

Integrated Coastal Observation Network (ICON) for real-time monitoring of sea-level, sea-state, and surface-meteorological data

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Abstract- National Institute of Oceanography (NIO) has established an Integrated Coastal Observation Network (ICON) of in-house designed and developed Internet-accessible real/near-real time reporting cellular based sea-level, sea-state, and surface meteorological (Met) stations at several locations on the Indian coasts & Islands (<http://inet.nio.org>). Subsurface pressure sensors and downward-looking microwave radars are incorporated in the sea-level station network. Sea-level, Met, and surface wave parameters are acquired using dedicated Linux based data loggers and uploaded to an Internet server at 5-, 10- and 30-min intervals, respectively with the use of GPRS cellular modems. The sensors and data loggers are powered from sealed lead acid batteries, which are charged through solar panels. The ICON provides graphical presentation of sea-level information (observed sea-level, predicted tide, residual sea-level); significant wave height and wave direction; and Met information (vector-averaged wind speed & direction, barometric pressure, atmospheric temperature, solar radiation, relative humidity, and rainfall). Installation of sea-level sensors free from the influence of stilling-wells and long narrow tubes renders the measurements ideal for tsunami and storm-surge studies by preventing waveform distortion and non-linearity of large-amplitude short-period signals. The network maintains accurate time-stamp of the dataset through Internet-time synchronization using network time protocol (NTP). Real-time reporting capability of ICON yields several benefits, such as (i) remote monitoring of proper working condition of individual stations; (ii) implementation of repair/maintenance in the shortest possible time, thereby minimizing break in the time-series data stream; (iii) periodic arrival of data stream from all stations at a single central server, thus yielding backup for the data from all the stations; (iv) access to the latest in-situ information; (v) allows possible use of data with automated real-time running numerical models for operational forecast. In contrast to the limited bandwidth provided by INSAT transmitters, coastal observations at high bandwidth at significantly low cost have become realizable using cellular GPRS network. The NIO-network allows, Internet based real/near-real time tracking and monitoring of sea-level, sea-state, and meteorological conditions along the Indian coasts and islands and from almost anywhere – an issue of considerable practical significance during natural disasters such as storm, storm-surge, and tsunami.

I. INTRODUCTION

Sea-level, sea-state and surface meteorological data are of considerable value to the research community in a variety of applications for a wide range of scientific studies including those of long-term changes and the statistics of extreme events. Long-term changes in atmospheric warming and global mean sea level due to climate change continues to be the focus of much research in recent years because of the potential impacts on the environmental, economic, and social infrastructure at the coast.

Apart from scientific research applications, sea-level, sea-state, and surface meteorological data have several applications in the rapidly developing field of 'operational oceanography'. For example, prediction of 'ocean weather' in analogous fashion to the use of air pressure and wind data within operational weather forecasts would yield valuable information to environmental managers and forecasters. Some of the other applications include management of ports and harbours (e.g., guiding ships entering or leaving harbour and management of sluices and barrages), fisheries and aquaculture; oceanic forecasting; optimizing offshore design and operations; and coastal zone management and related research. Besides these, sea-level data is of considerable value to governments, industries, and scientists to generate analysis and forecasts for the public to deal with marine related issues, including environmental issues, sustainable development, and the effects of the ocean upon environmental changes.

Considering vulnerability of the Indian coasts to storm surges and the recently felt threat of tsunamis, including the powerful December 2004 global tsunami [1] real-time reporting of sea-level, sea-state, and surface meteorological information has become all the more important for multi-hazard monitoring and warning purposes. Thus, establishment of a network of real/near-real time reporting sea-level, sea-state and surface meteorological stations providing high-quality data sets will lead to improved operational utilities and more efficient forecasting results. Further, good quality data availability will facilitate promotion of oceanographic and climatologic research programmes to improve understanding of critical global and regional ocean- and climatologic- processes and their relationship to the sustainable development and stewardship of ocean resources.

II. METHODS AND INSTRUMENTS

An important technical requirement for realistic measurements of any parameter, which would be used for scientific analysis and interpretation, is the linear response of the measurement device over the full range of interest. Recent tsunami events in the Indian Ocean suggest that, apart from study of global climate change and the resulting sea level variability, realistic interpretation of tsunami signal is an important scientific application of sea-level data analysis. Thus, sea-level measuring devices should have linear response in the above mentioned wave-period range even under the largest tsunami wave height expected. There are numerous instances in which tsunami heights were heavily underestimated because of these problems. Thus, it is important that current and future sea level measurements incorporate adequately linear sensors and optimal deployment methodologies.

