PAPER

Best Practices for Increasing Data Return: Case Study From Indian Ocean Observation Network

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ABSTRACT

Sustained real-time ocean observation systems using moored data buoys are vital for understanding ocean dynamics and variability, which are essential for improving oceanographic services including weather prediction, ocean state forecast, cyclone tracking, tsunami monitoring, and climate change studies. This paper describes the significant rapid restoration techniques implemented to increase the availability of the Indian Ocean observation networks over the past two decades. The efforts have helped in achieving availability of 97.9%, 82.3%, and 98.7% for the meteorological sensors, subsea surface oceanographic sensors, and tsunami buoy network, respectively.

Keywords: availability, data returns, reliability

Introduction

System availability and data returns are the key requirements for the offshore moored observatories used for acquiring meteorological parameters, essential oceanographic variables used for cyclone predictions and tracking (Stewart, 2008; Weller et al., 2016). The Indian Ocean observational network established by the Ministry of Earth Sciences under the Indian Ocean Observation System is configured for real-time and delayed-mode coastal and offshore observations, facilitating data assimilation in real time and validation of the operational nowcast/forecast of ocean variables in and around the Indian seas.

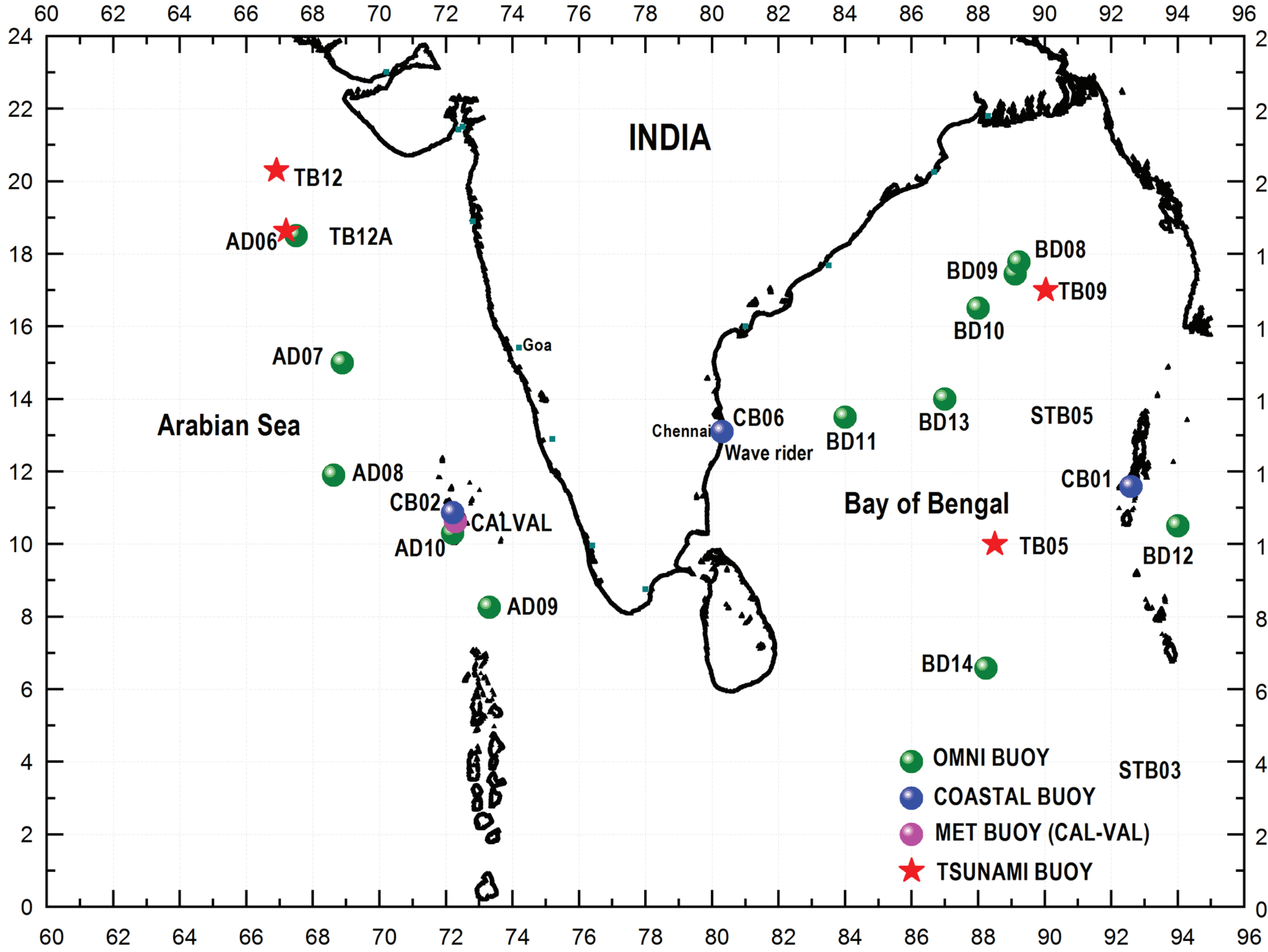
The Indian moored buoy network spanning between 63°E–93°E and 6° N–20°N (Figure 1) comprises three families: the meteorological ocean buoys (METOCEAN) for measuring and telemetering meteorological and sea surface parameters; the Ocean Moored Buoy Network for northern Indian Ocean (OMNI) buoys networks for measuring and telemetering meteorological, sea surface, and subsurface parameters; and the Indian Tsunami Buoy System (ITBS) for detection and reporting of the water level for tsunami warning (McPhaden et al., 2009; Ravichandran, 2015; Venkatesan et al., 2013). During the past two decades, these moored buoy networks have detected more than 42 cyclones, and data acquired during events served as important inputs to government agencies including the Indian Meteorological Department (IMD) (Johnston et al., 2016; Shukla et al., 2013; Venkatesan, 2017). The scientific observations are used for understanding the Indian Ocean dynamics for improved modeling of the evolution of seasonal monsoons (Chaitanya et al., 2015; Venkatesan et al., 2016). Based on experiences in the development and operation of these moored buoy networks over the past two decades, the paper details the techniques implemented for maximizing the system availability of the Indian Ocean observation networks.

