



A Compact Self-Recording Pressure Based Sea Level Gauge Suitable for Deployments at Harbour and Offshore Environments

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Abstract

A compact and lightweight self-recording pressure based sea level gauge has been designed to suit deployments from harbour and offshore environments. A novel hydraulic coupling device designed in-house was used to transfer the seawater pressure to the pressure transducer. This paper discusses the mechanical and electronic design of the instrument, calibration results, field-performance, and validation. The instrument was calibrated using an in-house facility and validation tests performed at Zuari estuary, Goa against a conventional analog-type float-driven sea level gauge, and a digital-type float-driven sea level gauge. All the three devices exhibited similar trends in their responses. The observed minor differences can be attributed to corresponding differences in the responses of these devices to changing site-specific environmental factors such as currents, waves, estuarine water density variations with changing phases of the tide, and so forth. The monthly-mean sea levels derived from the SOI and the NIO gauges were closer within ~ 1.5 mm.

The technology of this instrument has been transferred to two firms namely; M/s. R.A. Enterprises, Goa and M/s. Indomer Coastal Hydraulics (P) Ltd., Chennai.

INTRODUCTION

Measurements of low-frequency modulations in sea level is important to derive many useful information such as tidal oscillations, storm surge, tsunami, climate-induced signal, and so forth. Time-series measurements of sea level have traditionally been made using a variety of devices including tide-staff, stilling-well and float-driven gauge, pressure transducer, bubbler gauge, and more recently air-acoustic gauge, microwave gauge, electric step gauge and radio-wave interferometer [1]. Among these devices, the only one that is suitable for deployment in the offshore environments is the *absolute* pressure transducer based gauge. Recently, such gauges have gained importance with the growing requirement of time-series sea level measurements from locations that are far away from harbor environments. We have developed such a gauge using an indigenously available strain-gauge pressure transducer and

a novel hydraulic coupling device designed in-house. A novel approach in the design of the pressure housing resulted in a compact, lightweight, and non-corrosive sea level gauge.

DESCRIPTION

The sea level recorder of the present design consists essentially of a strain-gauge absolute pressure transducer, two optional temperature transducers, excitation & signal conditioning circuitry, a microprocessor-controlled data logger (TFX-11), and a 9-volts battery pack; all located in a pressure-proof housing. The data logger is provided with 470 kbytes of non-volatile (serial flash) memory that can record ~57,000 samples of data. An algorithm that we have stored in the data logger manages data acquisition and storage. Time-tagged digital data is recorded in the logger based on the user-selected data acquisition interval during initialization of the gauge. The recorded data can be offloaded to a notebook computer, which is pre-loaded with software for data offload and processing.

The methodology employed for measurement of sea-level/water-level is to detect the pressure corresponding to the water column over the pressure transducer, and to determine the height of this water column from knowledge of its depth-mean density. In the *absolute* pressure transducer used in the present gauge, the total hydraulic pressure (i.e., water column pressure plus the atmospheric pressure) is measured with reference to a vacuum reference chamber. The hydrostatic pressure, P_d , over the pressure inlet, at depth d below the sea-surface/water-surface is given by the relationship: $P_d = \text{Total pressure minus the atmospheric pressure}$. The water height can then be estimated from the well-known relationship: $P_d = (\rho \times g \times d)$, where ρ is the depth-mean density of the overlying column of water, and g is the acceleration due to gravity. From this the value of d is estimated. The pressure transducer incorporated with the present sea level recorder is an *electrical resistance strain gauge*, manufactured by M/s. Macurex Sensors Pvt Ltd., Bangalore. When excited with a suitable reference voltage source, the pressure transducer converts fluid pressure into an equivalent electrical signal utilizing four photo-etched matrix of electrical resistance foils that are configured in the form of a full Wheatstone bridge network.

Temperature of the surrounding water body and that of the air within the housing of the instrument are secondary parameters measured by the instrument. Measurement of water temperature has been included in the design because time-series record of water temperature data is considered to be valuable in many disciplines of limnology and oceanography. Measurement of the internal temperature of the instrument would provide an indication of the heat dissipation of the electronics circuits, and functions as a health indicator of the gauge. Other health indicators that are monitored and recorded are battery voltage and a reference voltage.

