PACT – a Bottom Pressure Based, Compact Deep-Ocean Tsunameter with Acoustic Surface Coupling

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***Abstract*-The German-Indonesian Tsunami Early Warning System (GITEWS) is currently established to minimize the risks of disastrous events such as the December 26, 2004 Indian Ocean tsunami. To maximize alerting periods, to avoid false alarms and to accurately predict tsunami wave heights, real-time observations of ocean bottom pressure are required from the deep ocean. To this end, the PACT system (Pressure Acoustic Coupled Tsunameter) was developed. PACT's bottom unit combines a highly-sensitive pressure sensor, a data processing unit for automatic tsunami detection, and an acoustic modem in a single, robust housing. The data are transferred via a bidirectional acoustic link to PACT's surface unit, which is mounted to a surface buoy (not part of the PACT system), allowing also remote activation of the tsunami mode in case a wave is expected from e.g. seismic data. The PACT system has successfully passed extensive laboratory and at-sea tests. The first deployments off Indonesia as part of GITEWS are scheduled for April 2009.**

I. INTRODUCTION

After the December 26, 2004 Indian Ocean tsunami, the development of the German-Indonesian Tsunami Early Warning System (GITEWS) was initiated [1]. This system differs from previous Tsunami Warning Systems through its multi-sensoric approach and high resolution, predictive modeling component. The fastest information channel is provided by seismometers and GPS instruments, which measure horizontal and vertical seismic movements. However, not every earthquake causes a tsunami, nor is every tsunami caused by an earthquake. To avoid false alarms and to also protect against tsunamis caused by landslides, oceanic sea-level is measured directly. This goal is pursued in the GITEWS work package "ocean instrumentation", which aims at highest reliability and redundancy by deploying a set of independent instruments, which – amongst other parameters – measure the sea-level both at the coast on islands off Indonesia (tide gauges), and offshore in the deep ocean (PACT ocean bottom pressure sensors attached to surface buoys).

Deep ocean sea-level changes less than a centimeter can be detected by pressure gauges deployed at the sea floor. Based on some of the concepts developed as part of the US Deep-ocean Assessment and Reporting of Tsunamis (DART®, [2,3]) system, a bottom Pressure based, Acoustically Coupled Tsunameter (PACT) was developed under the auspices of the Alfred Wegener Institute (AWI) in collaboration with two German SMEs, MARUM (University of Bremen, Germany) and the Graduate School of Oceanography (University of Rhode Island, USA). The PACT system records ocean bottom pressure, performs on-board tsunami detection and acoustically relays the data to the surface buoy. Using specially designed computing and communication technology, PACT integrates the entire sea-floor package (pressure gauge, data logger and analyzer, acoustic modem, acoustic release and relocation aids) into a single unit, i.e. a standard benthos sphere. PACT thereby reduces costs, minimizes the deployment efforts, while maximizing reliability and maintenance intervals.

After extensive laboratory and at-sea tests, several PACT systems are scheduled for their first deployment off Indonesia in April 2009.

In this paper, technical specifications, tsunami detection algorithm, operating modes and remote configuration capabilities of PACT are described.

II. THE PACT SYSTEM

A. General description

PACT aims to continuously measure ocean bottom pressure, automatically detect anomalies (tsunamis), and transmit data in near real-time from the sea floor to a surface buoy. PACT consists of two sub-systems (Fig. 1): The *bottom unit* (BU) is deployed at the seafloor. It autonomously measures bottom pressure and performs tsunami detection [4]. The data and alarm messages are transmitted via a bidirectional acoustic link to a *surface unit* (SU) [5]. The latter instrument is attached with a cable about 15 m below the GITEWS surface buoy. All data are relayed from the surface buoy via satellite to the GITEWS warning centre, where all observations and modeled tsunami scenarios are processed to issue hazard warnings in case of a major tsunami event. Additional to the automatic tsunami detection, the PACT system can remotely be set into alarm mode, and detection thresholds and other parameters can be reconfigured without the need to recover the system from the seafloor.

B. PACT Bottom Unit

The bottom unit (Fig. 2) consists of a single 17" Vitrovex glass sphere and plastic hard hat containing all components of the instrument [4]. The entire instrument is rated for a maximum pressure of 6000 dbar. The layout of the PACT-BU closely resembles the design of the Pressure Inverted Echo Sounder (PIES) developed by the University of Rhode Island [6,7,8]. Glass sphere, pressure sensor, release and steel stand are essentially identical to PIES, which have proven as reliable instruments in many oceanographic studies during the last three decades [9].