System Description and Reliability Metrics

Moored surface buoys (MSBs) have a polyurethane foam-filled fiber-reinforced plastic surface hull moored to the seabed using a dead weight and an anchor in an inverse catenary configuration. The mooring line structure includes a short polypropylene sheathed metal wire connecting the surface buoy to a long nylon line, which connects to a positively buoyant polypropylene line, which connects to the chain and dead-weight anchor. The floatation attached to the polypropylene line holds the chain vertically above the dead weight. A combination wire rope, which has polypropylene (PP) sheathing on the metal rope, interconnects the surface buoy and the nylon rope. The METOCEAN and OMNI buoys have a mast-mounted

FIGURE 1

Location of moored surface buoys in Indian seas.



meteorological instrument suite that includes air pressure, air temperature, wind speed and direction, precipitation, solar radiation, and humidity sensors. The central cylinder portion in the MSB is used to mount the energy storage batteries and data acquisition system (DAS), which are connected with the external environment monitoring instruments. The OMNI buoys, in addition to the metrological sensors, include subsurface instruments that are positioned up to 500-m water depths and interface with the DAS using induction mooring.

In the case of tsunami monitoring buoys, the standalone module located on the deep seabed makes pressure measurements and observations for tsunami wave characteristics. When a likely tsunami event is detected, it acoustically transmits the warning to a collocated MSB through an acoustic modem. The acquired data from the MSB are transmitted to the Mission Control Center (MCC) at the National Institute of Ocean Technology (NIOT) through International Maritime Satellite (INMARSAT). The contribution of the MSB sensors, more than 7.3 million demanding offshore hours, is represented in Figure 2. During that time frame, there have been 457 unavailability events, which are classified in Figure 3.

System Availability Improvements

Reliability and availability are the key requirements for moored observation networks, which include the offshore MSB, data telemetry networks, and the data reception systems in the MCC.

FIGURE 2

Contribution of subsystems to MSB unavailability (Venkatesan et al., 2016).

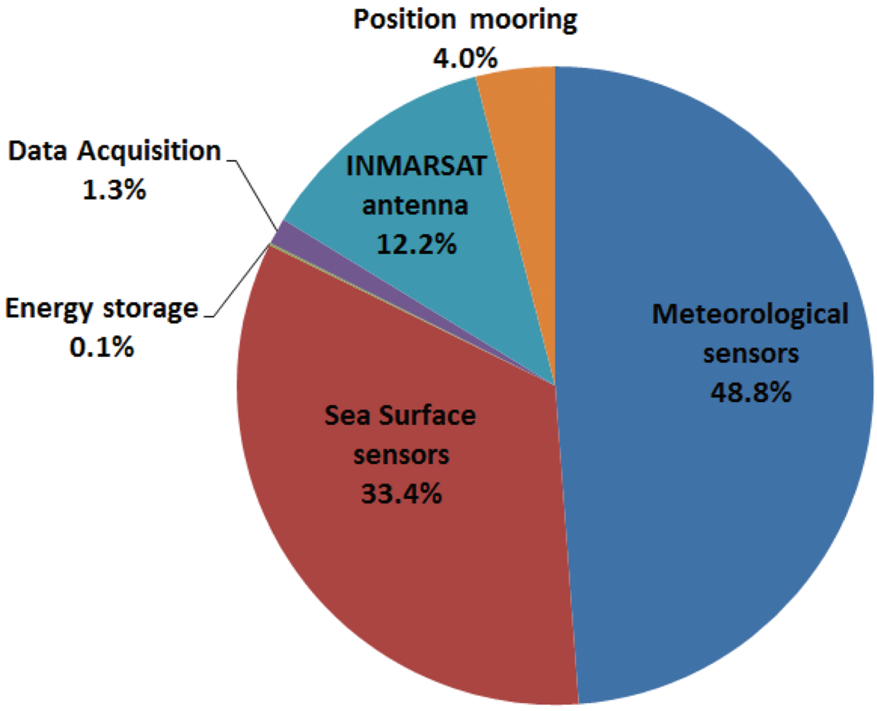
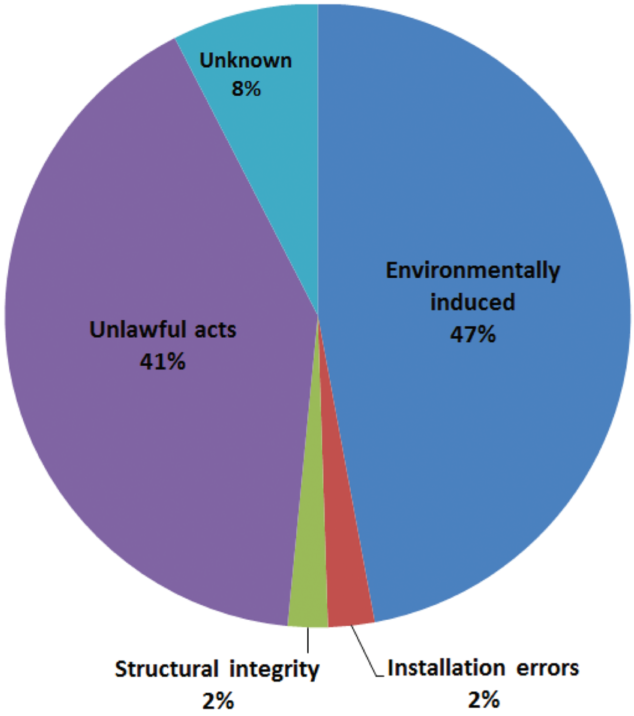


FIGURE 3

Unavailability mode details (Venkatesan et al., 2016).



The availability of a system for the intended function is

$$\text{Availability in \%} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \times 100 \tag{1}$$

where MTBF is the mean time between failure and MTTR is the mean time to restore.

The MTBF is inverse of the system failure rate (λ) and described as

$$\text{MTBF} = 1/\lambda \tag{2}$$

Thus, the availability of the system could be increased by increasing its reliability (so that MTBF is more) and by means of reducing the MTTR adopting rapid restoration techniques (Smith & Simpson, 2004). Based on the operational experiences, the significant techniques implemented for reducing the MTTR and maximizing the availability of the Indian Ocean observation networks are represented in Figure 4.

Availability Improvement Methods

MSB Watch Circle

A rugged mooring is the key requirement for the MSB, especially for tsunami buoys where the surface buoy and the bottom pressure recorder have to be within the acoustic communication range. About 4% of system failures (Figure 2) are due to moorings, which were mainly due to the nylon-wire rope interface degradation, PP rope failures, mooring walk during high sea states, and corrosion issues. Based on these observations, the reliability of moorings was improved over the years by ensuring the quality of the materials used, improving the

FIGURE 4

Rapid restoration methods for availability improvements.

