Development and implementation of cellular-based real-time reporting and Internet accessible coastal sea-level gauge – A vital tool for monitoring storm surge and tsunami

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We describe the development and implementation of real-time reporting and Internet-accessible coastal sea-level gauge, wherein data communication between the gauge and an Internet server has been established through a cellular modem utilizing General Packet Radio Service technology. Using the existing cellular phone network, a continuous real-time update of coastal sea-level changes is realized on a web-server. The system implemented, and accessible to every authorized personnel, provides a graphical illustration of the predicted fair-weather sea-level, current sea-level, and residual sea-level (i.e. measured minus predicted fair-weather sea-level), which can be monitored via Internet from any part of the world. This system provides a cost-effective and easily maintainable platform for real-time monitoring of coastal sea-level and for providing the requisite input for efficient implementation of any alert and warning mechanism in the event of oceanogenic natural disasters, particularly storm surges and tsunamis. The architecture of the system described herein, and operational since 24 September 2005 at Verem jetty in the Mandovi estuary, Goa, would complement the INSAT-based sea-level gauges that are proposed to be put in place by the Government of India by the year 2007.

Keywords: Internet-accessibility, real-time monitoring, storm surge, tsunami.

IMPLEMENTATION of a network of sea-level gauges spread all along the coasts, with capability for providing information on real-time sea-level elevation and its trend, would have provided the requisite data to the disaster management agencies for dissemination of disaster alert warnings to the coastal communities. Presence of such a network, with wide accessibility to the coastal communities and beach tourism centres could have saved many lives during the devastating tsunami of 26 December 2004. Unfortunately, such a network was not in place. This lacuna, together with frequent storms that hit many coastal locations in India and the Indian Ocean rim regions and elsewhere in the world, necessitated development of a real-time coastal sea-level data communication system for the benefit of the coastal communities and the local administrators[1]. Further, real-time sea-level data would form an important input to storm-surge predictive models and warning systems. Given the popularity of the Internet on a global scale, providing such state-of-the-art accessibility to sea-level gauges would mean that the current coastal sea-level scenario could be viewed in real-time by anyone from any part of the world during anomalous and disastrous events of the coastal seas. If an Internet access to the sea-level gauge website is made available to television channels, real-time visualization of the coastal sea-level and its trend from the previous day to the present instant can be seen by everyone on television. Providing Internet accessibility to the sea-level gauge website at other media centres such as radio stations and the press would serve an equally important role in the quick dissemination of the current anomalous sea-level scenario to the navigators, and the coastal communities. If a network of several real-time transmitting sea-level gauges along the Indian subcontinental coastline and islands is built and made operational, such a network would provide useful information to mariners sailing in the coastal waters and also contribute to various engineering projects associated with coastal zone management. Moreover, information obtained would be of great value to the national and international scientific community. The data from the server can also be used for disaster alert generation in a manner similar to the earthquake notification system reported by Sriramchandr et al.[2] for nuclear reactor sites.

Thus, a network of innovative and cost-effective monitoring systems that provide requisite information on coastal sea levels is an important requirement at present. Cellular-based real-time reporting and Internet-accessible sea-level gauge developed by us would provide a cost-effective platform to fill the void that exists in the country at present.