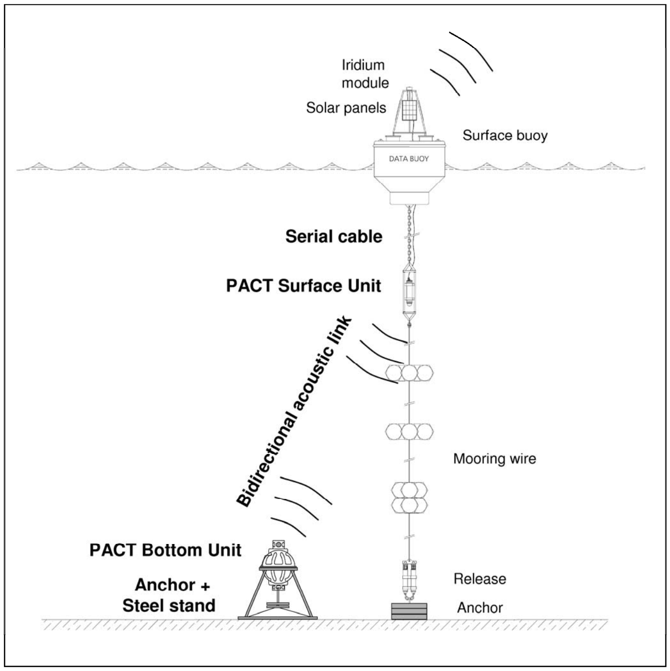

Figure 1. Sketch of the PACT system, with the bottom unit located at the sea floor, and the surface unit attached to a surface buoy for satellite transmission of the data. Note that in reality the vertical distance between bottom and surface units may be up to 6000 m.

Figure 2. PACT bottom unit and steel stand. The black cylinder at the top is the HAM.NODE modem; the burn-wire release of the BU is located in the lower cage. For deployment, additional weights are attached between the release and the steel stand.

The PACT-BU uses a piezo crystal (Paroscientific Digiquartz model 410K) as pressure sensor, which has a resolution equivalent to 1 mm of sea-level change. Pressure is calculated by integration of the number of oscillations over a 15 s time span determined by a temperature-compensated reference frequency – thus, PACT measures the average pressure over consecutive 15 s time windows.

A specially designed microcontroller-based on-board computer optimized for low power consumption performs the tasks of pressure measurements, on-board tsunami detection and modem control.

For the acoustic transmission of data and alarm messages to the surface unit, the BU is equipped with a HAM.NODE hydro acoustic modem [5] developed by develogic GmbH, Hamburg (c.f. subsection C).

A battery package of 86 Lithium D-size cells with a total capacity of 4000 Wh provides power for the controller, modem and release, sufficient for more than two years of operation in "normal capturing mode".

At-sea operations – Deployment: The BU is set in an expendable steel frame (Fig. 2) and tied with its release hook to an anchor weight (not shown), ensuring a stable position of the pressure sensor on the seafloor. The entire assembly is designed for a free-fall deployment. Tilt sensors allow to verify a close-to upright position of the deployed instrument, which is necessary for optimal acoustic communication with the surface unit.

Recovery: When the BU detects an acoustic release command, a burn wire release is activated. After 5 – 20 min, the anode wire is electrolytically dissolved, and the BU ascends with about 1 m s^{-1} to the surface. A relocation module with a VHF transmitter and xenon flasher (at night) aids the localization of the instrument at the surface.

C. HAM.NODE Modem, Acoustic Communication

In the PACT system, the acoustic link from bottom to surface is provided by a pair of HAM.NODE hydro acoustic modems developed by develogic GmbH, Hamburg [5]. PACT is equipped with MF directional modems with 65° –3 dB beam width, transmitting in the 11 – 14 kHz carrier band suitable for high-speed data transmission in vertical channels up to more than 6000 m. The transmitter of the bottom unit is integrated in the BU housing, and powered by a separate set of BU batteries. The projected lifetime of the 2200 Wh modem batteries in the bottom unit is 36 months between service.