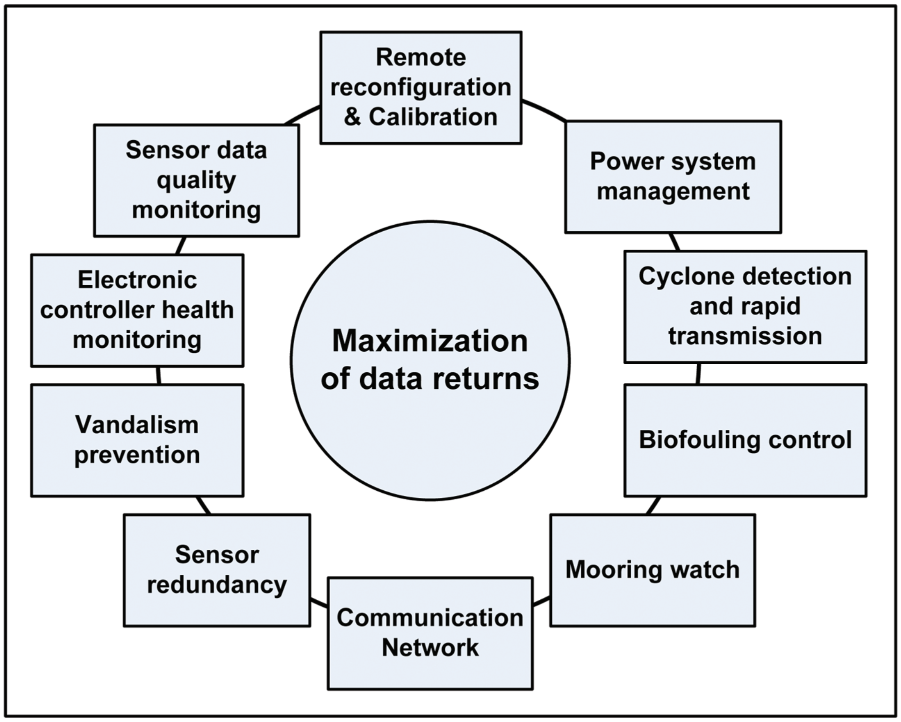
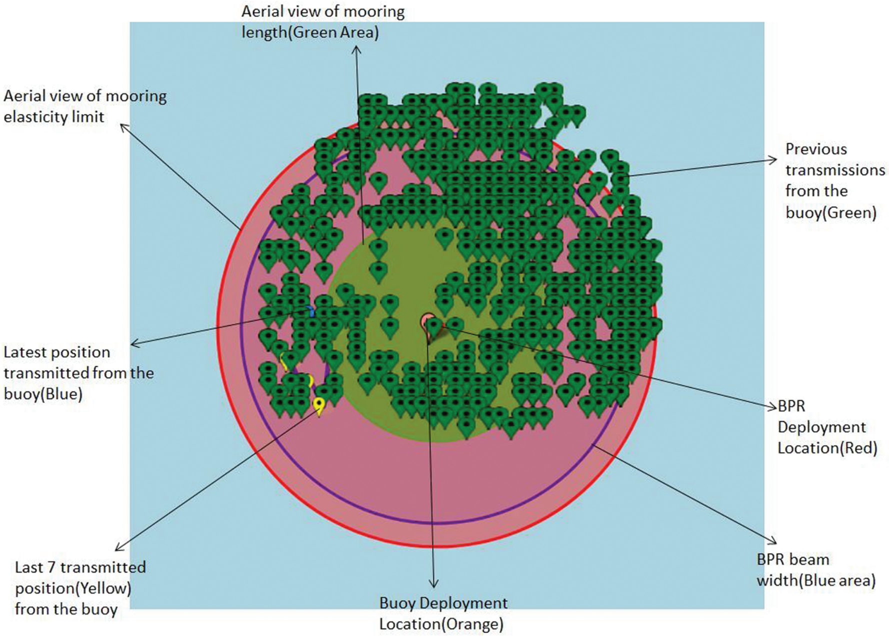


FIGURE 5

Buoy watch feature implemented in the MCC.

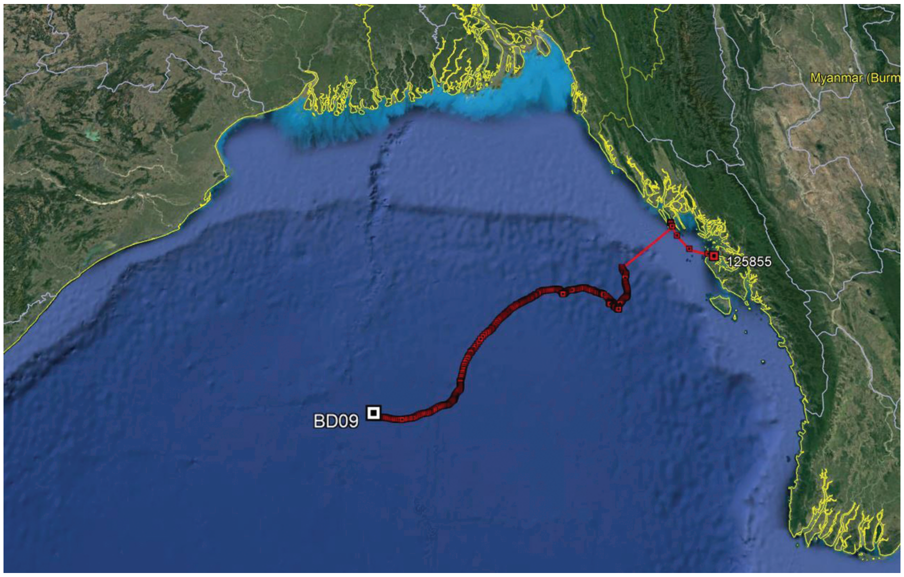


structural integrity of the mooring through load measurements during extreme conditions (Kaliyaperumal et al., 2015), and following deployment methodologies suitable to the depth and location of the release. Standardization was accomplished in stages including hardware realization, predeployment, deployment, and postdeployment phases. The hardware realization phase covers design, procurement, and testing methods. The predeployment phase covers component verification, packing, safe onboard storage, mooring assembly checks, deployment precheck by experienced personnel, and checklists. The deployment phase covers having reliable and safe deployment deck gears, launching in suitable weather conditions, orienting the vessel with respect to the mooring, and confirming the anchor landing on the seabed. The postdeployment phase involves verifying the correctness of the deployed location based on the data received by the MCC after deployment. Subsequent to the standardization, the MTBF of the moorings increased from 1 year in 2010 to 12.2 years in 2014 (Venkatesan et al., 2015, 2018).

For early restoration of the mooring soon after a failure, a Mooring Integrity Management and Corrective Action System (MIMCAS) is employed. The MIMCAS is implemented through onboard GPS data being transmitted to the MCC along with the data that are transmitted by the MSB at regular intervals. Figure 5 shows the view of the MIMCAS watch circle feature automated in the MCC to generate an alert if the buoys start drifting beyond the watch circle. The feature helps to track the drifting MSB in real time and ensure early restoration so as to reduce the MTTR. As an example, Figure 6 shows the

FIGURE 6

Drifting buoy tracked from the MCC.