A major limitation of existing float-driven and guided air-acoustic sea-level gauges in India and elsewhere is that during extreme surge events, these devices can be flooded or saturated. Further, such gauges do not provide real-time/near-real-time sea level information. The new system developed and implemented by us and described herein has incorporated pressure transducer as the sensing element. The reasons behind the choice of bottom-pressure transducer over other sea-level sensors are the following: (1) absence of saturation at extraordinarily large elevations of sea-levels such as those occurring during storm surge and the crest phase of the tsunami; (2) the pressure transducer does not require stilling-well for deployment and, therefore, some of the errors inherently associated with stilling-well-based gauges[3] are absent in the pressure transducer-based gauge if it is deployed outside a stilling-well. The sensor used in the present design is a temperature-compensated piezo-resistive semiconductor pressure transducer, whose performance is found to be adequate
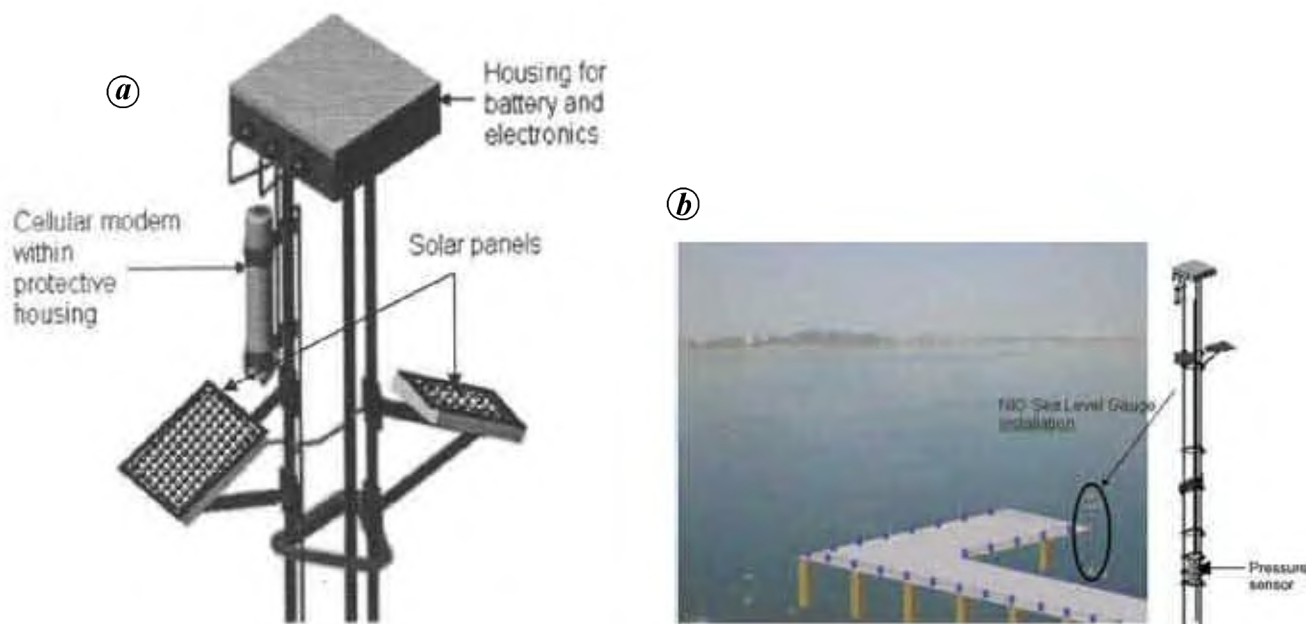
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Figure 1. *a*, Top portion of mounting structure of the gauge, where battery, electronics, solar panel and cellular modem are fixed. *b*, Illustration of NIO sea-level gauge installed at Verem Jetty, Mandovi estuary, Goa, India.

for coastal sea-level measurements[4] and has been successfully collecting sea-level and water temperature data from the Gulf of Guinea (West Africa)[5] since July 2004. The data are normally sampled at 2 Hz and can be averaged over a duration of 15 s to 15 min interval, in conformity with the revised GLOSS requirements to detect tsunami and storm-surge events, as well as for mean sea-level studies. In the past, data recording at intervals less than 15 min was practically difficult because of memory capacity limitations. However, this limitation has been overcome in the present design by incorporating multimedia cards, with storage capacity ranging from 128 to 1000 Mb. Additionally, real-time/near-real-time data access capability is also implemented for effective operational applications during anomalous sea-level conditions, such as those occurring during storm surges and tsunami episodes. The sea-unit of the gauge is mounted within a cylindrical protective housing, which in turn is rigidly held within the vertical legs and the interconnecting triangular collar of the mechanical structure used for mounting the entire gauge.

Figure 1 *a* shows the top portion of the mounting structure of the gauge, where battery, electronics, solar panel and cellular modem are mounted. The pressure sensor and the logger are continuously powered on, and their electrical current consumption is 30 and 15 mA respectively. The cellular modem consumes 15 and 250 mA during standby and data transmission modes respectively. Figure 1 *b* illustrates installation of the gauge at Verem Jetty, Mandovi estuary, Goa, India.