Mechanical assembly: The mechanical assembly was designed to satisfy a set of desirable features such as compactness, lightweight, and ease in assembly. From past experience, the depth of deployment would be usually within 50m. However, allowing for a good safety margin, the depth rating for the pressure housing was set at 200m. Another design criterion was that the gauge be suitable for installation at dam, harbour, and offshore environments. The outside diameter of the instrument was not to exceed 100mm. Further, the instrument

would have a suitable mounting mechanism for its attachment to marine/underwater structure or mooring line. Delrin material was chosen for fabrication of the instrument housing because of its desirable properties such as non-corrosiveness, lightweight, strength, elegance and ease in machining. The instrument housing would have two compartments — transducers-cum-electronics chamber and a battery chamber. The rationale behind this design choice was to keep the transducers and the electronics in a dust-free and clean environment during occasional battery replacement — a process usually performed in a field environment.

Hydraulic Coupling Device: Being an in-water pressure based instrument, the present sea level recorder requires a suitable device that would hydraulically couple the pressure port of the transducer without affecting its sensitivity to the hydraulic pressure variations and simultaneously prevent corrosion of its metallic diaphragm by inhibiting its physical contact with saline water. With the addition of a novel hydraulic coupling device (HCD), we have converted the Macurex strain-gauge pressure transducer, which was designed primarily for space applications, into one that is suitable for oceanographic measurements. This coupling device (Fig. 1a) has been designed to form an integral part of the pressure transducer as well as the bottom end-cap of the pressure housing. An isometric view of the HCD is shown in Fig. 1b.

The hydraulic coupling device used in the present design has a female and a male component that hydraulically connect the pressure sensor's diaphragm to the seawater pressure via a viscous oil chamber. The former consists of a copper cylinder having internal and external threading. The male component of the HCD is a copper counter-sunk mechanism that mates with the female component, and together forms the HCD. The HCD is located in such a manner that it does not make physical contact with the metallic body of the pressure transducer. This arrangement prevents the possibility of electro-chemically-induced corrosion of the transducer head during long-term deployments in the sea. The narrow gap between the threads of the male and the female components of the HCD provides the requisite path for transmission of water-pressure to the pressure-port of the transducer, via the oil medium, thereby hydraulically connecting the pressure transducer to the surrounding saline-water medium. Copper has been selected as the material for the HCD because of its ability to repel marine growth [2] that might adversely affect the sensitivity response function of the transducer to hydraulic pressure changes. Thus the HCD of the present design inhibits closure of its pressure inlet by marine growth during its prolong exposure to the euphotic water medium where bio-fouling is a common occurrence. The main advantages of the present HCD over previous designs ([3], [4], [5], [6]) are its miniature size, ease in construction, elegance, ease in oil replacement, and resistance to bio-fouling.

As indicated in Fig. 1a, the female component of the HCD is screwed onto the center of the bottom seal plate (BSP) of the pressure housing. With this arrangement, the pressure inlet remains at the center of, and flush with a flat surface, thereby minimizing the undesired Bernoulli dynamic pressure effects arising from flows, waves and a combination of flows and waves [7]. Because the BSP is made of a non-metal (Delrin), the HCD does not suffer from electro-chemical deterioration during prolong submergence in sea/estuarine environments. The pressure transducer is located on the other side of the BSP in such a manner as to effectively couple with the HCD without making physical contact with it.