Another important criterion to be taken into account in data collection of scientific interest is sufficient accuracy and proper data sampling. New sensors capable of measuring sea-level variations with high precision and sufficiently fast sampling interval are needed to detect and record even weak tsunamis and storm surge signals. Uninterrupted time-series data from such sea-level stations would allow identification and separation of seismically generated tsunami waves and atmospherically generated seiche oscillations, which is a key problem for the disaster warning personnel and an important scientific problem. The sensor and the data logger should have excellent accuracy and resolution, and be also free from electrical noise. If these criteria are achieved, even weak signals of interest will be sufficiently clear and easily distinguishable from the background noise.

Adequately close sampling interval is an important pre-requisite to distinguish and separate out the desired signal from the data record. The net effect of reducing the data-sampling interval is to deprive us of important information about the signal in the frequency band of interest and possibly to create serious aliasing problems. Signals are not well represented (adequately distinguished) if the sampling interval is not sufficiently shorter than half the actual wave periods that are desired to be measured. It is obvious that long sampling intervals can lead to either totally masking the desired signal or introducing a marked distortion of the properties of the signal that is sought to be recovered from the time-series record. In any case, closer sampling interval is the preferred criterion. In the network presented here sea-level, surface meteorological data, and surface wave parameters are acquired at 5-, 10- and 30-min intervals, respectively. Taking into account the ~43 min dominant period of the tsunami signals observed during the December 2004 global tsunami [1], [2], [3] and September 2007 Indian Ocean tsunami [4] sea-level data sampling at 5-min interval incorporated in the present network is well within the theoretical requirements for adequately distinguishing the signals of interest. Surface meteorological data sampling at 10-min interval incorporated in the present network is also well within the requirement for scientific analysis of such data. Acquiring significant wave height and direction information at 30-min interval is at considerably closer interval in contrast to the conventional practice of surface wave data acquisition at 3-hour interval. While in the past, longer sampling intervals were often used due to limited capacity of memory devices, in the present era cost-effective memory modules of very large capacity (e.g., SD cards and pen drives) are commonly available and therefore fast data-sampling is no longer a constraint. The above concerns have been given due attention in the design of the NIO-network presented in this article.

A. Sea-level measurements

The primary purpose of the majority of sea-level gauges existing all over the world used to be the measurement of relatively low-frequency processes, such as tides and seasonal to climatic sea-level variations. When relatively short-period and high-amplitude oceanic waves such as tsunami and storm-surge occur, the measuring equipment needs to be capable of recording such sea-level variability without waveform distortion or amplitude attenuation, which happens with conventional measurement schemes incorporating stilling-wells as in [5]. Different applications of data imply different standards for measurements. For example, applications such as monitoring of storm-surge/tsunami or operations such as ship movements demand accuracies better than 0.1 m, long-term monitoring of trends calls for accuracies of order 0.1 cm or better. However, in practice, there are advantages in making all observations to the highest possible standards so that the data are usable for all applications. Based on this realization, there has been a continuing trend in recent years to upgrade and renew the existing lower quality sea-level gauges to high quality ones (e.g., temperature-compensated quartz pressure sensors for deep-sea measurements; downward-looking aerial microwave radar sensors for measurements from offshore platforms and coastal regions). Whereas subsurface pressure sensor is regarded as the “tsunami sensor” suitable for tsunami network applications [6] and therefore sea-level gauges based on them are the recommended ones for tsunami detection and monitoring, the accuracy obtainable from them depends on how well the local barometric pressure at sea-level is incorporated in the data processing scheme. Also, the formation of sediment suspension and micro-bubbles during tsunami and storm surge events can lead to reduced accuracy of subsurface pressure based sea-level measurements [7]. While tsunami is generally a geophysical phenomenon having little connection to meteorological factors, storm-surge is purely a surface meteorological phenomenon and therefore a measurement scheme in which the sensing devices are insensitive to meteorological influences would be the most suitable one for storm-surge monitoring. The recently introduced downward-looking aerial microwave radar sensor is insensitive to meteorological influences, and therefore, we have incorporated microwave radar sensors as well in our sea-level station network. Thus, sturdiness of installation is an important requirement for achieving uninterrupted data from a network of sea-level and surface meteorological data logging installations. Taking this into account, each station that forms an integral part of the present network has been constructed with reasonably adequate sturdiness.

