

# Cellular-based and Internet-enabled real-time reporting of the tsunami at Goa and Kavaratti Island due to $M_w$ 8.4 earthquake in Sumatra on 12 September 2007

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**The tsunami at Goa (west coast of India) and Kavaratti Island (Lakshadweep archipelago) in the Arabian Sea, caused by the 12 September 2007 Sumatra earthquake, was reported from cellular-based sea-level gauges in real-time on the Internet designed and established by the National Institute of Oceanography, Goa. The tsunami arrived at Kavaratti Island and Goa after travelling nearly 5 h : 15 min and 8 h respectively, from the source region in Sunda trench. The maximum trough-to-crest wave height at Kavaratti and Goa was  $\approx$ 5 and 29 cm respectively, and the dominant period was about 43 min. Arrival of a detectable tsunami signal first at Kavaratti Island and 2 h : 45 min later at the shallower Goa coastal region (Verem jetty) of the mainland indicates the importance of having high-sensitivity real-time monitoring and Internet-accessible sea-level stations on India's island locations for effective tsunami-warning purposes for the mainland.**

**Keywords:** Internet-accessibility, real-time monitoring, sea-level gauge, tsunami.

THE tsunami caused by the  $M_w$  8.4 earthquake on 12 September 2007 in southern Sumatra (Indonesia) at 11 h : 10 min (UTC) in the Indian Ocean (4.517°S, 101.382°E) is a relatively much weaker one compared to the powerful 26 December 2004 tsunami, which occurred on a global-scale travelling across the World Oceans, covering continental coasts, islands and polar regions<sup>1-3</sup>, causing large-scale destruction and human casualty in the Indian Ocean regions. However, available sea-level records demonstrate the ability of even this weak tsunami to reach relatively far-off distances in the Indian Ocean (e.g. Maldives, Sri Lanka, India and the Persian Gulf). Two cellular-based real-time reporting and Internet-accessible sea-level gauges designed and established by the National Institute of Oceanography (NIO), Goa (India) recorded and reported on the Internet, the arrival of the tsunami on

the coasts of Goa in the west and Kavaratti Island (Lakshadweep archipelago) in the Arabian Sea. This article presents the features of the tsunami that arrived at these two sites together with the judicious selection of sea-level sensing methodology and the technology incorporated for cost-effective real-time graphical reporting of tsunami waves on the Internet using cellular technology.

## Methods and instruments

Examination of past tsunami records indicates that special care needs to be taken in the design of sea-level gauges, if the data recorded by them are to be used for quantitative scientific analysis of the properties of tsunamis. Besides the catastrophic and highly destructive 26 December 2004 Indian Ocean tsunami, powerful tsunamis have occurred a couple of times in the past; for example, 27 August 1883 Krakatau tsunami, which is the first known global tsunami<sup>4</sup> and the 22 May 1960 Chilean tsunami, which was one of the most destructive trans-Pacific and the second known global tsunami<sup>5</sup>. These tsunamis have been recorded on graphical charts of float-driven gauges, which was the only technology available in those days. These gauges are used even today in many parts of the world, including India. A major limitation observed with such gauges is that during strong tsunami events many of them tend to get saturated, as a result of which the crests and troughs of the largest waves get frequently clipped<sup>6</sup>. This precludes quantitative analysis of the tsunami properties and global propagation pattern<sup>7</sup>. This was the situation in the case of the 1960 Chilean tsunami as well, where the event was measured by about 250 gauges in the Pacific Ocean<sup>5</sup> and very strong waves (more than 3–4 m) were observed at many far-field sites (10,000 km from the source area). This inherent limitation of the stilling-well gauges was felt even during the December 2004 Sumatra tsunami propagation along the coasts of Thailand and Indonesia, because of which the derived wave characteristics (especially arrival times) are not fully reliable<sup>7</sup>.