The effectiveness and usefulness of the system depends on uninterrupted transmission of data during the occurrence of a hazardous event. For this purpose, it is necessary that the system should not be disturbed or damaged during such events. In view of this, the overall structure of the system has been designed to cater to this important requirement. Accordingly, unlike the conventional tide-gauge installations, the present system does not require a 'tide-gauge hut' to house the instrument. Further, electrical power requirement is met by a 17 AH sealed lead acid battery, which is charged from a solar panel. The electronics part of the system and the data communication modem are well protected within a weather-proof housing; and the battery and this weather-proof housing are rigidly mounted within another sturdy FRP housing. This housing is mounted on the top portion of a sufficiently tall structure, which is erected on the jetty and is strong enough to withstand anticipated extreme forces.

In the present sea-level gauge, a single-crystal silicon, thin-diaphragm, piezo-resistive strain gauge is used for estimation of sea-level through measurements of absolute pressure (i.e. water column pressure + atmospheric air pressure). Silicon wafer, which is the piezo-resistive pressure-sensing element of the transducer, exhibits change in its resistivity when subjected to stress. Application of silicon strain-gauge transducer for pressure measurement relies on the following concept. The change (Δr) in resistance in a deformed strain gauge is composed of two terms, and is given by the expression[6]:

$$\Delta r = \{s \times \Delta(l/a)\} - \{(l/a) \times \Delta s\}, \tag{1}$$

where *s*, *l* and *a* represent the specific resistance of the material of the conductor, its length and cross-sectional area respectively. Δs represents change in resistivity caused

by water pressure-induced stress acting on the wafer. While $\{s \times \Delta(l/a)\}$ describes the change of electrical resistance directly caused by the ordinary deformation effect of the conductor, $\{(l/a) \times \Delta s\}$ represents change in resistivity (piezo-resistance effect). In single-crystal silicon, piezo-resistance effect is substantially larger than its ordinary deformation effect.

Usually, the thin diaphragm of the transducer designed for marine applications is protected from corrosion effects associated with its prolonged contact with saline water. The protective device for the pressure port is conventionally an oil-filled capillary tube, whose one end is coupled to the diaphragm of the transducer and the other end exposed to sea water pressure. The precision pressure transducer used with this sea-level gauge is provided with a special 'Hastelloy' material isolation-diaphragm to protect the transducer port against corrosive effects during its prolonged exposure to sea water.

The methodology employed in the present gauge for measurement of sea-level is to detect the hydrostatic pressure, and to estimate the water column height over the pressure transducer from knowledge of the effective depth-mean water density.

An absolute pressure transducer senses the total pressure (i.e. atmospheric pressure + pressure exerted by the water column above the transducer). The total pressure $P_{(total)}$, over the pressure inlet, at depth d below the water surface is given by the relationship:

$$P_{(total)} = P_a + P_w, \tag{2}$$

where P_a is the atmospheric pressure and P_w is the pressure exerted by the overlying water column on the transducer. The following well-known relation gives the latter:

$$P_w = (\rho \times g \times d). \tag{3}$$

In the relation, ρ is the effective depth-mean density of the overlying column of water, g is the acceleration due to gravity, and d is the depth of the pressure transducer below the water surface. Thus, the value of d is estimated. In general, because of the complexities associated with effective density of suspended-sediment-laden shallow water bodies[7,8], it is advisable to use alternate sensing methods[9] in heavily suspended-sediment-laden water bodies (e.g. Hooghly estuary).

There are various communication technologies that could be utilized for real-time transmission of sea-level data. These include wired telephone connection, VHF/UHF transceivers, satellite transmit terminals and cellular connectivity.

Wired telephone connections are severely susceptible to loss of connectivity during natural disasters such as storm surges, primarily because of telephone line breakage under the force of storm-winds (e.g. uprooted trees and broken branches). Communication via VHF/UHF trans-ceivers is limited by line-of-sight distance between trans-ceivers and normally offers only point-to-point data transfer. However, satellite communication via platform transmit terminals has wider coverage and, therefore, allows data reception from offshore platforms. Nevertheless, data transfer speeds are limited to 9600 baud. Further, many satellites (e.g. INSAT, GOES) permit data transfer only at predefined time-slots, thereby inhibiting continuous data access. While satellite communication is relatively expensive, wirelesses networking infrastructure and ubiquity of cellular phones have together made cellular communication affordable. Low initial and recurring costs are an important advantage of cellular data communication.