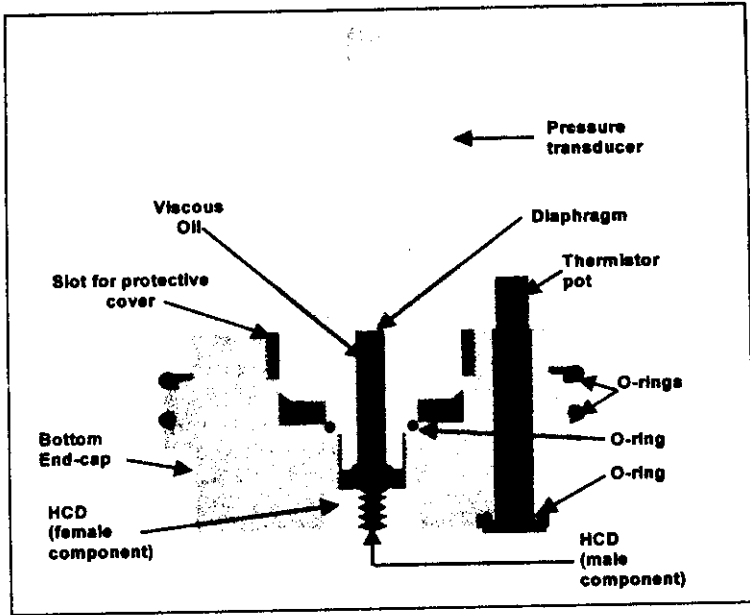


Fig. 1 (a) Cross-sectional view of the hydraulic coupling device that forms an integral part of the pressure transducer and the bottom end-cap of the pressure housing.

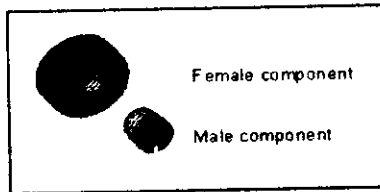


Fig. 1 (b) Isometric views of the male and female components of the HCD

The viscous oil of ~500 centi-Stokes (preferably silicon oil or hydraulic oil) trapped between the HCD and the diaphragm of the pressure transducer (Fig. 1a) protects the transducer from direct physical contact with seawater, thereby preventing its damage due to corrosion effects. Based on the above design criteria, the mechanical assembly consists of a pressure-proof housing that can be mated to a mounting attachment (Fig. 2). The former is fabricated from a combination of non-metallic materials such as delrin and PVC, and the latter is constructed from stainless steel (SS), wherein the SS rings have been provided with PVC collars at their inside portion.

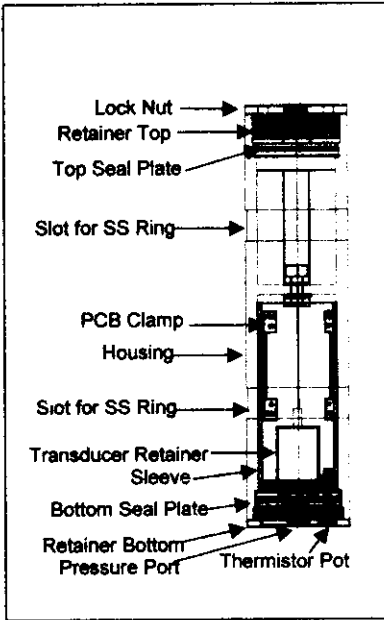


Fig. 2 (a) Cross-sectional view of pressure proof housing of the instrument.

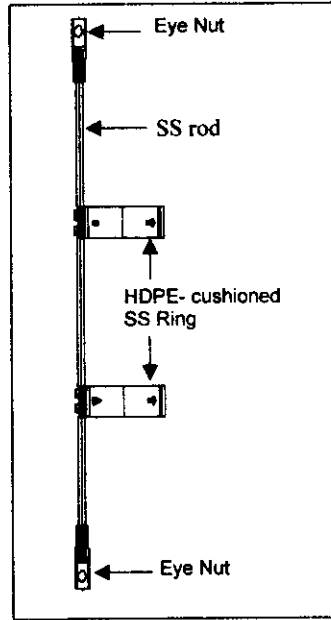


Fig. 2 (b) Cross-sectional view of mounting attachment of the instrument.