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Considering the above limitations of existing sea-level gauges and the need for real or near-real-time sea-level information accessibility by multiple users and user-agencies in the country, Joseph and Prabhudesai<sup>8</sup> advocated the urgent need for the development of a reliable real-time sea-level data communication facility. At present, the Pacific Tsunami Warning System telemeters sea-level data in real-time using the meteorological satellite (e.g. Meteosat or GOES) Data Collection Platform (DCP) system. However, in contrast to fast tsunami travel times (TTT) in the deep Pacific Ocean, the TTT are much shorter in other ocean basins and the latency in DCP transmissions is less acceptable<sup>9</sup>. As a result, INMARSAT satellites, which make use of the Broadband Global Area Network (BGAN) technology, that provides 'always on' connectivity from almost anywhere on the earth's surface, are the currently preferred alternative satellite technology for real-time sea-level telemetry<sup>10</sup>. However, this methodology is costly.

Given the popularity of the Internet on a global scale, providing state-of-the-art sea-level information accessibility at significantly low cost seemed to be a practical proposition. Based on this requirement for Indian coasts, Prabhudesai *et al.*<sup>11</sup> designed and developed in-house, a cellular-based real-time reporting and Internet-accessible sea-level gauge and established such a sea-level monitoring station at Verem Naval jetty, Mandovi estuary, Goa (Figure 1). This gauge is an improvised and value-added version of the one established by NIO at Ghana, on the east coast of the Atlantic Ocean<sup>12</sup>. Although the Ghana station has since been enhanced by a new radar and pressure system, the NIO gauge proved the value of recording at this site, by providing a new set of tidal and non-tidal residual information and by the clear identification of the 2004 Sumatra tsunami<sup>9</sup>. Subsequently, the system was further improvised and another sea-level monitoring station was established at Kavaratti Island (Lakshadweep archipelago) for the Lakshadweep Development Corporation Ltd (Figure 2).

Conventional tide-well systems are known to introduce nonlinearity to large amplitude waves<sup>13,14</sup>, and cause large underestimation of the tsunami signal (by a factor of 2–5) relative to those inferred from inland inundations<sup>15,16</sup>. In addition, these gauges suffer from overestimation of sea-level elevation resulting from trapping of low-density water<sup>17</sup>. Further, these gauges are not sensitive enough to detect weak tsunami signals.

Several methods are available for sea-level measurements<sup>18,19</sup>. Although the recently introduced radar gauge has advantages such as relative ease in installation and insensitivity to ambient temperature changes<sup>18</sup>, it suffers from an inherent height limit in the case of tsunami measurements. Based on this, the Intergovernmental Oceanographic Commission (IOC) has recommended the use of sub-surface pressure sensor as a backup to the radar gauge because of its ability to record any water

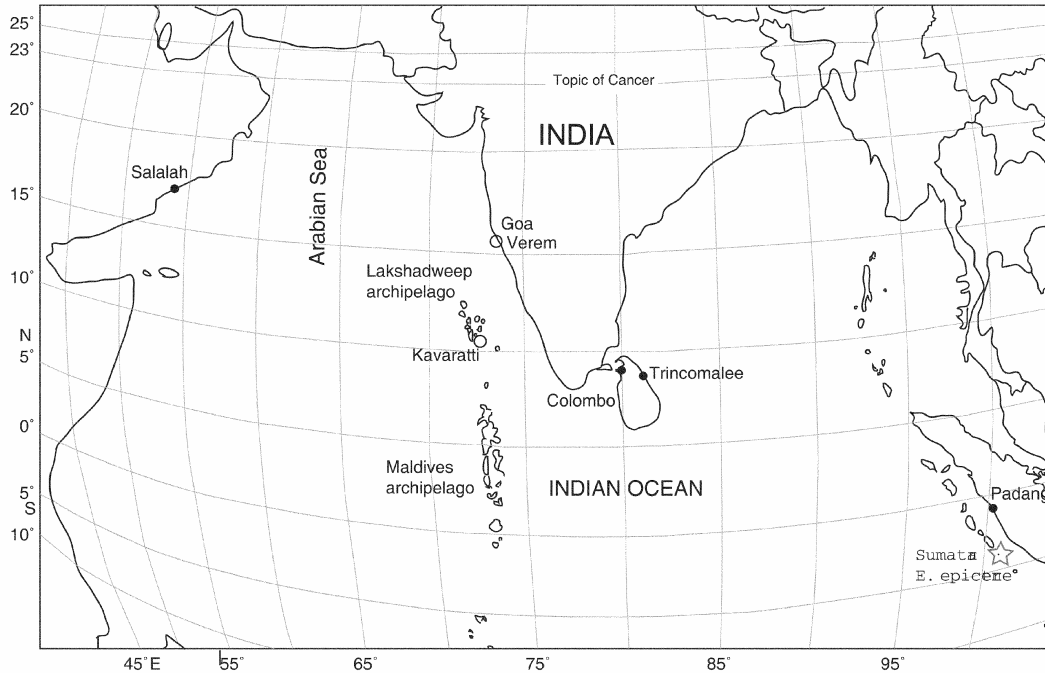
level which exceeds the limited height of the radar sensor. Also, the pressure sensor has advantages such as the ability to be sampled at a higher rate, linear response to large-amplitude waves such as tsunamis, and has a reasonably good accuracy except in heavily suspended sediment-laden water bodies<sup>21</sup>. Consequently, the sub-surface pressure sensor is regarded as the main 'tsunami sensor', suitable for tsunami network applications<sup>9</sup>. Thus, delivery of scientific inferences on tsunami signals derived from sub-surface pressure measurements is expected to be more realistic than those inferred from conventional stilling-well-based gauges, such as float-driven and guided air-acoustic gauges.