Subsurface pressure sensor

The pressure sensor used in the present sea-level station network is “absolute” type silicon thin-diaphragm strain-gauge (Honeywell make) which provides absolute pressure (i.e., pressure of the water column above the sensor plus atmospheric pressure) in RS-485 format [8]. Here Sub-surface 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 storm-surges, and has a reasonably good accuracy except in heavily suspended sediment-laden water bodies [7]. Consequently, the sub-surface pressure sensor is considered to be suitable for incorporation in tsunami network applications [6].

The approach used for estimation of sea-level elevation using sub-surface pressure sensor is to measure the hydrostatic pressure, P_d , at depth d below the sea surface, and to convert this pressure to water level above the pressure inlet of the transducer by using the relationship: $P_d = P_a + (\rho \times g \times d)$ where P_a is the atmospheric pressure, ρ is the mean density of the overlying column of water, and g is the local acceleration due to gravity. The measured pressure varies as the sea-level varies. Local dynamic effects such as flows, waves and a combination of both that operate in the vicinity of the pressure inlet influence the performance of a pressure based sea-level gauge. However, these effects can be significantly reduced by the use of an appropriate hydro-mechanical front-end at the pressure inlet [9]. Typical installation of subsurface pressure sensor based sea-level gauge incorporated in the present network is illustrated in Fig. 1.



Fig. 1 Typical installation of subsurface pressure sensor based sea level gauge

Downward-looking aerial microwave radar sensor

Two variants of downward-looking aerial microwave radar sensors (OTT Kalesto make and RLS) are incorporated in the sea-level station network of NIO. These are non-contact devices that are capable of remote measurement of sea-level elevation from the air. The transmission frequency of the radar sensor is 24 GHz and the beam width is $\approx \pm 5^\circ$. The basic premise involved in the operation of the radar sensor used here is transmission of microwave pulses towards the sea surface and reception of the reflected/backscattered energy. The reflected microwaves are analyzed to estimate the aerial distance travelled by a given pulse. The aerial distance is determined by measuring the phase of the return wave and knowing the frequency of the microwave signal that was transmitted. The water level y with reference to a preferred datum (e.g., CD or harbour datum) is estimated as $y = (b - a)$, where ‘ b ’ is the known vertical height of the sensor head from the chosen datum and ‘ a ’ is the measured aerial distance of the sensor head from the water surface. As in the case of subsurface pressure sensor, wind-induced high-frequency oscillations on the sea-level measurements are filtered out with the online application of an integrated software filter. The accuracy of sea-level measurement using the microwave radar principle is within ± 1 cm [10]. The measurements are transferred to a data logger by means of a RS-485 interface. Typical installations of microwave radar sensor based sea-level gauges incorporated in the present network is illustrated in Fig. 2.

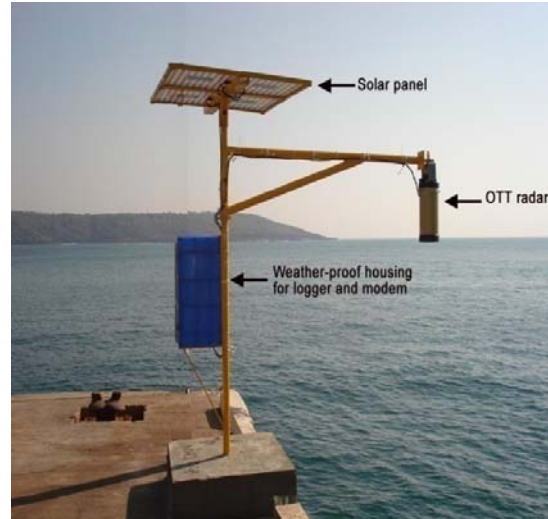


Fig. 2 Typical installation of downward-looking OTT aerial microwave radar sensor based sea-level gauges incorporated in the NIO’s ICON network;

The main advantages of the downward-looking aerial microwave radar based sea-level measurements are the following:

- Sea-level measurements are insensitive to variations in air temperature, humidity, and rainfall. Linear operation (absence of waveform distortion and non-linearity of large-amplitude short-period signals such as storm surge and tsunami).
- Installation does not require conventionally used 'tide gauge cabin' and stilling-well.
- Can be installed from coastal jetties, bridges, harbour piers, or offshore platforms with relatively lesser logistic problems.
- Trouble-free installation and maintenance due to the absence of physical contact with the water body.