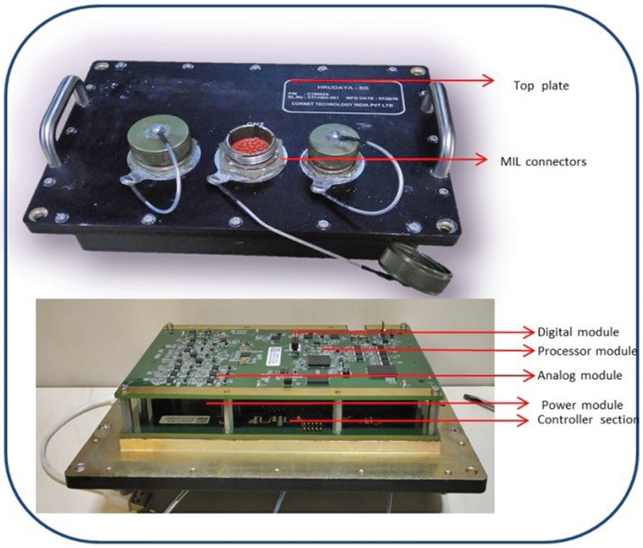
track of the drifting buoy observed on June 11, 2019, and recovered by the Myanmar Navy on June 21, 2019.

MSB Electronic Controller Health Monitoring

The functions of the MSB are managed by an onboard electronic controller (EC), which comprises a CPU, a power management section (PMS), and a health monitoring module (HMM) (Venkatesan et al., 2015). About 1.3% of the system failures are due to firmware failure in the CPU (Figure 2). The CPU and PMS are connected by means of board-to-board mating connectors, as shown in Figure 7. The CPU is a 1-GHz Sitara ARM Cortex-A8 32-bit reduced instruction set computer with an integrated 15- to 35-MHz high-frequency oscillator.

FIGURE 7

EC with interfaces.



The HMM is based on a complex programmable logic device housed in a DIN-mounted case. It exchanges signals in RS232 level and monitors the hardware health of the CPU using the heartbeat pulse generated by the microcontroller (μC) of the CPU (Figure 8). In the event that the CPU fails to communicate, the HMM will not receive the “heartbeat pulse.” Under such circumstances, the HMM will reset the CPU, thus restarting the application.

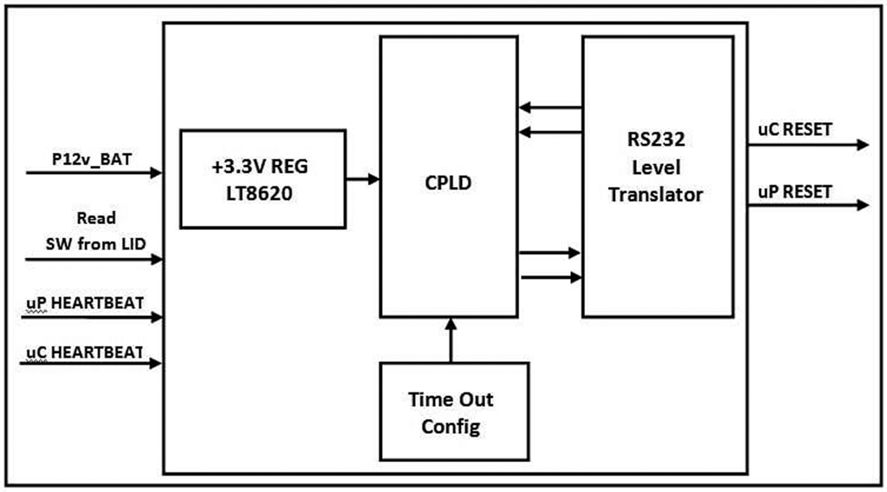
A watchdog timer is implemented to wake up the CPU by means of power cycling when it is in the sleep or standby mode. The DONE, WAKE, and RESET signals are used to implement the watchdog function (Figure 9). The CPU is programmed to issue a periodic WAKE pulse to a μC when it is in sleep or standby mode. After receiving the WAKE pulse, the μC issues a DONE signal to the watchdog timer at least 20 ms before the rising edge of the next WAKE pulse. If the DONE signal is not asserted, it asserts the RESET signal to reset the μC. Provision is also given to reset the CPU externally by an independent magnetic reset switch, which is mounted on the buoy lid so that it can be reset without opening the cylindering portion. An external reset switch is also provided to reset the system. The resetting architecture for power cycling based on the AND gate logic is represented in Figure 9.

EC Remote Reconfiguration Capability

The basic system design requires physical recovery of the MSB for

FIGURE 8

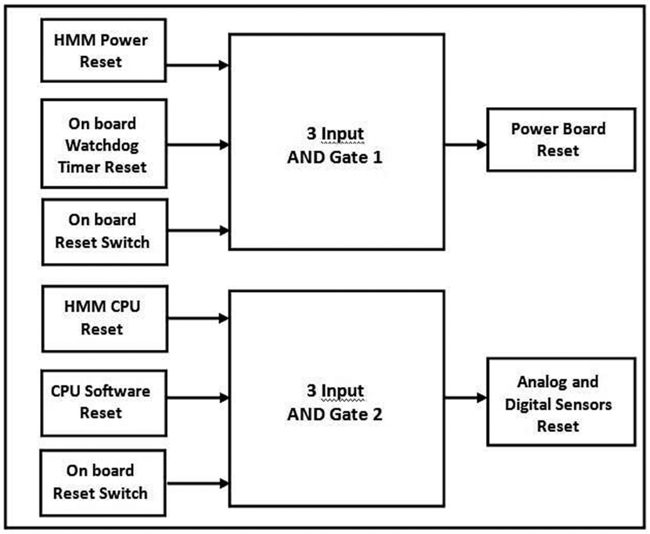
Principle of health monitoring.



software reconfigurations, incurring costly ship time for recovery and redeployment. The remote reconfiguration facility helps to change the system configuration within a few minutes, reducing outage time and lowering costs. The feature is implemented such that the INMARSAT provides a bidirectional communication window on a daily basis for the scheduled duration. During the period, the EC could be programmed with the required modifications. The interrogation windows (Figure 10) show the EC communicating with the MCC during the bidirectional connectivity period.

FIGURE 9

Power cycling architecture.