In view of these advantages, we have incorporated the pressure sensor in the design of our sea-level gauges. The sensing element is a temperature-compensated piezoresistive strain-gauge transducer (Honeywell), whose performance is found to be adequate for coastal sea-level measurements<sup>22</sup>. The pressure inlet of the transducer is located such that it remains at the centre of, and flush with, the flat surface of the pressure housing. This methodology minimizes Bernoulli dynamic pressure effects arising from flows, waves and a combination of both<sup>23</sup>.

Absolute pressure is sampled at a frequency of 2 Hz and averaged over an interval of 5 min. This fast sampling rate, as against the previously recommended 15-min



**Figure 1.** Internet-enabled real-time reporting sea-level gauge installation at Verem Naval jetty (Mandovi estuary, Goa).



**Figure 2.** Map of Internet-accessible cellular-based real-time sea-level reporting gauge sites at Verem jetty (Goa), and Kavaratti Island (Lakshadweep archipelago) in the Arabian Sea (Source: Google Earth).



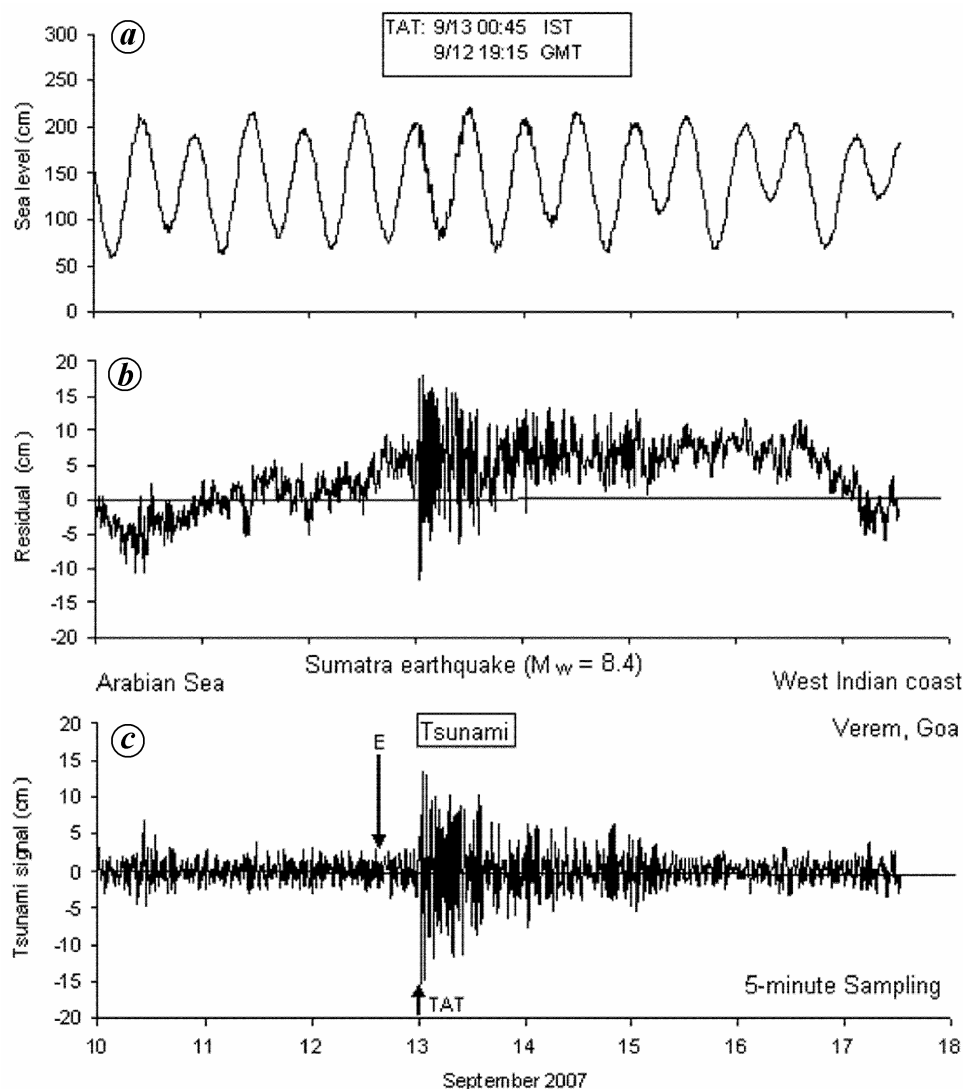
**Figure 3.** Graphical display of predicted (astronomical) tide, measured sea-level, and residual (i.e. measured sea-level minus astronomical tide) from Verem Naval jetty, provided through the Internet (<http://inet.nio.org/index.html>).