From an operational point of view, an advantage with the non-contact measuring principle used in the microwave radar gauge is that problems such as disruption of measuring operation caused by high water, silt accumulation, debris, plant growth and so forth, as well as time-consuming maintenance are reduced considerably. In the event of any maintenance requirement, the difficulty involved is relatively less because of land-based operation. Because of its compact design and the non-contact measuring principle, the gauge can be installed easily and inconspicuously, without the use of cumbersome stilling-well/protective-well. Further, the device is particularly suitable for areas where conventional measuring systems cannot be used or where a station needs to be set up quickly and inexpensively. Because the gauge does not come in direct physical contact with water, it is particularly useful for measurement from locations where the water contains a large amount of suspended matter.

A relatively meritorious feature that can be attributed to radar gauge is its suitability for measurement of large sea-level oscillations such as those occurring during tsunami. However, this feature can be achieved only if the gauge is suitably installed, taking this requirement into consideration. For example, the measurement range of the radar used in the present network is 1.5 to 30 m. However, the footprint of the beam increases as the distance of the radar from the sea surface increases. Thus, the more the distance between the radar sensor and the sea surface, the more is the safety distance between the vertically oriented central axis of the radar beam and the wall of the jetty where the gauge is erected. The recommended safety distance for the radar used in the NIO-network (radiation angle = $\pm 5^\circ$) to achieve the full range of 30 m is 3m.

An observed limitation with the radar gauge sensing scheme is contamination of sea level measurements by man-made lapses such as anchoring of floating objects below the radar sensor. This indicates the sensitivity of aerial microwave radar gauge to floating objects, and the importance of protecting the footprint area of the microwave radar from contamination by such objects, if high quality data that the radar gauge is capable of providing is to be fully realized in practice.

B. Surface meteorological measurements

The surface meteorological parameters acquired by the meteorological stations (Automatic Weather Station [AWS]) incorporated in the present network are vector-averaged wind speed and direction, barometric pressure, atmospheric temperature, solar radiation, relative humidity, and rainfall. The mechanical parts of the AWS consist of Stevenson's cage with a mounting stud for wind monitor and an electronics-housing mountable on a suitable flange. Typical installation schemes used for the AWS system incorporated in the NIO-network is illustrated in Fig. 3. Hinge-and-lock arrangement used for fixing the sensor-mounting tower allows relatively trouble-free installation and servicing. Rain gauge is mounted as an independent device. However, like other sensors, it is electrically connected to the logger.

In the AWS, each parameter is sampled at an interval of 10 seconds. Surface meteorological measurements are recorded at 10-minute interval, and each measurement is an average over 10 minutes (*i.e.*, average of 60 samples). Wind is vector-averaged. Gust (maximum wind speed within every 10-minute sampling) is also recorded. Thus, the 'gust' value recorded is the largest wind speed amongst an ensemble of 60 samples that are detected during the 10-minute sampling span. Brief descriptions of the sensing methodologies are provided below.



Fig. 3 Typical installation of AWS in NIO's ICON network

Wind velocity

An anemometer (RM Young Model 5103) consisting of a propeller and a vane integrated into a single unit measures the horizontal wind speed and direction. The sensor features near neutral torque. The speed sensor is an 18-cm diameter 4-bladed helicoid polypropylene propeller, which is coupled to a centrally mounted stationary coil. The wind direction sensor is a balanced vane (38 cm turning radius), which is free to turn on sealed bearings, coupled to a linear precision potentiometer (10 K Ω resistance, 0.25% linearity). During wind-driven rotation of the propeller, a six-pole magnetic disc mounted on its shaft induces an AC sine wave signal in the coil at a rate of 3 cycles per revolution. The output frequency and amplitude are directly proportional to the wind speed. The AWS circuits mask the amplitude-signal through a back-to-back diode limiter-circuit and clamp the signal to ± 0.6 V. A comparator converts the clamped signal into a square wave at a threshold level corresponding to a wind speed of 0.5 m/s. The built-in hysteresis in the comparator avoids false triggering.

Barometric pressure

The pressure sensor incorporated in the AWS consists of a Honeywell precision Pressure Barometer (HPB), based on a silicon piezoresistive sensor coupled with a microprocessor. With pressure- and temperature-sensitive elements, the microprocessor corrects the sensor's non-linearity using a built-in calibration facility.