The *surface unit* (Fig. 3) consists of a modem with a corrosion-free housing attached to a frame 15 m below the surface buoy in order to avoid disturbance from wind waves and air bubbles. Powered externally from the surface buoy, it is equipped with a set of rechargeable LiMH batteries as a buffer for peak demand during communication.

A key feature of the HAM.NODE system is the flexible modulation and coding which can be automatically adjusted to the prevailing acoustic conditions. For communication along the near-vertical direction between PACT BU and SU, n-m-FSK and DPSK modulation is used. CRC checksums and handshaking between bottom and surface modems ensure that each message is received without any bit errors. The operation

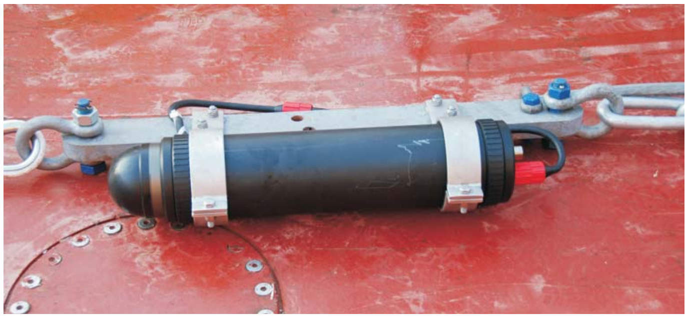

Figure 3. HAM.NODE modem (surface unit) attached to a steel frame which takes the load of the surface buoy.

profile of PACT's HAM.NODE modems is optimized for a highly reliable, but energy-efficient transmission of moderate amounts of data (about 100 Byte per message). At a data rate of 200 bps, each message takes a few seconds for transmission; if necessary, messages are re-sent up to 5 times.

D. Tsunami Detection

The automatic detection of a tsunami event is performed identical to the proven DART® tsunami detection algorithm published in [10; US patent 11]. The basic concept is to compare the actual pressure which is measured every 15 s with a predicted pressure based on a polynomial extrapolation (Fig. 4). The nodes of this cubic polynomial are four 10 min averages covering the most recent 10 minutes and intervals 1, 2 and 3 hours in the past. The polynomial is updated for every 15 s measurement.

In the deep ocean, short surface waves (wind waves) have no influence on ocean bottom pressure – only long gravity waves like tides and tsunamis with wave-lengths of hundreds of kilometers affect the bottom pressure. In case of tides, the predicted pressure closely matches the actual pressure due to their long timescales of several hours. In contrast, tsunami waves have timescales of only a few minutes – hence they are detected by larger anomalies between prediction and actual observations.

A tsunami event is triggered when the two most recent 15 s observations both exceed a pressure anomaly threshold of 30 mm (Fig. 4). Further, a spike criterion must be passed (not shown) to exclude false measurements. For this, the second-last 15 s reading must not depart more than 100 mm from the mean of the most recent and the third-last reading, i.e. the pressure change should be reasonably "smooth" during the course of the last 45 s.

Immediately after the detection of an event, a *tsunami message* is generated and transmitted to the surface unit. This message contains the 8 most recent actual pressure readings covering the last 2 minutes, and the corresponding pressure anomalies (actual minus predicted pressure) – in the first tsunami message, the two most recent of these will be larger than the 30 mm threshold. Further, a timestamp, alarm message ID starting with "1", and the nodes of the last undisturbed polynomial when the event was triggered are

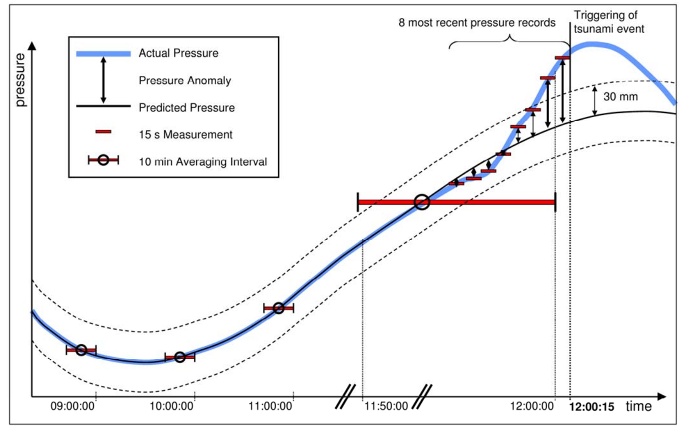

Figure 4. Sketch illustrating the tsunami detection algorithm. The solid curves show actual pressure (heavy line) and the prediction (thinner black line) based on four 10 min averages (horizontal bars). Note, that the time axis is not to scale to enlarge the last 10 min and 2 min intervals. In this example, the two most recent 15 s records (short bars) starting at 11:59:45 exceed the 30 mm anomaly threshold (dashed lines), triggering the tsunami mode at 12:00:15.