sampling rate for GLOSS requirements (IOC, 2002) is necessary to adequately recover high-frequency signals, which are crucial for tsunami detection. Sufficient closely sampled observations are needed to assimilate datasets into numerical models to gain insight on the principal factors that control the transport of tsunami energy and its distribution and propagation characteristics. The 5-min

data-averaging time used in the present gauge avoids the possibility of artificial attenuation of the tsunami in the sea-level record, as was suspected in the cases where 15-min averaging was used during the December 2004 Sumatra tsunami<sup>2,12</sup>.

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 mega bytes. Additionally, remote data communication facility is also implemented for real-time or near-real-time graphical reporting of sea-level on the Internet to facilitate operational applications such as navigation control, and warning and rescue operations in the event of anomalous sea-level conditions, such as those occurring during storm-surge and tsunami episodes.

The effectiveness and usefulness of the tsunami detection/monitoring system depends on the uninterrupted transmission of data. For this, 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 requirement. Accordingly, the present system has been designed to eliminate the requirement of a 'tide gauge hut' that necessarily forms an essential component of a conventional sea-level station. The electronics parts of the system and the cellular modem used for data communication are well protected within a weather-proof housing. Battery and the weather-



**Figure 4.** *a*, Time series of approximately a week-long sea-level record from Verem site, covering the period prior to, during and subsequent to the 12 September 2007 Sumatra earthquake. *b*, De-tided sea-level record from Verem. *c*, Tsunami signal. E, Earthquake time; TAT, Tsunami arrival time.

proof housing are rigidly mounted within another sturdy fibre reinforced plastic (FRP) housing. The housing and the solar panel are mounted on the top portion of the mounting structure mentioned above.

Real-time data communication is implemented via cellular connectivity incorporating GPRS technology<sup>11</sup>. The Internet server that disseminates the real-time sea-level information in graphical format is located at NIO, Goa.