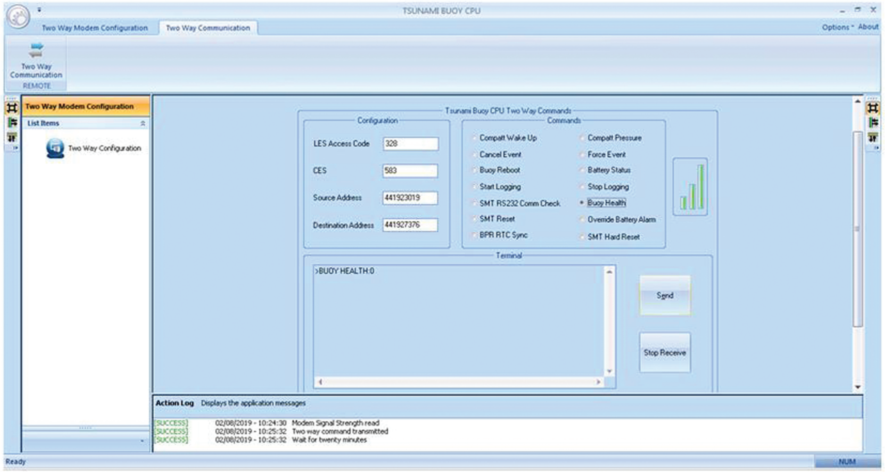
Remote Calibration Provisions

The MSBs are deployed from the ship after carrying out the required predeployment checks and procedures to ensure system functionality. After deployment, the proper function of the MSB systems was ascertained by the deployment team from the MCC personnel based on the first transmitted data sets received at the MCC. In order to have direct communication between the deployment vessel and the deployed MSB for a brief period after deployment, the MSB is equipped with an external GPS receiver, an ultra high frequency (UHF) radio modem (Figure 11), and a receiver in the deployment vessel. The system is programmed to exchange data every 1 s to 15 min, with the MSB position details and system performance data. This arrangement in the MSB is equipped with a standalone battery pack to ensure continuous undisturbed power.

Subsequent to the deployment, the functionality of the MSB meteorological sensors is normally verified using the weather station data onboard the deployment vessel. However, verifying the functionality of the MSB oceanographic instruments requires deploying a similar sensor array from the deployment vessel and moving the deployment vessel for acquiring spatial data, which requires ship time. As a cost-effective solution, a twin propeller electrically powered remotely operated boat (ROB) capable of operating with a subsurface sensor string up to 4 knots of speed in the open ocean is developed. The ROB could be deployed from the deployment vessel and remotely controlled using a four-channel 2.4-GHz transmitter and receiver module. The track of the boat is transmitted using a 433-MHz telemetry module. The functionality of the ROB with oceanographic sensor array up to a 10-m depth is tested in the Bay of Bengal (BoB)

FIGURE 10

Communication between the MCC and the EC in the MSB.



LES Access Code 328
CES 583
Source Address 441923019
Destination Address 441927376

○ Compatt Wake Up ○ Compatt Pressure
○ Cancel Event ○ Force Event
○ Buoy Reboot ○ Battery Status
○ Start Logging ○ Stop Logging
○ SMT RS232 Comm Check ● Buoy Health
○ SMT Reset ○ Override Battery Alarm
○ BPR RTC Sync ○ SMT Hard Reset

```
>BUOY HEALTH:0
```

Action Log Displays the application messages

```
[SUCCESS]      02/08/2019 - 10:24:30  Modem Signal Strength read
[SUCCESS]      02/08/2019 - 10:25:32  Two way command transmitted
[SUCCESS]      02/08/2019 - 10:25:32  Wait for twenty minutes
```

Ready

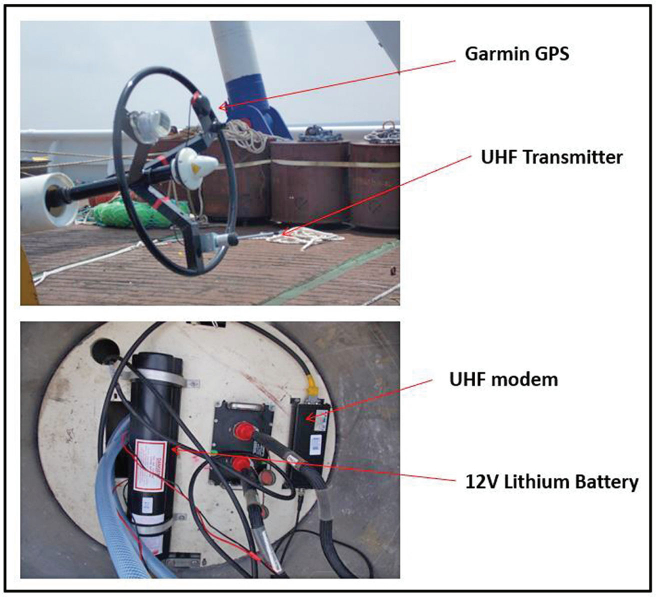
(Figure 12), during the time the ROB streamed data and video in real time to the deployment vessel from a distance of 300 m.

Power System Management

The MSB energy storage system, comprising solar-powered lead-acid batteries backed with lithium thionyl chloride ($LiSoCl_2$) batteries, is managed by the power management module (PMM). This configuration has the best possible trade-off between the required on-demand reliability of SIL4 and the data transmission cost of US$1.12 per data set (Venkatesan et al., 2015). The PMM is built with 16-bit μC operated with 32-MHz clock frequency. A fuel gauge integrated circuit (IC) measures the battery state of charge, voltage, and load current of both the lead-acid and $LiSoCl_2$batteries and communicates with the PMM through I^2C interfaces. The fuel IC is a precision coulomb counter, which integrates current through a sense resistor between the battery's positive terminal and the load or charger.

FIGURE 11

UHF communication with the deployment vessel.



The system uses a charging controller, a high-performance buck-boost converter with a Perturb and Observe algorithm for identifying the maximum power point and constant-current constant voltage charging profile charging algorithm to implement a maximum power point tracker (MPPT) function and flexible charging profiles. An MPPT charge controller is an electronic DC-DC converter, which extracts the maximum power from the photovoltaic (PV) module by forcing the PV module to operate at a voltage close to the maximum power point. They convert a higher voltage DC output from solar panels down to the lower voltage needed to charge batteries with efficiency ranging between 90% and 95% compared to pulse width modulation (PWM) chargers. The MPPT will change dynamically throughout the day depending on the irradiation conditions. Figure 13 shows the PMM switching the load from lead-acid batteries to $LiSoCl_2$ batteries and back to lead-acid batteries.

Cyclone Mode Transmission

Based on the observations made during various cyclonic events, it is identified that the semidiurnal variation in the atmospheric pressure could be used for cyclone detection.