Various services exist for data communication, e.g. SMS, Data Call, and GPRS. SMS (short message service) is a common method of sending text messages of up to 140 bytes between cellular devices. This mode of transmission is probably the easiest to implement when data size is small. However, the recurring cost can be substantial if data need to be reported frequently. Further, keeping track of lost SMS can easily override its simplicity. Data Call is another alternative, which can also turn out to be expensive if data have to be frequently reported. Both SMS and Data Call services would require modems on the remote transmitting device as well as on the receiving side. This adds to the hardware cost as well as software overheads on the receiving side to check the data integrity for transmission errors[10]. The main benefit of cellular connectivity with GPRS technology is that it utilizes radio resources only when there are data to send. In addition, GPRS offers improved quality of data services as measured in terms of reliability, response time and features that are supported. Another advantage of GPRS over other data communication services is that it provides an 'always on' communication channel without incurring time-based costs. That is, there is no difference in costs whether data are collected once a minute or once a day. Further, GPRS data transmission speeds are of the order of 3 to 4 times that of a traditional cellular data connection. The GPRS allows data rates of 115 kilobits per second. Also, GPRS enables a constant TCP/IP connection with the Internet, so that data can be easily uploaded. Since data can be posted on the Internet server, there is neither any need for a modem on the receiving side nor the requirement to have special software at the server side to collect data from the remote site. Figure 2 illustrates implementation of real-time coastal sea-level data reception utilizing GPRS technology.

GPRS modem with built-in TCP/IP stack incorporated in the present design frees the host controller, which is responsible for acquisition of data from sea-level gauge, from communication overload. These modems need only a few simple commands to upload data on a remote FTP server.

Data communication is always initiated by the sea-level gauge. After the communication link is established, a bi-directional data transfer is possible between the Internet
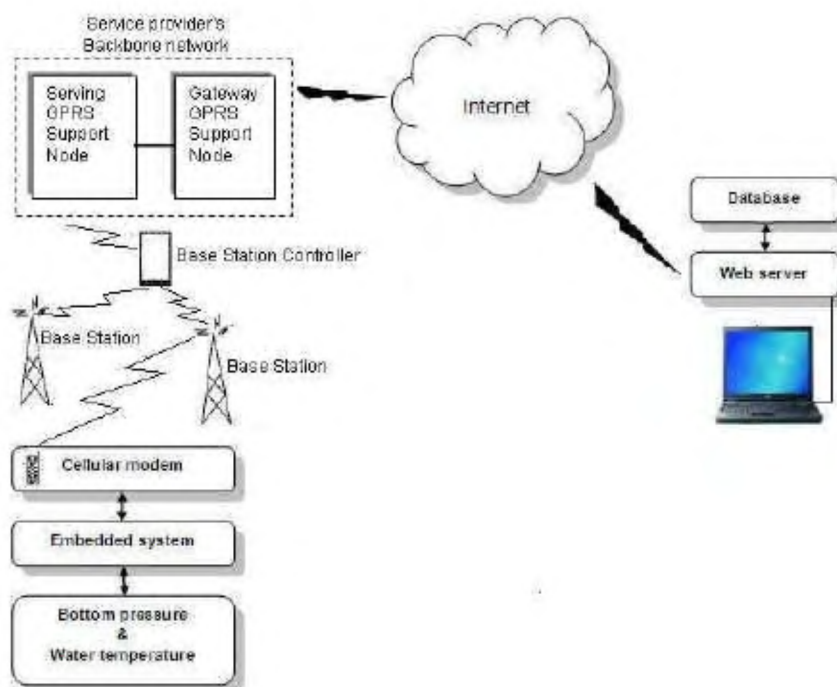
Figure 2. Schematic diagram illustrating implementation of real-time coastal sea-level data reception utilizing GPRS technology.
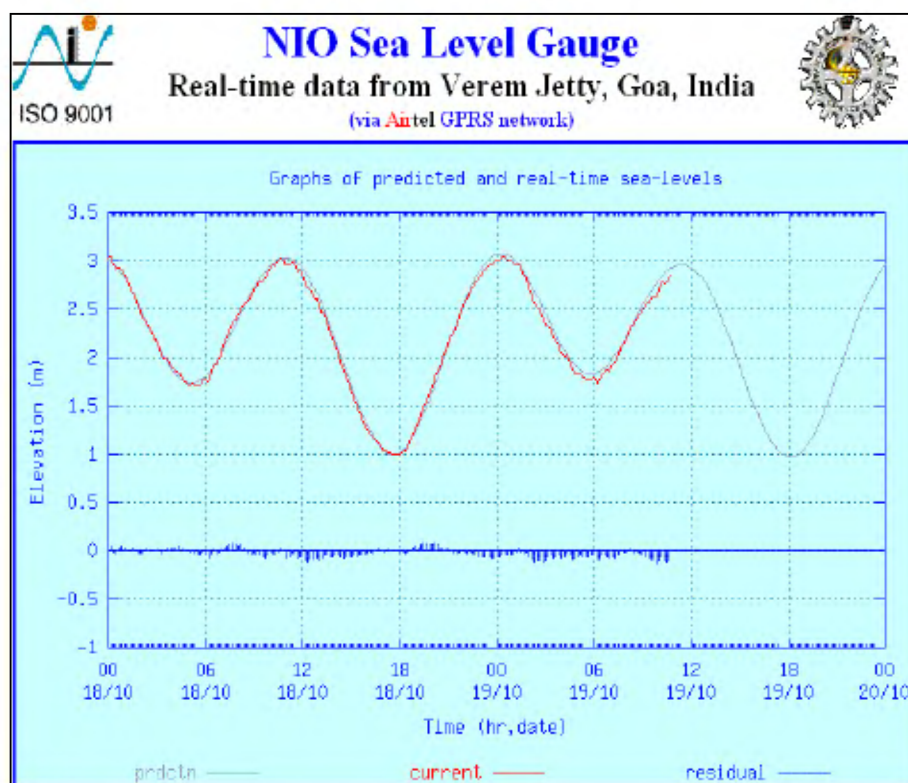