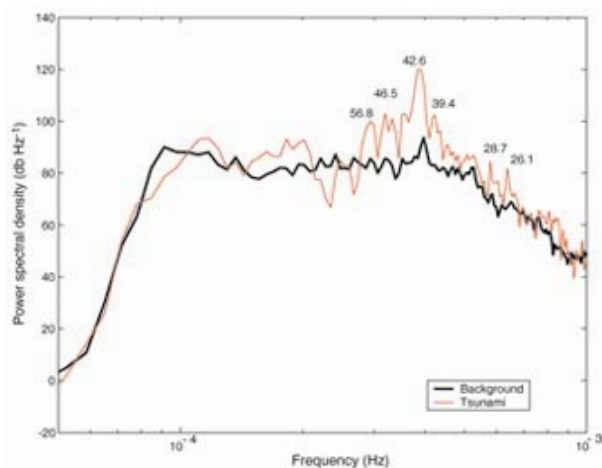
### Tsunami signals at Goa and Kavaratti Island

Figure 3 shows the graphical display of predicted (astronomical) tide, measured sea-level and residual (i.e. measured sea-level minus astronomical tide) from Verem

Naval jetty, provided through the Internet. While the sea-level record on 12 September 2007 is relatively quiescent, the record from 13 September is clearly modulated by a higher frequency signal. This clearly discernable modulation remained consistent for about 14 h. Subsequently, the modulation became weak and gave the appearance of quasi-periodic disturbances, which continued to persist up to 14 September noon.

Figure 4*a* shows the time series of approximately a week-long sea-level record (from 10 to 18 September 2007) from Verem station, covering the period prior to, during and subsequent to the 12 September 2007 Sumatra earthquake. The data had no erroneous spikes and gaps. To examine the possible presence of a tsunami signal, astronomical tides were removed from the measured sea-level

record by calculating the tides from the sea-level measurements of one-month duration using a tidal analysis software package, TASK<sup>24</sup>. The de-tided sea-level record (i.e. sea-level after removal of astronomical tides) shows the presence of a residual low frequency (Figure 4*b*). This low-frequency was removed by high-pass filtering of the de-tided sea-level record using Butterworth filter of order 5, with a cut-off frequency 1/3 cycles/day (cpd). Signals of frequency below 1/3 cpd were removed and higher frequencies were allowed to pass through. The resulting series (Figure 4*c*) was used for analysis of tsunami. From Figure 4*b* and *c* we can clearly see a discernible tsunami signal, whose arrival time (TAT) is 45 min IST on 13 September (19 h:15 min UTC on 12 September 2007). From the residual record before the tsunami arrival at Verem (Figure 4*b*), it is clear that the background sea-level variability at this location is negligibly small. To examine the relative energy levels of the tsunami signal and the background signals, spectral analysis was performed on the time-series data (Figure 5). The background spectrum has been computed for a long segment before the tsunami [for about 7200 samples, corresponding to approx. 24 days (17 August–10 September 2007)]. On the other hand, the tsunami spectrum has been computed for a short segment covering the tsunami (for about 1728 samples), corresponding to approx. 5 days (11–16 September 2007). Use of a long segment for the background spectrum achieved an average spectrum, reflecting mainly the ‘mean’ background conditions and the topographic resonant characteristics of the Verem station. The background spectrum derived from a reasonably long segment would enable an estimation of the topographic admittance function (see for example, Rabinovich and Stephenson<sup>25</sup>). On the contrary, selection of only 1–2-day segment just before the tsunami would have resulted in only a rough estimate of the background spectrum during the time of the event. We note that the spectrum consists of a pre-



**Figure 5.** Spectrum of tsunami and background signal at Verem.

dominant tsunami spectral peak corresponding to a period of 42.6 min, at which the spectral energy of the tsunami signal is considerably larger than that of the background spectrum. In comparison, the period of the December 2004 Sumatra tsunami spectral peak in Ghana (West Africa)<sup>12</sup> was 42 min. In fact, the 42–45 min spectral peaks were the most common for the December 2004 Sumatra tsunami observed all over the World Oceans<sup>3,7</sup>. Apparently, these spectral peaks are related to the tsunami source characteristics.

Sea-level measurements and the de-tided sea-level from Kavaratti (Figure 6) reveal the presence of a distinctly clear signal a few hours prior to the arrival of the tsunami at the Verem site. This signal persisted only for a short time and the limited number of cycles present (only three cycles) precluded computation of its spectral density. However, estimates from these three cycles show that the observed period is comparable to the tsunami period from the Verem station in Goa. The tsunami arrival time (TAT) at Kavaratti Island is 22 h on 12 September. Thus, the tsunami arrived 2 h and 45 min earlier at Kavaratti Island than at the Verem station on the mainland.