transmitted with the first and every following tsunami message. This message format ensures that (a) the exact start time of the event, and (b) the exact shape of the wave can be reliably determined, which is important to assess the hazard potential of the tsunami with highest possible accuracy. Even in case that the first tsunami message is lost (e.g. due to satellite communication error), the start time and the shape of the ongoing wave can be reconstructed using message ID, actual pressure and the "frozen" undisturbed polynomial in all later messages transmitted in 2-minute intervals.

E. Operating Modes

The PACT system operates in different modes (Fig. 5), which can be remotely activated by the warning centre through acoustic commands of the surface unit.

Capturing normal mode is the default mode during a deployment. Pressure is recorded every 15 s. Every 4 hours, a *status message* containing all 10-minute pressure averages of the last 4 hours is generated and transmitted to the surface unit. The status message also contains engineering data (battery voltages etc.), time stamp and message ID which permit to verify the correct operation of the bottom unit. This mode is entered whenever the BU is resetted (command "1" in Fig. 5), or when the tsunami mode (see below) has expired.

Further, a remote reconfiguration of the measurement schedule, averaging and polynomial extrapolation parameters, and tsunami detection thresholds is possible via specific commands ("9-17" in Fig. 5) without the need to take the PACT bottom unit out of the water.

Capturing tsunami mode is triggered automatically when the tsunami detection algorithm detects two successive 15 s pressure readings exceeding the 30 mm anomaly threshold. A *tsunami message* is immediately transmitted; further messages are sent every 2 minutes. After 30 minutes, the unit falls back into capturing normal mode, but is immediately re-triggered, if

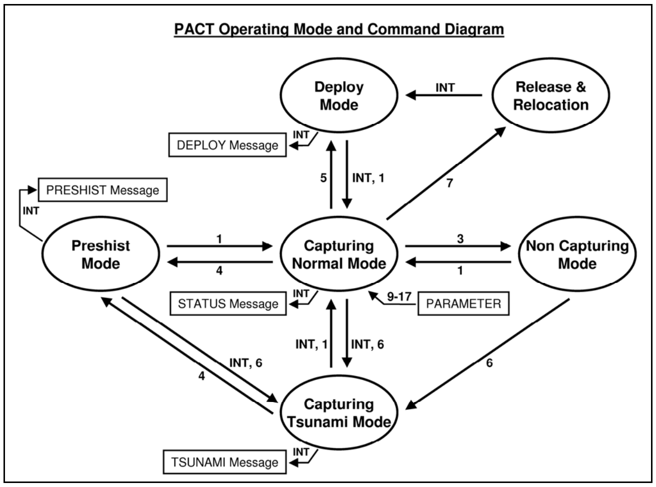

Figure 5. Operating modes of PACT. "INT" marks changeovers to another operating mode automatically controlled by the PACT software, and automatic generation of messages. Numbers refer to explicit commands necessary to switch to another mode.

the pressure readings still depart from the predicted pressure.

The tsunami mode can also be entered manually by a command from the warning centre, allowing the timely detection of even smaller tsunamis not exceeding the 30 mm anomaly threshold. Note that in manually entered tsunami mode, there is currently no internal re-triggering of the tsunami mode implemented when the actual wave arrives at the instrument.

Pressure history mode allows a download of full-resolution 15 s data of the last 3 hours. However, the tsunami detection algorithm remains active at all times and switches the bottom unit into tsunami mode if required. Note that the Pressure History Mode of PACT is not yet supported by the current general GITEWS specification, but it can be accessed manually via acoustic commands during servicing, e.g. from a research vessel.

Three other modes are for operational purposes during deployment and recovery only:

Deploy mode is designed to get frequent pressure and tilt data in order to check the upright orientation of the bottom unit at the seafloor. The deploy mode times out automatically.