Solar radiation

A photodiode sensor (LICOR-LI200) which generates a DC current proportional to the incoming solar radiation (90 μ A per 1000 W/m²) in a broad spectrum of wave length, is used for the measurement of solar radiation.

Air temperature

A linearized thermistor [YSI 44202] based temperature probe is used. This probe is mounted within a sun-shield similar to Stevenson's grid to inhibit direct solar heating.

Relative humidity

Rotronic MP-100 a capacitive type sensor, exclusively designed for outdoor applications, is used. Its dielectric properties vary in response to changes in the amount of water content in air and the ambient temperature. The active part of the sensor is a condenser, made of polymer foil sandwiched between two flat electrodes. A porous Teflon foil protects the sensor. The humidity probe mounted inside a Stevenson's cage protects it from direct solar heating and allowed free circulation of air.

Rainfall

An electrical version of the conventional tipping bucket rain gauge (RM Young Model 052202), whose catchments area is 200 cm² and measurement resolution is 0.1 mm, is used for measurement of rainfall.

C. Surface wave measurements

The devices incorporated in the present network for acquisition of surface wave parameters are wave rider buoys deployed by the Ocean Engineering Group of NIO. Of the several surface wave parameters received at land-based stations at 30-min interval from wave rider buoys, significant wave height and direction only are uploaded to the Internet server through a cellular modem interfaced to a dedicated Linux based data logger.

D. Data acquisition system

An embedded Linux based single board computer (SBC) TS-7260, which is found to be extremely reliable and robust, is used for sea-level, sea-state and surface-meteorological data acquisition. A wide range of integrated peripherals on this board and built-in operating system makes it suitable to implement complex data acquisition tasks. The SBC incorporates (i) interfaces such as Ethernet, USB (Universal Serial Bus), SD (Secure Digital), multiple serial and digital I/O; (ii) Memory (64-MB RAM, 32-MB flash); (iii) battery backed real-time clock; (iv) 12-bit analog-to-digital converter; and (v) PC-104 expansion bus. The SBC run on a 200-MHz ARM9 processor and its design is optimized for power consumption as low as $\frac{1}{4}$ Watt. Fig. 4 shows the schematic diagram of the data acquisition system at each station within the network. The field station is powered using sealed lead acid battery which is charged by solar panel. A 42-AH battery and 75-Watt solar panel are used for uninterrupted operation, particularly during monsoon season. The sensors are connected to the SBC using RS-485 interface. The acquired data are stored on the SD card.

A well established Point-to-Point Protocol (PPP) provides a mechanism for running the network protocols over a serial link. With PPP setup, standard networking utilities built into the embedded Linux are used for Internet connectivity, file transfer, network time synchronization etc.

The commonly used crystal oscillator time-base in computers and embedded systems is often imprecise, temperature-sensitive and exhibits significant frequency variations over time, thereby resulting in inaccuracies of the order of a few minutes per month. There are several servers on the Internet that synchronize their internal clocks to an external source such as GPS satellite system, providing accuracy better than 1 microsecond. An NTP client program running on the SBC periodically synchronizes its clock with that of the network time servers to maintain an accurate time-base.

The dataset collected from the sensors are compressed using gzip.exe program before uploading it on the Internet server. Typically, the dataset is compressed by a factor of 5 or more, which considerably saves the time and power required for ftp upload.

The Internet Server located at NIO is based on Microsoft Internet Information Server (IIS). The embedded systems from the remote stations in the network upload their data file onto this server at preprogrammed interval. The server-resident program continuously monitors the status of ftp upload. On successful completion of the ftp operation, the received compressed data file is decompressed and checked for its validity. Subsequently, the plots of each parameter are created and presented on the web server in the form of an HTML page.