Pressure-Proof Housing: The housing (382mm length \times 100mm external diameter) is of cylindrical shape, and fabricated from a single solid piece of Delrin (off-white in color). The housing is provided with two separate chambers that have been carved out from a solid piece. The circular disc (75mm diameter \times 10mm thickness) so formed separates the two chambers. The lower chamber (217mm depth \times 75mm diameter) is designed to house the HCD, pressure transducer, temperature transducers, and the electronics of the instrument. The pressure transducer is axially located at the center portion of the bottom seal plate. The temperature transducer is a thermistor (manufactured by YSI, U.S.A). The thermistor is placed in a stainless steel pot (Fig. 1a), which is located on the bottom seal plate of the gauge. The pot is filled with a thermally conducting epoxy, and the thermistor is then inserted into this epoxy to achieve excellent heat transfer between the ambient water body and the thermistor. Subsequently the upper head is sealed using a mixture of Araldite. The electronics of the instrument, consisting of a pair of printed circuit cards mounted on PVC clamps, and rigidly fitted on to a PVC hollow cylinder are located immediately above the pressure transducer. This assembly is threaded onto the top portion of the bottom seal plate. This cylinder thus serves as a protective device to the pressure transducer and the electronics. The upper chamber (163mm depth \times 75mm diameter) houses the battery pack & battery connector and an RS-232 connector. The latter is used for communication between the instrument and a notebook computer during initialization/data offloading. The battery has been assembled into a single main unit of 9 volts output, from 6 sub-units of 1.5 volts cylindrical C-size primary cells (DURACELL). The multi-cell battery pack used with the present instrument has a

hollow passage, along its longitudinal axis, which permits trouble-free routing of the electrical cables of the instrument. The rated capacity of the battery pack is 7.8 Ampere-Hour. Electrical connection to the lower chamber is facilitated via an underwater connector located at the center of the bulkhead disc. This scheme enables the transducers and the electronics to be kept in a clean environment, free of contamination from dust and humidity during occasional battery replacements and data offloading in the field.

The bottom seal plate (protected by two O-rings) is push-fitted into position and retained in place by a 'retainer bottom' that has been machined from PVC. The upper chamber has been made watertight by the use of a top seal plate (protected by two O-rings). The bottom and the top seal plates have been machined from Delrin. The top seal plate is push-fitted into position and secured in place by the 'retainer top' that has been fabricated from PVC. The middle portion of the retainer top is provided with a threaded hole, which can be coupled with the protruding threaded portion of the top seal plate to facilitate trouble-free opening of the top seal plate. Both the bottom and the top retainers have been machined from black PVC, which imparts excellent colour contrast against the off-white Delrin housing, thereby providing an aesthetic appearance to the instrument. A lock nut (PVC) that can be screwed on top secures the retainer top in its locked state. Two annular grooves that have been cut around the pressure housing facilitate insertion of two HDPE-cushioned stainless steel rings, which form part of the stainless steel mounting arrangement. An exploded view of the instrument housing is shown in Fig. 3. The housing, whose weight in air is ~ 4.2 kg, has been successfully tested to an external pressure rating of 25 kg/cm^2 .

Electronics: The electronics of the present instrument consists of an analog circuitry that supervises the power supply, buffering of excitation voltages to the pressure and temperature transducers, noise rejection and small-signal amplification, generation of appropriate offset voltage required for conditioning of the pressure transducer signal, smoothing of wind-wave induced oscillations in the pressure signal, and buffering of all the signals before being input to an Analog-to-Digital Converter (ADC) of the TFX-11 data-logger. The pressure transducer has been configured as a full-bridge network, excited from the ADC's 5-volts reference source, providing a differential output with an "offset voltage" of ~ 25 milli-volts at atmospheric pressure. This offset voltage allows the amplifiers to operate in their linear range, even at atmospheric pressure. A $0.01 \mu\text{F}$ capacitor provided at the output terminal of the pressure transducer suppresses ambient noise pick-up. Two stages of precision instrumentation amplifiers (LT-1101) — the first and second stages set to gain of 100 and 10 respectively with no external components — have been used to amplify the pressure transducer output. A precision "offset-suppression-signal" introduced at the (-) input of the second stage allows amplification of the pressure signal variations without saturation, thereby achieving optimum dynamic range for the pressure signal. The amplified pressure signal has been integrated using a precision R-C network. With this arrangement, the ADC output is ~ 450 counts at atmospheric pressure. The thermistor-outputs are not amplified because they are in the volts-range at the temperatures that we encounter in our oceans.

