et al. 1985]



References

Alpers, W. , H. Wang-Chen and L. Hock, 1997: "Observation of internal waves in the Andaman Sea by ERS SAR," Proc. 3rd ERS Symp. on Space at the Service of our Environment, Florence Italy, 17-21 March 1997, pp.1287-1291.

Apel, J. R., 1979: "Observations of Internal Wave Signatures in ASTP Photographs," Apollo-Soyuz Test Project II, F. El-Baz and D. M. Warner, eds., NASA SP412.

Apel, J. R., D.R. Thomson, D.G. Tilley, and P. van Dyke, 1985: "Hydrodynamics and radar signatures of internal solitons in the Andaman Sea," *John Hopkins APL Technical Digest*, Vol. 6, No. 4, 3330-337.

Cimino J. B., and C. Elachi, 1982: *Shuttle Imaging Radar A* (*SIR-A) Experiment*, NASA/JPL 82-77, pp. 5-53.

Ford, J. P., J. B. Cimino and C. Elachi, 1983: *Space Shuttle Colombia Views of the World with Imaging Radar: The SIR-A Experiment*, NASA/JPL 82-95, pp. 144-145.

Maury, M. F., 1861: The Physical Geography of the Sea and Its Meteorology (Harper, New York), pp. 404-405.

Osborne, A. R., T. L. Burch, 1980: "Internal solitons in the Andaman Sea," *Science* **208**, 451-460.

Osborne, A. R., T. L. Burch, and R. I. Scarlet, 1978: "The Influence of internal waves on deep-water drilling," *J. Petroleum Tech*., 1497- .

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

Smith, W. H. F., and D. T. Sandwell, 1997; Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, v. **277**, 1957-1962
http://topex.ucsd.edu/marine_topo/mar_topo.html

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

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

University of Hamburg website: The tropical and subtropical ocean viewed by ERS SAR
http://www.ifm.uni-hamburg.de/ers-sar/Sdata/oceanic/intwaves/index.html

THIS PAGE INTENTIONALLY LEFT BLANK