Figure 3. Display of predicted fair-weather sea-level, observed real-time sea levels, and residuals from Verem Jetty, Mandovi estuary, Goa, India.

server and the sea-level gauge. This is because GPRS Gateway Support Node (GGSN) uses Dynamic Host Configuration Protocol (DHCP) to assign private IP (Internet Protocol) addresses to cellular devices. This IP address is invisible to the Internet network. Although GPRS is termed as an 'always on' network, if there are no data exchanged
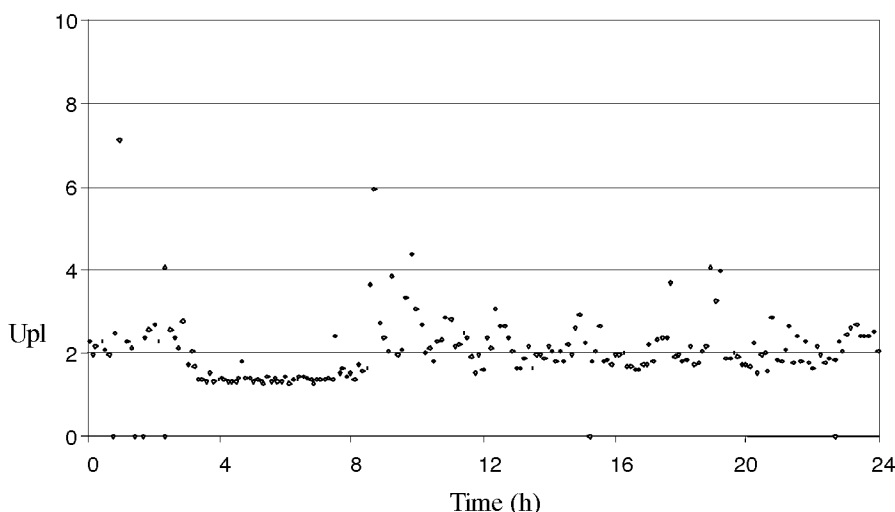
Figure 4. FTP upload time during a period of 24 h for a 100 kb test data.

beyond some timeout periods (in the present case, 1 min), the connection is dropped and a new IP address is assigned to the cellular modem. Because of this scheme, the IP address of the cellular modem can change frequently. One obvious benefit of such a connection mechanism from the security point of view is that risk of attack from hackers and third party is reduced.