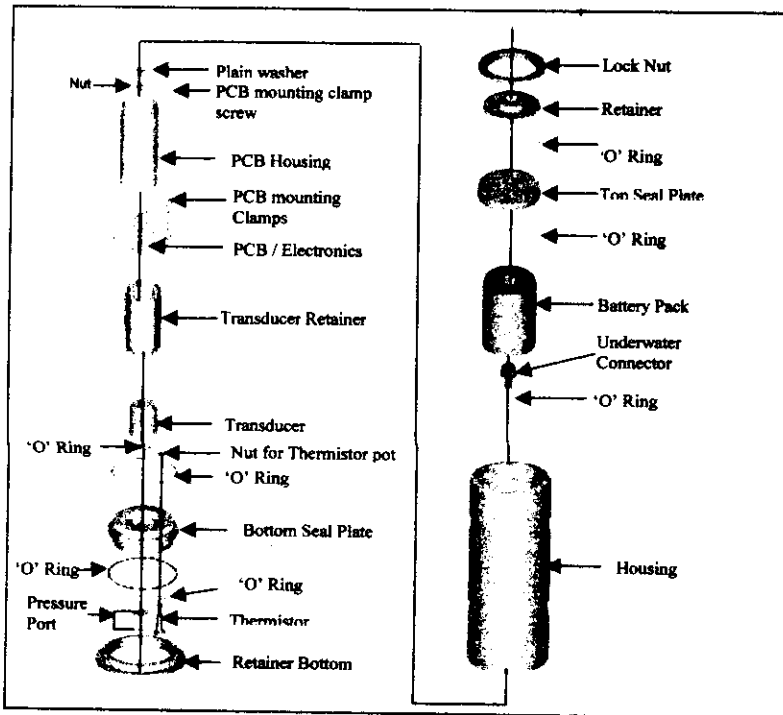


Fig. 3 An exploded view of the instrument housing

Data Acquisition: An algorithm that we have stored in the instrument's data logger controls the data acquisition and storage. Communication between the operator and the instrument for initialization and data retrieval is established via a notebook computer connected to the serial interface of the logger. During initialization, the operator enters initial parameters such as login name; date & time; wake-up interval; warm-up interval; acquisition interval; sampling frequency; calibration constants m & c ; and the serial number of the instrument. Upon entry of these parameters, the control of the instrument is taken over by the logger. During data acquisition a ratiometrically-operating 12-bit ADC digitizes the signal at user-selected sampling intervals. Averaging of numerous successive pressure samples over a period of ~1 minute is sufficient to filter out short-period fluctuations in the tidal records, arising from wind-waves ([8], [9], [10]). The technique of rapid sampling and averaging filters out wave-induced fluctuations from the sea level data, thereby recording only the desired low-frequency oscillations in the sea level.

CALIBRATION

Calibration of the pressure gauge is the determination of the transducer's response to the hydrostatic pressure acting at its input. The calibration relation is a best-fit of one or more linear segments over the range of interest, expressed as an intercept and slope [11]. Pressure

calibration was carried out at an in-house facility, wherein a hydraulic coupler attached to a precision quartz pressure transducer, a strain-gauge pressure transducer, and a dead-weight tester permitted transfer of hydraulic pressure generated by the dead-weight tester to the pressure transducers. In this set-up, the dead-weight tester functioned merely as a tool for variation of hydraulic pressure in a controlled fashion. The output of the precision quartz pressure transducer functioned as the pressure reference against which the present gauge was calibrated. The accuracy of this pressure reference is 0.01%FS and the drift of its output with time is in the range -3 to -11 ppm per year [12]. The pressure channel outputs from the ADC were calibrated against the outputs of the Digiquartz pressure reference. This methodology ensured that the total system — including the pressure transducer, pressure signal conditioning electronics, and the electronics of the data logger — was calibrated.

Accuracy, which is the most important performance indicator of the instrument, was deduced from the least-squares-fitted calibration graph derived from the outputs of the two transducers. Accuracy refers to the closeness of the instrument output to the true value. In the present case, the output from the Digiquartz pressure transducer was taken as the true value. Quantitatively, accuracy is the difference between the instrument output and the corresponding true value, taken positive if the instrument output is greater than the true value [13]. More often, accuracy is quoted as a percentage figure based on the full-scale reading of the instrument (3.5 bar in the present case). Figure 4(a) shows the calibration graph for a typical pressure transducer used. Figure 4(b) shows the percentage accuracy. The results show that, except for two scattered data points, the accuracy was predominantly within 0.05%.