III. Network of real-time reporting sea-level, sea-state, and surface-meteorological stations

Whereas several locations in India and the Indian Ocean rim regions are known to be vulnerable to storms and storm-surges, incidents in the last few years show their vulnerability to tsunamis as well. The network of spatially distributed real/near-real time reporting sea-level, sea-state, and surface-meteorological stations reported here (Fig. 5) acquire these

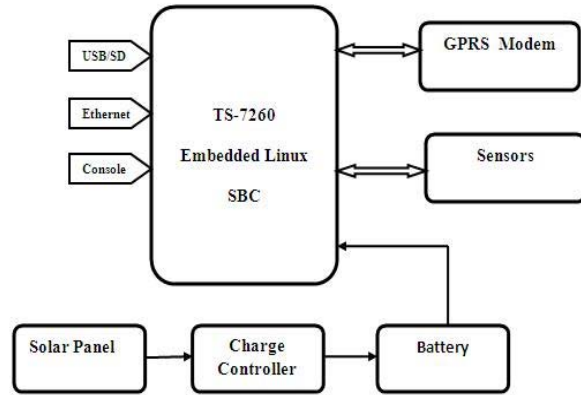


Fig. 4 Schematic diagram of data acquisition system

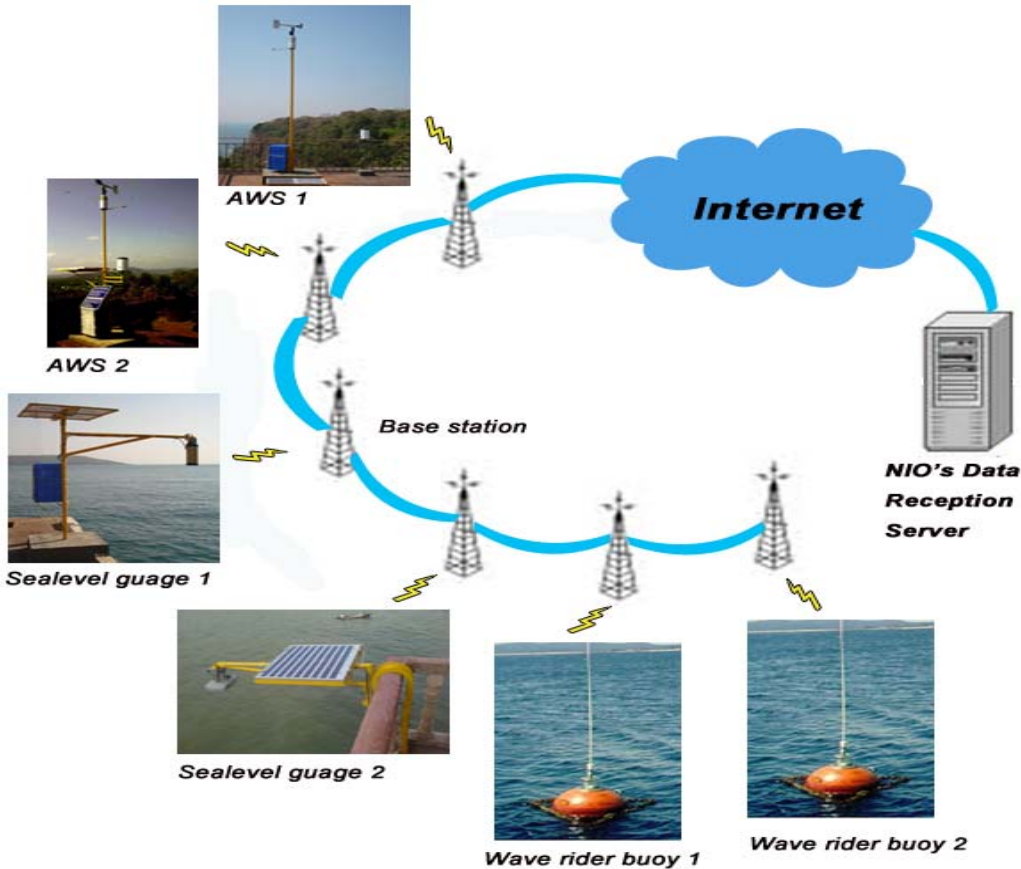


Fig. 5 Schematic Network of distributed real time reporting sea level, sea state and MET stations.

datasets using dedicated Linux based data loggers and upload them to an Internet server at 5-, 10- and 30-min intervals respectively, with the use of modular cellular modems. In contrast to the limited bandwidth provided by INSAT transmitters, coastal observations at high bandwidth at significantly low cost have become realizable using cellular GPRS network [11]. Maintenance of accurate time-stamp of the dataset through Internet-time synchronization of the data loggers' real time clock (RTC) twice in a day using Internet Network Time Protocol (NTP) allows error-free estimation of the arrival time and speed of propagating oceanic and meteorological events such as coastal waves, storm surges, tsunamis etc. Location map of stations available as on July 2010 under NIO-network (Fig. 5) is shown in Fig. 6. Although the NIO-network is primarily meant for high resolution data acquisition for various research and limited operational programmes; real/near-real time visual display of sea-level, sea-state, and surface meteorological information on the Internet on a continuous basis from a network of coastal and island stations will be of considerable practical value to the coastal and island dwellers as well as the general public and disaster management agencies.