FIGURE 12

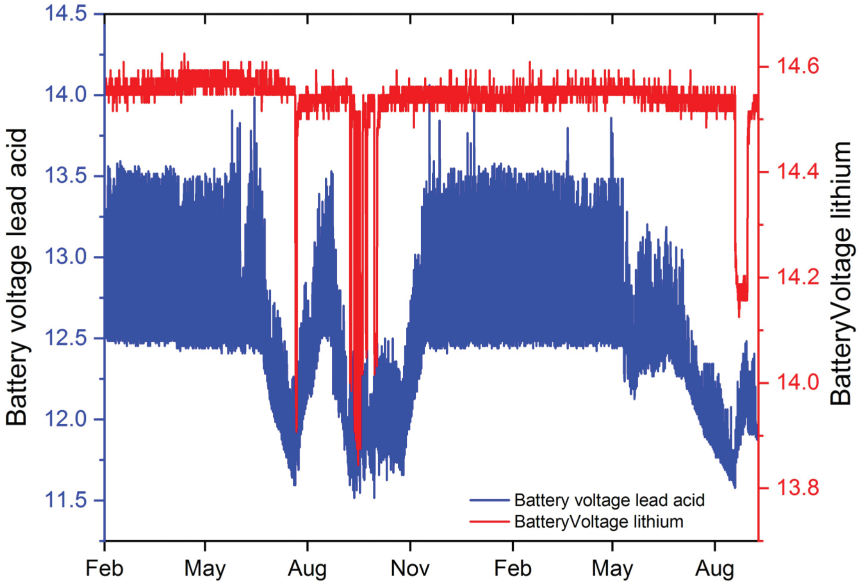
ROB operated from the deployment vessel SAGAR NIDHI.

Under normal conditions, the pressure difference between the present and previous days at the same time shall be < 2.3 hpa, while a threshold of 4 hpa indicates a cyclone. The observations during Cyclone Lehar are shown in Figure 14.

The EC in the MSB is programmed to collect the meteorological and oceanographic parameters at preset intervals and transmit to it to the MCC every 3 h. Increasing the transmission frequency during the passage of the cyclone helps in better prediction of the track and intensity of the cyclones. Based on this, an algorithm described in Figure 15 is implemented in the MSB EC, in which the atmospheric pressure threshold is used for switching the transmission from a normal 3-h interval to shorter preprogrammed intervals. The cyclone detection and switching of the normal transmission to rapid mode during the Vardah cyclone in 2016 are shown in Figure 16.

FIGURE 13

Event of switching from lead acid to $LiSoCl_2$ battery.



Sensor Redundancy

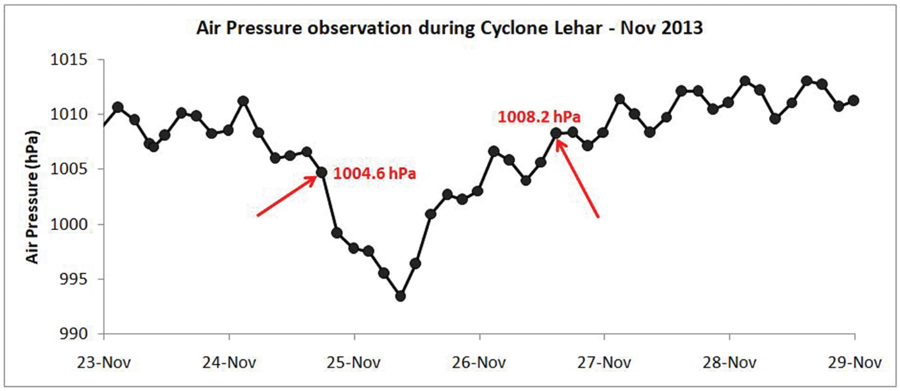
The increased number of MSB instruments reduces the MTBF of the system, which in turn requires frequent maintenance for ensuring higher data returns. Reliability analysis is done based on achieved field failure data for a configuration with a redundant meteorological sensor suite, and it is found that its MTBF increases from ~ 0.6 to 0.9 years (Sundar et al., 2016). In order to evaluate the practical feasibility, an MSB is realized with a configuration incorporating two sensor masts with redundant meteorological instruments and is deployed off Lakshadweep islands of India (Figure 17) and operated for a period of 1 year. The encouraging configuration is now implemented in a remotely located MSB. The configuration was also used for the qualification of sensors/instruments of different manufacturers operating in similar environmental conditions.

Vandalism Prevention

From the failure modes represented in Figure 3, about 41% of the failures reported are due to unlawful acts including vandalism. In order to

FIGURE 14

Observed atmospheric pressure during Cyclone Lehar.

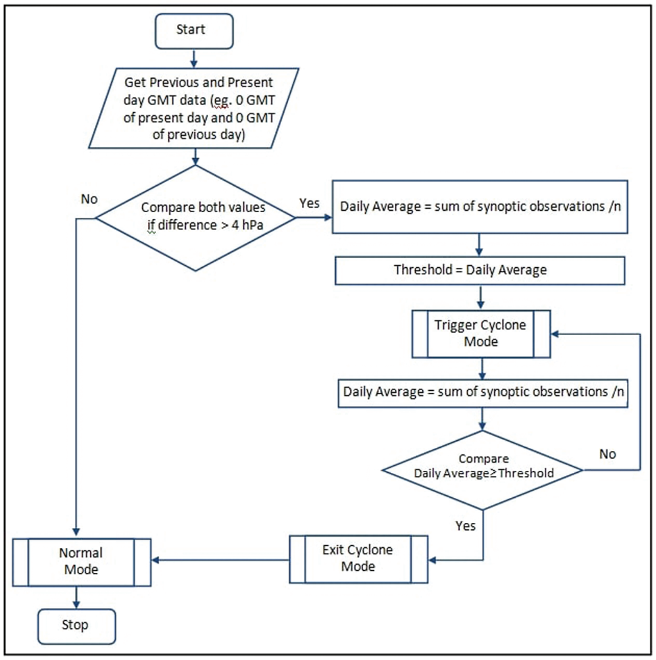


reduce vandalism, programs and workshops are periodically conducted in coastal regions to discuss the importance of the technology, and improved working mechanisms have been formulated with eight neighboring countries in the BoB (Venkatesan, 2014). Furthermore, as vandalism is more prevalent in coastal areas, engineering efforts, such as using welded fasteners for antivandalism and visual observation support using video telemetry, are being implemented. A remote video observation system for real-time visual observation using 3G telemetry has been implemented in a coastal buoy and deployed off Goa (Figure 18) and has been operational since May 2014. The cameras installed on the sensor mast capture videos and still pictures of the entire area surrounding the buoy system. These high-resolution cameras are capable of taking nighttime videos and underwater images, with an infrared (IR) range of up to a 30-m distance. This system records and transmits the images every alternate 15 min, and the dedicated authorities are able to view the live videos and pictures.