VALIDATION

We have conducted validation measurements at Zuari estuary, Goa because of the existence of a Survey of India (SOI) sea level station. This site has a conventional analog-type float-driven sea level gauge, whose long-term performance has been studied by us in detail [14]; and a digital-type float-driven sea level gauge. For purpose of validation measurements, our (NIO) instrument was mounted on a rigid structure, such that its pressure inlet was located at a distance more than 1m below the Chart Datum (CD). This satisfied a conventionally followed practice during deployment of sea level gauges. The analog-type float-driven sea level gauge of SOI consists of a cylindrical float that rests on the surface of water within a cylindrical hollow pipe (80cm diameter) known as a stilling-well. At the bottom of this well is a cone whose open end, known as *orifice*, is located at a point ~1m below CD. The orifice-to-well diameter ratio is 0.1. This inlet dampens wave motions inside the well, thereby permitting the float to rise and fall with the sea level motions with a much-reduced disturbance from wind-wave action. The float is attached to a counter-weight via a taut flexible wire that passes over a pulley. As the float rises and falls with the tide, the shaft of the pulley makes corresponding turns about its axis. The motion of the shaft is coupled to an ink-pen that traces the water level variations in the well on a graduated paper that is rolled over a drum. A mechanical clock-work facilitates indication of the sea level motions against time. The digital-type float-driven sea level gauge, designed and developed by the Western Regional Instrumentation Centre (WRIC), Mumbai is similar to the SOI gauge except for some minor differences. For example, the sea-level-induced angular motion of the shaft is converted to corresponding linear distance by an optical encoder. The digital data is processed and the time-tagged sea level data with reference to CD is recorded in semiconductor memory

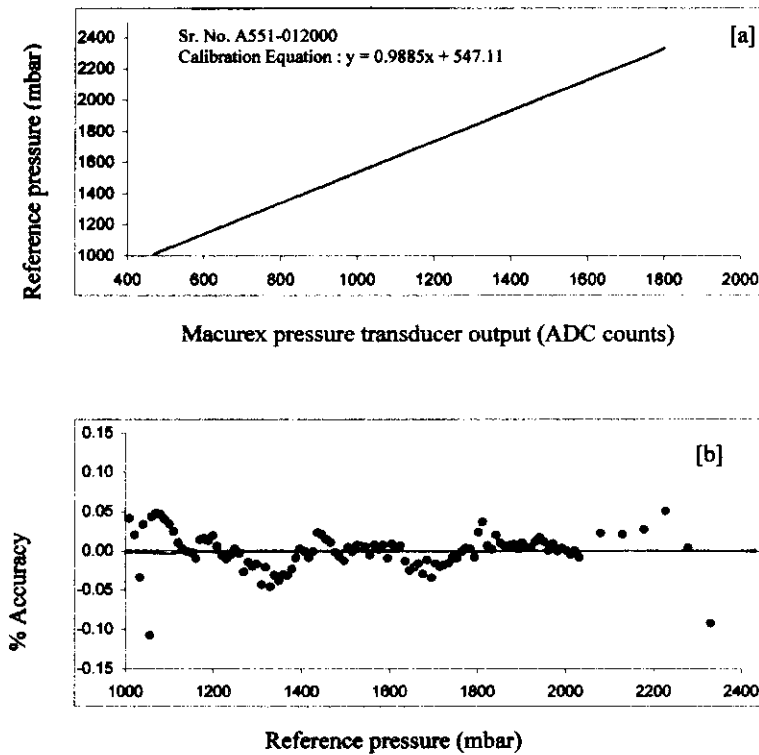


Fig. 4 Calibration results of Macurex pressure transducer used in the instrument: [a] Calibration graph, [b] Percentage accuracy.

bank under microprocessor control. The float of the WRIC gauge is located in a conventional type stilling-well whose diameter is 60 cm and the orifice-to-well diameter ratio is 0.1 In the case of NIO gauge, atmospheric pressure data at sea level — supplied by India Meteorological Department, Panaji, Goa — were used to extract the desired water column pressure from the absolute pressure measurements. Density of water sample was measured using a precision density meter [15] having an accuracy of $\pm 0.001 \text{ gm/cm}^3$. These differential pressure measurements and the water density value were used to yield the sea level record above the pressure transducer. The sea level record so obtained was referenced to CD from knowledge of the position of the pressure inlet of the gauge below the chart datum level.