An ideal network should consist of field stations having minimum amount of maintenance and maximum trouble-free operation. As any single measuring /communication equipment can fail, redundancy should be a critical design feature to minimize total data loss when they are needed the most. ICON is designed to take care of temporary interruptions of the communication link network, server failures etc. by being able to receive old data as soon as the network is up. New client server TCP/IP socket based communication is under test which supports interrogation of the field stations to download past data, to modify configurations parameters of the data acquisition and to modify firmware in the embedded system on the fly.

IV. REAL TIME REPORTING ON THE INTERNET

Real/near-real time sea-level, sea-state, and surface meteorological information from the present network can be accessed through the Internet link <http://inet.nio.org>. The "Location Map" icon on this Main Screen provides spatial distribution of various stations of the ICON-network (See Fig. 5). Typical screen displays of sea-level, sea-state, and surface meteorological information are shown in Figs. 7, 8 and 9 respectively. Display of battery voltage is useful in identifying the power supply status and taking immediate measures to service the field stations for un-interrupted operation.



Fig. 6 : Location map of stations available as on July 2009 under NIO-network illustrated in Fig. 5

Real-time reporting capability of the network yields several benefits, such as (i) possible use of the data for running automated real-time numerical models for operational forecast; (ii) validation of models and remotely sensed satellite data; (iii) availability of real/near-real time data from a network of stations, thereby giving the disaster response team access to the latest in-situ information from several locations; (iv) periodic arrival of data stream from all stations at a single central server, thus yielding backup for the data from all the stations at a single location; (v) remote monitoring of the working condition of individual stations; and (vi) implementation of repair/maintenance in the shortest possible time, thereby minimizing break in the time-series data stream.

The data and information gathered by the network will thus benefit the coastal communities which are at risk from tsunamis, storm surge and sea-level changes in general. Real time information on sea-level variability, sea state and surface meteorological conditions available through Internet can be utilised for the safety of the people at large by concerned agencies to more effectively mitigate the effects of natural hazards.

The network is also useful for providing the requisite real-time data to aid navigation, for climate change monitoring, coastal oceanic processes and related studies. The high-resolution meteorological and coastal sea state data gathered from such a network is being used operational agencies and researchers to validate outputs numerical models and to improve weather forecasts.