By means of reliability analysis, it is identified that three tsunami buoys are required to maintain the ITBS network in IEC61508 SIL4. Unavailability of a buoy degrades the safety integrity level (SIL) of the network to unsafe levels, which are unacceptable (Srinivasa Kumar et al., 2016; Venkatesan et al., 2015). In order to avoid vandalism by means of keeping the surface buoy below the visible zone, a tsunami buoy that is capable of remaining submerged below under normal conditions and capable of surfacing during a tsunami event has been developed and demonstrated off Goa in a 50-m water depth (Figure 19). The system comprises an underwater winch, which is driven by1 a brushless direct current motor (BLDC) motor and buoy. This enables the even-driven ascent with a velocity of 120 m/min.

FIGURE 15

Cyclone detection algorithm programmed in the EC.



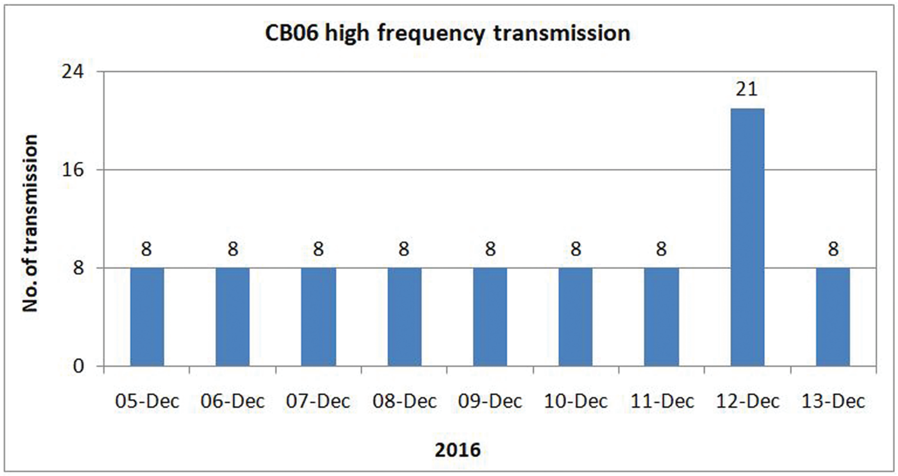
Sensor Date Quality Monitoring

Historical trending and analysis of the instrument data helps in early identification of the sensors under performance and advancing maintenance decisions. This also helps in quality assurance of sensor selection, improved sensor application practices, and developing application standards for long-term quality management.

The MCC is equipped with an in-house developed software ADvanced Data REception and analysiS System

FIGURE 16

Switching from normal to rapid mode during the Vardah cyclone.



(ADDRESS), which compares the outputs of similar sensors in a closely located MSB during the same time period (Venkatesan et al., 2015). The historical data analysis done for air pressure measurements in closely located buoys, which are operational in the BoB, is shown in Figure 20. The ADDRESS can store complete instrument details including sensor calibration certificates and deployment history. The data quality control feature has helped in identifying technological flaws, which has led to product reengineering for reliable operation in the demanding offshore environment (Venkatesan et al., 2018).

Biofouling Control

Biofouling is mainly due to the conducive ecological environment in the surface mixed layer with an increased availability of nutrients. Biofouling significantly affects the measurement of continuous real-time data in offshore moored data buoy sensors. Biofouling remains the primary limiting factor in terms of measurement accuracies and deployment longevity for deep oceans. The seawater conductivity sensor in a coastal buoy off Goa at a 1-m water depth affected by biofouling after 2 months of deployment is shown in Figure 21. From Figure 22, it can be seen that 47% of failures are environment-induced. Biofouling of sensors measured spatially in the Arabian sea and BoB indicates that biofouling and abrasive scouring of cells due to the flow of high concentrations of plankton in the euphotic zone causes drift in the conductivity sensor measurements (Venkatesan et al., 2019). The average drifts of conductivity in the surface layer in the Arabian sea and BoB are 0.00335 and 0.00275 PSU/month, respectively (Venkatesan et al., 2017).

FIGURE 17

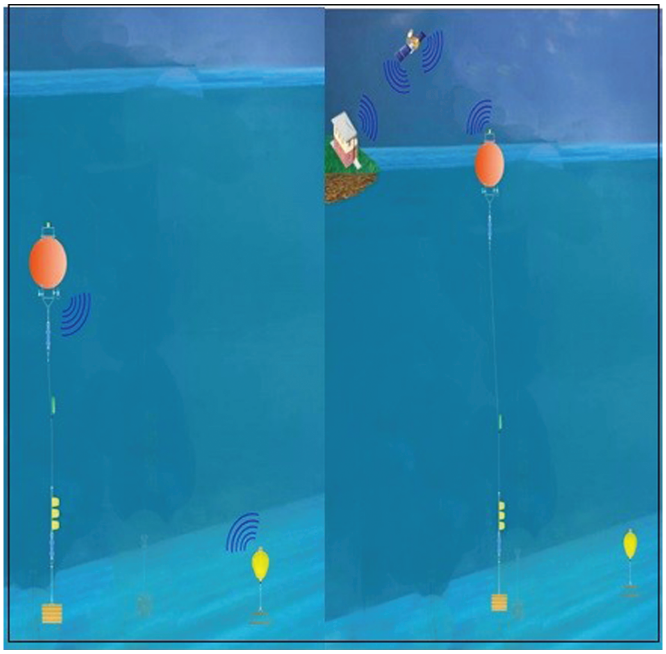
Dual-sensor buoy deployed off Lakshadweep (Venkatesan et al., 2016).

FIGURE 18

Coastal buoy with a surveillance camera (Venkatesan, 2014).

FIGURE 19

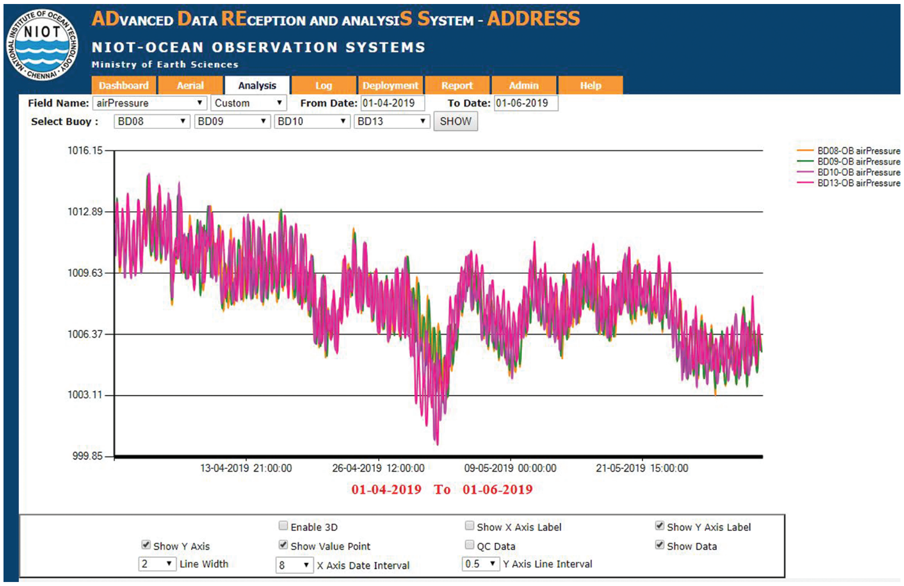
Submerged tsunami buoy description.