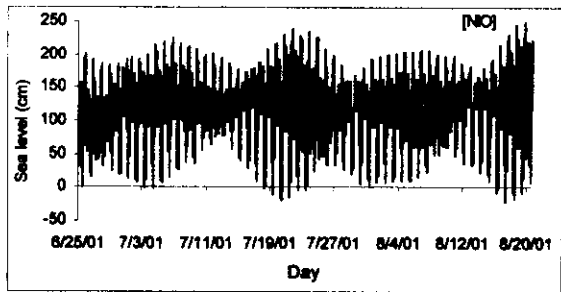
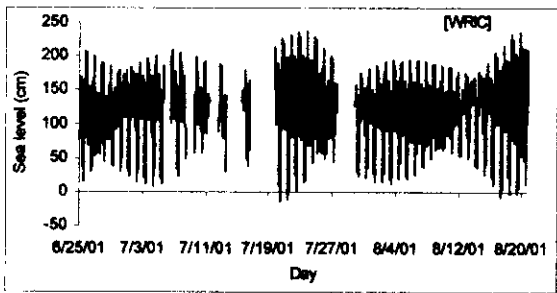
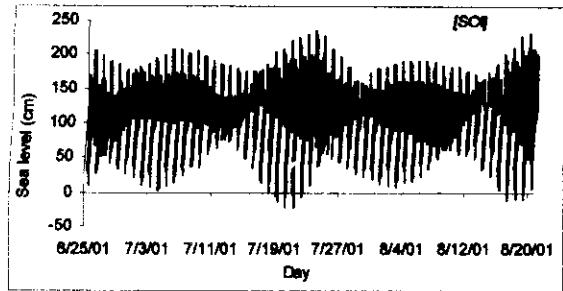


Fig. 5 Sea level records obtained from three instruments at the Marmugao sea level station, Goa; (1) analog-type float-driven sea level gauge (SOI); (2) digital-type float-driven sea level gauge (WRIC); (3) pressure transducer-based digital-type sea level gauge (NIO).

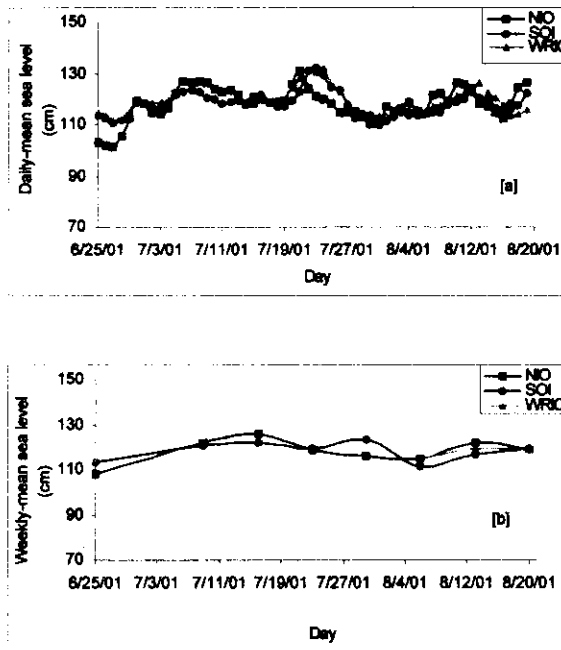


Fig. 6 Time-average data from different sea level gauges; (a) daily-mean from gauges of NIO, SOI, and WRIC; (b) weekly-mean from gauges of NIO, SOI, and WRIC.

As the modern air-acoustic gauge of M/s Sutron, U.S.A, which was erected in the vicinity of the gauges, was not functional our validation studies are based on the data obtained from the float-driven gauges. Among these, only the gauges of NIO and SOI provided uninterrupted data. Sea level records of the WRIC gauge had several breaks during the validation period (Fig. 5).