### Tsunami signals at other closer locations in the Indian Ocean

The closest location to India from where the September 2007 tsunami signal has been reported in the Indian Ocean is Colombo (8°59'N, 79°51'E) followed by Trincomalee (8°20'N, 81°11'E), which are located on the west and east coasts respectively, of Sri Lanka. As expected from the relative proximity to the tsunami source region, the tsunami arrived first at Trincomalee (TAT: 14 h:58 min UTC [20 h:22 min IST] on 12 September) and then at Colombo (TAT: 15 h:12 min UTC [20 h:42 min IST] on 12 September). The next closest location is Male (Maldives archipelago), where it arrived at 15 h:31 min UTC [≈21 h IST]. The trough-to-crest tsunami wave height at Colombo, Trincomalee and Male was 56, 49 and 24 cm respectively. Except Padang (00°57'S, 100°22'E) in Indonesia and Salalah on the Arabian coast (Persian Gulf), which reported of trough-to-crest tsunami wave height 2.40 and 1.45 m respectively, all other locations recorded less than a metre. The relatively larger wave height reported from far-off Salalah could be due to focusing or interference from the Carlsberg Ridge. Similar focusing/interference-dependent tsunami amplification has been observed in the case of the December 2004 Sumatra tsunami on the west coast of Africa as well<sup>12</sup>. A legitimate explanation that can be offered for the observed relatively small height of the wave at Male is its open-ocean position. Tsunami wave height at Kavaratti Island was still weaker (5 cm). Verem station is located on the mainland coast and a tsunami signal normally strongly amplifies while approaching the coast (for example, satel-

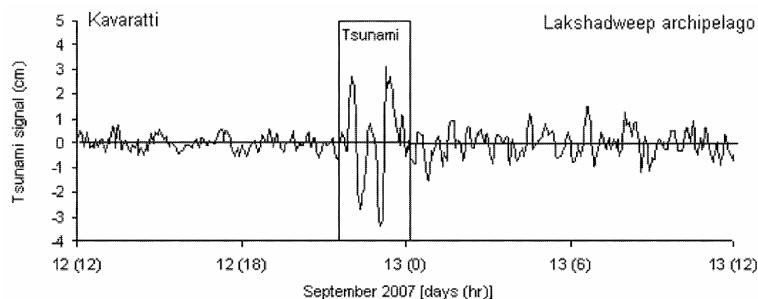


Figure 6. Tsunami wave from Kavaratti Island.

lite-recorded waves in the open part of the Indian Ocean during the December 2004 Sumatra tsunami were about 70–80 cm, but when these waves arrived at the coast of India they were 3–5 m)<sup>7,26,27</sup>.

### Summary and conclusions

The Internet-enabled real-time sea-level monitoring system designed and established by the Technology Group at NIO, Goa on 24 September 2005 and working without interruption since then, recorded and graphically reported on the Internet in real-time (updating at 5 min interval) the arrival of the September 2007 Indonesian tsunami in Goa. Our system at Kavaratti Island also indicated the presence of a weak tsunami signal, although its spectrum could not be obtained because of limited cycles in the signal. This shows the practical utility of the monitoring system for operational applications in the event of sea-level-related issues.

The tsunami arrived at Verem station after travelling approx. 8 h from the tsunami source region (Sunda trench). The first wave was negative (trough) and the observed period was 42.6 min. The maximum trough-to-crest wave height was 29 cm. The presence of just one distinct burst indicates that there was no reflection and focusing of the waves. Bathymetry along the west coast near Goa influenced the amplification of the waves as observed at the Verem Naval jetty (about six-fold larger than at Kavaratti Island). On the other hand, Kavaratti is an open-ocean island site, much less affected by topographic/bathymetric effects and therefore, the observed relatively small trough-to-crest tsunami height (5 cm) is not surprising. In comparison, the prominent December 2004 Sumatra tsunami signal at Ghana (West Africa) was about 13-fold larger than that at St. Helena Island, which is the closest coastal location to the Ghana site in the Atlantic Ocean<sup>12</sup>. The prominent signal found in the Verem sea-level record indicates that the waves could be traced also at other locations in the west coast of India.

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