Various methods of antifouling approaches (Figure 22), including copper guard protection, polyester tape on sensor casing, and copper tape on sensor casing, are used in the NIOT MSB-located oceanographic sensors. Protective plastic sleeves around the sensing parts and antifouling paints on frames are also used for biofouling prevention.

FIGURE 20

Data comparison between instrument outputs at the MCC.


ADVANCED DATA RECEPTION AND ANALYSIS SYSTEM - ADDRESS
NIOT-OCEAN OBSERVATION SYSTEMS
Ministry of Earth Sciences

Field Name: airPressure
Custom
From Date: 01-04-2019
To Date: 01-06-2019
Select Buoy : BD08 BD09 BD10 BD13

01-04-2019 To 01-06-2019

☐ Enable 3D
☐ Show X Axis Label
☑ Show Y Axis Label
☑ Show Y Axis
☑ Show Value Point
☐ QC Data
☑ Show Data
2 Line Width
8 X Axis Date Interval
0.5 Y Axis Line Interval

Communication Networks

The MSB data from the INMARSAT are received at the MCC through the INMARSAT modem at NIOT and also from the Land Earth Station through the public network and NIOT mail server. The data thus received through redundant links are retransmitted to INCOIS through the Very Small Aperture Terminal (VSAT) telemetry and to a public network by e-mail (Figure 23). The probability of failure of the data transfer by the File Transfer Protocol through the public network, which was 44.86%, is reduced to 4.3% (an MTTF of 22 years) when the VSAT telemetry is used as a redundant telemetry link (Venkatesan et al., 2015). In order to confirm receipt of the NIOT-INCOIS transmitted data, which is done every 1 h, an acknowledgment is received from the INCOIS server. Likewise, a watchdog algorithm is implemented in the supervisory workstations in the 24/7 manned MCC and programmed to automatically poll the redundant server's healthiness every 5 min to generate the required alarms (Venkatesan et al., 2018). This helps to advance troubleshooting and maximize the availability of the ADDRESS and communication networks of the Indian Ocean observation system.

Discussion and Conclusion

Increasing the reliability of ocean-moored buoy networks beyond certain levels is practically limited by footprint, capital, and operating expenditure. Based on achieved reliability metrics, maintenance of the Indian Ocean observation systems in

FIGURE 21

Observations from a 15N/74E-located conductivity & temperature (CT) sensor (Venkatesan et al., 2019).

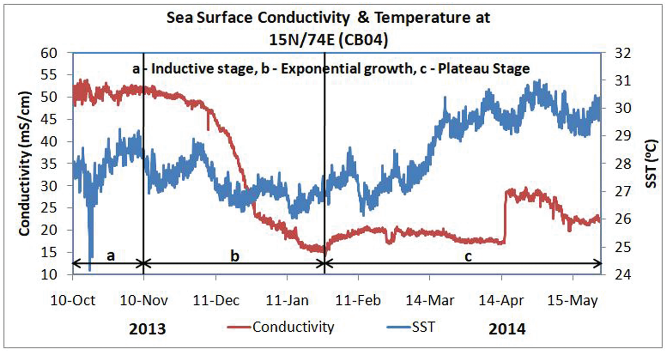


FIGURE 22

Various biofouling prevention methods (Venkatesan et al., 2017).

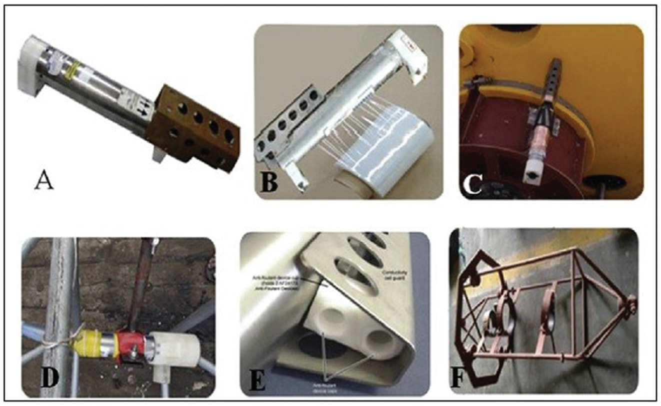
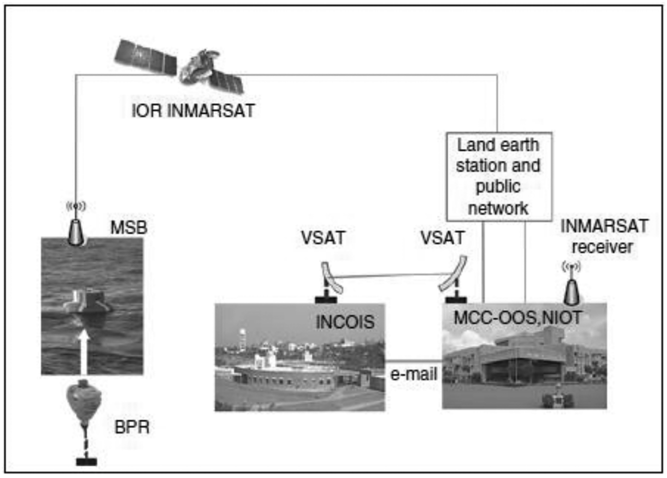


FIGURE 23

Network architecture of data buoy network.



the BoB and Arabian Sea is carried out with an annual four-slot maintenance program. The maintenance program ensures deep ocean-moored buoy maintenance vessel availability for four slots of 15 days each in each slot, totaling 60 days/year. However, with the expanding network for increased spatiotemporal data collection, the availability of ships during the limited weather window is challenging. Hence, implementing rapid restoration techniques are the only means to increase the availability of the Indian Ocean observation networks. Based on the reported degradations, the techniques adopted for increasing subsystem availability over the past two decades could be useful for other global ocean observation networks.

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