For a realistic validation analysis, we begin with daily-mean of the data records in order to circumvent the possible time-mismatch of the data records obtained from the different instruments. Fig. 6 (a) provides the daily-mean data for the three instruments. Fig. 6 (b) provides the weekly-mean data from the SOI and the NIO gauges. Because of interruptions in the data record from the WRIC's gauge, this data is used for estimation of weekly-mean in the last 3 weeks only. The monthly-mean sea level data derived from the SOI gauge and the NIO gauge is within 1.5mm.

CONCLUSIONS

We have described the design and performance of a compact self-recording pressure based sea level gauge that is suitable for harbor and offshore deployments. Field-deployment in the

Zuari estuary has indicated that the novel hydraulic coupling device incorporated in the design of the present gauge worked efficiently. Validation studies were conducted with reference to a conventional analog-type float-driven sea level gauge and a digital-type float-driven sea level gauge. All the three devices exhibited similar trends in their responses. The observed minor differences can be attributed to corresponding differences in the responses of these devices to changing site-specific environmental factors such as currents, waves, water density variations with changing phases of the tide in this estuary during the monsoon period, and so forth. The monthly-mean sea levels derived from the SOI and the NIO gauges were closer within ~1.5mm.

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REFERENCES

- [1]. Joseph, A (1999), Modern techniques of sea level measurement, *Encyclopedia of Microcomputers*, Marcel Dekker, Inc., New York, Vol. 23, pp. 319-344.
- [2]. Huguenin, J.E and F.J. Ansuini (1975), The advantages and limitations of using copper material in marine aquaculture", *Proc. IEEE Oceans '75*, pp. 444-453.
- [3]. Filloux, J.H (1970), Deep sea tide gauge with optical readout of bourdon tube rotations, *Nature*, Vol. 226, pp. 935-937.
- [4]. Dietrich, G., K. Kalle, W. Kraus, and G. Siedler (1980), *General Oceanography: An Introduction*, pp. 128-131.
- [5]. Cox, C., T. Deaton, and S. Webb (1984), A deep-sea differential pressure gauge, *Journal of Atmospheric and Oceanic Technology*, Vol.1, pp. 237-246.
- [6]. Desa, E.S., A. Joseph, D. Rodrigues, V. N. Chodankar, and S.Tengali (1999), An improved hydraulic coupling device for use with in-water pressure based systems, Indian patent pending [Ref: 487 / DEL / 99].
- [7]. Joseph, A., J.A. E. Desa, P. Foden, K. Taylor, J. McKeown, and E. Desa (2000), Evaluation and performance enhancement of a pressure transducer under flows, waves, and a combination of flows and waves, *Journal of Atmospheric and Oceanic Technology*, American Meteorological Society, Vol. 17, No. 3, pp. 357- 365.
- [8]. Peshwe, V.B., S.G. Diwan, A. Joseph, and E. Desa (1980), Wave and Tide Gauge, *Indian Journal of Marine Sciences*,.9, 73-76.
- [9]. Joseph, A., and E.S. Desa (1984), A microprocessor-based tide measuring system, *Journal of Physics, E. Scientific Instruments*, 17,1135-1138.

- [10]. Lamy, A (1988), Sea level measurement in the India sector of the Antarctica, IOC Workshop Report No 54, 36-39.
- [11]. Dean, J.P (1985), Advances in underwater technology and offshore engineering, Graham & Trotman Ltd.
- [12]. Houston, M. H., and J.M. Paros (2000), High accuracy pressure instrumentation for underwater applications, Digi quartz Pressure Instrumentation Application Notes, pp. 1-6.
- [13]. Doebelin, E. O (1983), Generalised performance characteristics of instruments, *Measurement Systems, Application and Design*, McGraw-Hill, pp. 37-206.
- [14]. Joseph, A., Vijaykumar, E.S. Desa, E. Desa, and Vani B. Peshwe (2001), Over-estimation of sea level measurements arising from water density anomalies within tide-wells — A case study at Zuary estuary, Goa”, *Journal of Coastal Research* (in press).
- [15]. Kremling, K (1972), Comparison of specific gravity in natural sea water from hydrographical tables and measurements by a new density instrument, *Deep-Sea Research*, Vol.19(5), pp. 377-384.