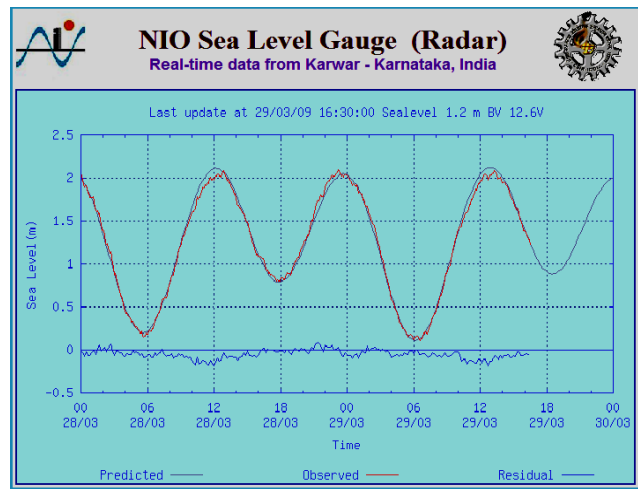


Fig. 7 Typical screen display of sea-level data

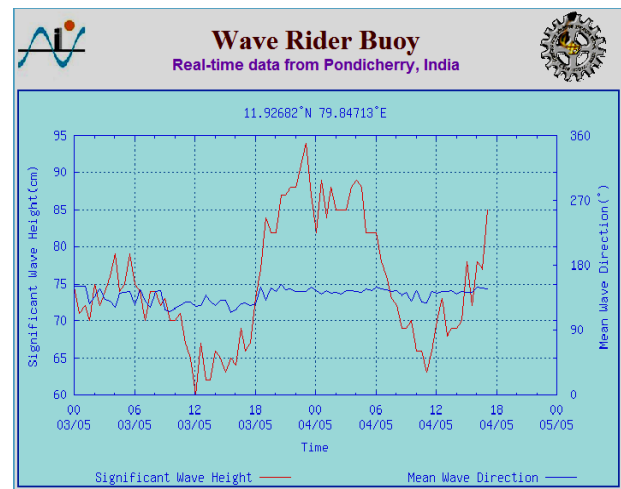


Fig. 8 Typical display of sea surface wave data

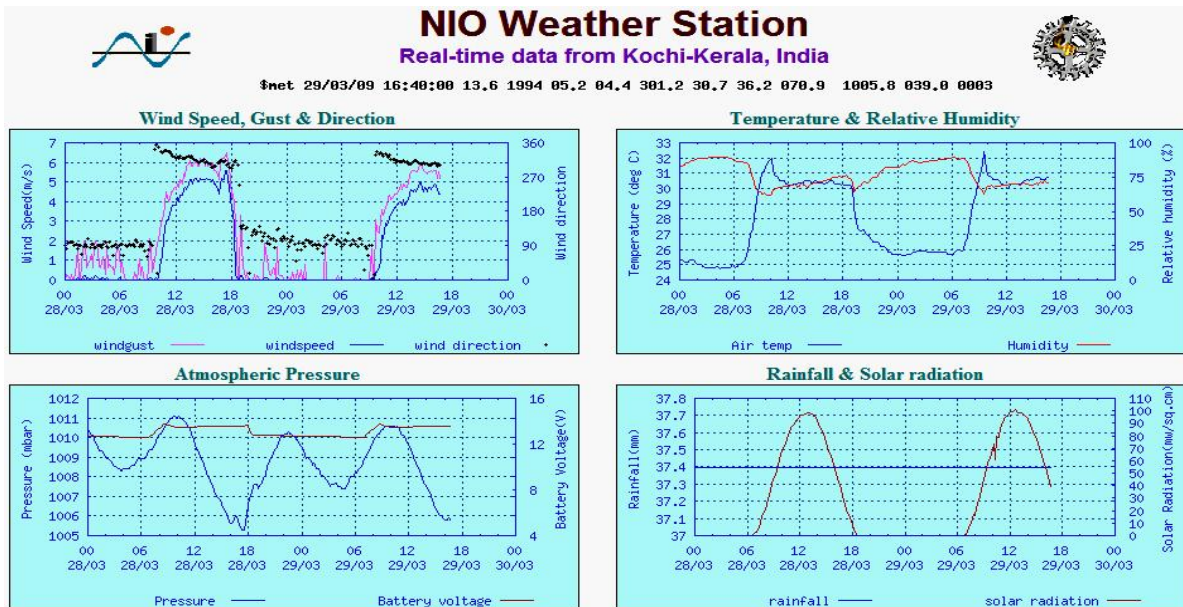


Fig. 9 Typical display of surface meteorological data

V. CONCLUSIONS

An Integrated Coastal Observing Network (ICON) for real/near-real time reporting sea-level, sea-state, and surface meteorological stations has been described. Implementation of ICON (design, development, and establishment) was prompted because of the absence of an easily accessible network of real/near-real time reporting sea-level in India during the progress of the disastrous December 2004 Sumatra tsunami along the boundaries of the Indian peninsula. The sea-level stations of the network have incorporated sub-surface pressure sensor and two variants of downward-looking aerial microwave radar sensors. The sea level gauges are installed on simple sturdy mounting-structures without the use of conventional 'tide gauge huts'. Uploading of the acquired data to an Internet server using GPRS cellular modem allows Internet-based data reporting at significantly low cost. Internet-time synchronization allows maintaining accurate time stamp. Real-time data from some of the stations of the present NIO-network are routinely used by a few ports and industrial institutions for their regular operational applications, and by Indian National Centre for Ocean Information Services (INCOIS) for providing advisories to the fishermen and the coastal communities at Pondicherry, besides the use of data from the network for a variety of scientific studies by universities and research laboratories.

VI. ACKNOWLEDGMENT

The authors would like to acknowledge Director, NIO and Council of Scientific and Industrial Research (CSIR), New Delhi for the support. The authors also thank to Miss. Blossom Viegas for her help in preparation of this manuscript and Mr. Anil Shirgaonkar for all his help in establishing the network.

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