The software consists of two main components, namely (1) embedded system software for data acquisition and communication with Internet server, and (2) web server-based user-interface to visualize the received sea-level data. In the present application, 5-min averaged sensor output data are logged by the embedded system at 5-min intervals. Subsequently, all the data logged from the previous day to the current time are uploaded to the Internet server that is located at NIO, Goa. The data received at the Internet-server are stored in the back-end database and simultaneously presented in graphical format, together with the predicted fair-weather sea-level and the residual. The residual, which is the measured sea level minus predicted fair-weather sea level, provides a clear indication and a quantitative estimate of the anomalous behaviour of sea-level oscillation. The driving force for such anomalous behaviour could be atmospheric forcing (storm) or geophysical (tsunami). Figure 3 displays predicted fair-weather sea level, observed real-time sea-levels, and residuals from Verem Jetty. The scale of real-time display is dynamically adjusted based on the maximum elevation observed.

In order to examine the performance of data upload from the sea-level gauge to the Internet server, 100 kbytes of test data were uploaded continuously for 24 h using standard File Transfer Protocol (FTP). Figure 4 shows the distribution of time taken (throughput) for successive FTP uploads during the above experiment. The minimum and maximum transfer times were in the range 1.29 to 7.1 min

for uplink (average time was 2.06 min). Data were transferred between sea-level gauge and the FTP server using Airtel GPRS service. On an average, 97.47% of data transfer attempts was found to be successful.

We have described a real-time sea-level reporting system utilizing existing cellular communication infrastructure. Several issues involved in the implementation of Internet-accessible sea-level gauge have been addressed. It is anticipated that the growth in communication infrastructure will further improve our capability in coastal sea-level data collection in real time and its utilization for running predictive models as well as for warning and alert purposes. The architecture of the system described herein, which has been operational since 24 September 2005, would complement the INSAT-based sea-level gauges that are proposed to be put in place by the Government of India by the year 2007. In contrast to INSAT, where data transmission is restricted to certain time-slots, the system developed and implemented by NIO offers continuous data access.

The system can also be effectively used in dams and reservoirs for water-resource management, flood management, sharing of water resources between states and neighbouring countries, and monitoring and implementation of Joint River Water Treaties with increased transparency.

1. Joseph, A. and Prabhudesai, R. G., Need of a disaster alert system for India through a network of real time monitoring of sea level and other meteorological events. *Curr. Sci.*, 2005, **89**, 864–869.
2. Sriramchandr, S. A. V., Murty, S., Athinarayanan. S., Swaminathan, P. and Raj, B., Earthquake notification system. Paper presented at the International Symposium organized by IAEA, Kalpakkam, 25 August – 2 September 2005.
3. Joseph, A., Vijaykumar, Desa, E. and Peshwe, V. B., Over-estimation of sea level measurements arising from water density anomalies within tide-wells – A case study at Zuary estuary, Goa. *J. Coast. Res.*, 2002, **18**, 362–371.

4. Vijaykumar, Joseph, A., Prabhudesai, R. G., Prabhudesai, S., Nagvekar, S. and Damodaran, V., Performance evaluation of Honeywell silicon piezoresistive pressure transducers for oceanographic and limnological measurements. *J. Atmos. Ocean. Technol.*, 2005, **22**, 1933–1939.
5. Joseph, A., Mehra, P., Odametey, J. and Nkebi, E. K., Pressure gauge based GLOSS sea level station at Takoradi harbour (Ghana, West Africa) – Experiences over a year. In *IOC Manual on Sea Level Measurement and Interpretation*, 2006, vol. 4 (an update to 2005), pp. 108–110.
6. Gieles, A. C. M. and Somers, G. H. J., Miniature pressure transducers with a silicon diaphragm. *Philips Tech. Rev.*, **33**, 14–20.
7. Joseph, A., Desa, E., Desa, E. S., Smith, D., Peshwe, V. B., Kumar, V. and Desa, J. A. E., Evaluation of pressure transducers under turbid natural waters. *J. Atmos. Ocean. Technol.*, 1999, **16**, 1150–1155.
8. Joseph, A., Desa, E., Kumar, V., Desa, E. S., Prabhudesai, R. G. and Prabhudesai, S., Pressure gauge experiments in India. Intergovernmental Oceanographic Commission Workshop Report No. 193, Workshop on New Technical Developments in Sea and Land Level Observing Systems (eds Holgate, S. and Aarup, T.), 14–16 October 2003, Paris, France, 2004, pp. 22–37.
9. Joseph, A., Modern techniques of sea level measurement. In *Encyclopaedia of Microcomputers*, Marcel Dekker, New York, 1999, vol. 23, pp. 319–344.
10. Joseph, A. and Prabhudesai, R. G., Web-enabled and real-time reporting cellular based instrumentation for coastal sea level and surge monitoring. In *The Indian Ocean Tsunami* (eds Aswathanarayana, U. and Tad Murthy), A. A. Balkema Publishers, Taylor & Francis Group, Leiden, The Netherlands, 2006, in press.

Imaging trench-line disruptions: swath mapping of the Andaman subduction zone

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Analogous to other subduction zones in the world where the heavier oceanic plate shoves below the lighter continental plate, crustal movement along the Sumatra–Andaman trench line over the last two centuries released enormous stress causing earthquakes of highest impunity and generating, at times, devastating tsunamis. Such significant earth movements are presumed to have wide-ranging implications, stretching from geology to climate and to astronomy. A sea expedition within three months from the 2004 Sumatra–Andaman earthquake, and during the 2005 Sumatra earthquake is able to image the exact trench line, west of the Andaman Island. The multibeam bathymetry, gravity and fractal studies of about twenty-five thousand square kilometres off the west of Andaman Island have brought out several interesting features unknown earlier, including atypical disruption of the trench line.

Keywords: Disruption, subduction zone, Sumatra–Andaman earthquake, trench line.

THE M_w 9.0–9.3 Sumatra earthquake of 26 December 2004 (26/12), the most severe among the top nine earthquakes reported during the last two hundred years (Table 1), occurred at the shallow interface in near proximity to four plates – two oceanic (Indian, Australian) and two continental (Burma and Sunda)[1]. This earthquake (epicentre location 3.3°N, 96°E; focal depth 30 km) was probably the first such major phenomenon that was recorded with modern equipment such as satellites offering information on ocean heights, in addition to a global seismic network with seismographs and a networking of global positioning system (GPS) to document even minor crustal movements[2]. The distribution of aftershocks suggests progressive rotation of the strike of the fault plane towards right as the rupture progressed towards north[3], implying increase in strike slip component towards north. Again, as recorded by seismometers in Russia and Australia, in the beginning the crust broke 100 km patch slowly, then rapidly to 3 km/s for the next 4 min, and thereafter maintained an average speed of 2.5 km/s for the next 6 min (average rupture speed 8050 km/h)[4].

Analysis of regional geodetic (GPS) data further suggests that a highly oblique motion between Indo-Australian and Burma–Sunda plates is partitioned between the trench normal thrust motion at the subduction zone in the Sumatra region to arc-parallel dextral strike-slip faulting off the Andaman Islands[5]. The enormity of the earthquake, considered to have been initiated at a depth of about 30–40 km below the seafloor, has been so huge that almost 0.25 million km^2 of the crust in the subduction zone was estimated to have been ruptured[6], raising the Burma plate

Table 1. Historical seismic ($Mw > 7.0$) and volcanic activities along Andaman–Sumatra subduction zone

Year	Intensity	Area	Remarks
2005	M 8.6	Sumatra–Andaman	Major quake
2004	M 9.3	Sumatra–Andaman	Tsunami
2002	M 7.2	Ache, Sumatra	Major quake
1941	M 7.9	Andaman Island	Tsunami
1907	M 7.8	North-northcentral Sumatra	Tsunami
1883	–	Krakatoa volcanic eruption	Tsunami
1881	M 7.9	Nicobar Island	Tsunami
1861	M 8.5	Northcentral Sumatra	Major quake
1833	M 9.3	South Sumatra	Major quake
1797	M 8.4	Southcentral Sumatra	Major quake

Source: United States Geological Survey website.

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