Release and relocation mode can only be triggered by commands directly entered to an acoustic surface modem (and not via the GITEWS surface buoy controller). The burn-wire release is activated, and frequent "deploy messages" are transmitted acoustically. At the surface, the VHF transmitter and flashlight aid relocation.

Non capturing mode – is essentially a sleep mode when the instrument is not deployed, i.e. during transport.

III. TESTS AND SCHEDULED DEPLOYMENTS

The mechanical dimensions of PACT, the burn-wire release and relocation module resemble the well-proven PIES design

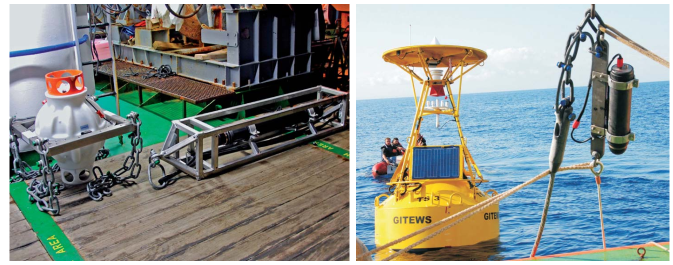

Figure 6. Left: PACT and HAM.NODE modem prepared for a short-term at-sea test, attached to the ship's hydrographic wire. Right: Test deployment of GITEWS GPS buoy with HAM.NODE modem.

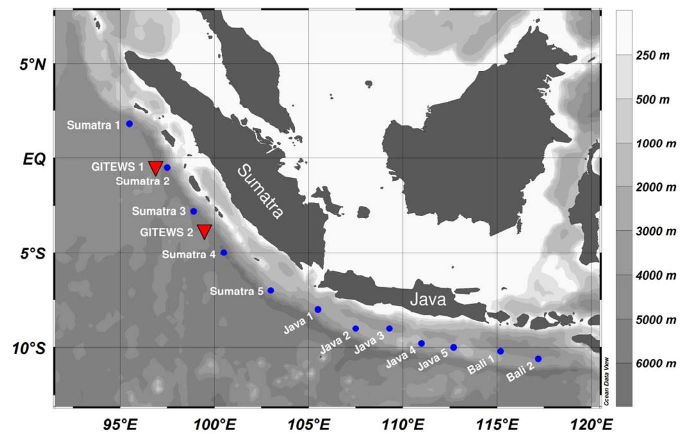

Figure 7. Proposed GITEWS deployment positions of Indonesia. Triangles mark the two moorings already deployed in 2005. Sumatra 1-5 and Java 1-5 (dots) are scheduled for deployment in April 2009, five of these with PACT.

developed by URI [8]. Hence, the handling characteristics during free-fall deployment and recovery of PACT are expected to be comparable with PIES. Further, the Paroscientific pressure sensor is of the same type as in PIES. HAM.NODE acoustic modems have been developed and tested in the framework of the DAMOCLES project in the Arctic Ocean [12]. They are also employed in GITEWS Ocean Bottom Units (OBU; including both pressure sensor and seismometer; Fig. 6).

More critically, however, is the evaluation of the long-term functionality of the entire PACT system.

Extended laboratory tests included high-pressure loading, triggering of tsunami events, remote acoustic control of the bottom unit, and a simulation of the surface unit to buoy interaction. A first at-sea test under realistic conditions was performed at the DOLAN mooring site [13] located 60 nm north of the Canary Islands (Fig. 6). In November 2007, a PACT bottom unit was deployed to a depth of 3300 m in the vicinity of the DOLAN mooring, while a HAM.NODE modem was attached to the DOLAN surface buoy. Via an Iridium satellite link, the bottom pressure data were relayed to the AWI in Bremerhaven. During a 6 month deployment period the system reliably transmitted the data across a near vertical distance of 3900 m, even under severe weather conditions.

At the time of writing (March 2009), several PACT systems are on their way to Indonesia. In April 2009, they are scheduled for their first deployment in the GITEWS mooring array, whose positions were determined by tsunami scenarios numerically modeled at AWI [14]. At 5 of the 10 proposed GPS surface buoy sites off Sumatra and Java (Fig. 7), PACT will provide deep-ocean bottom pressure data in real time. The remaining 5 sites are planned for a later addition with OBU.

IV. Summary

In order to provide deep ocean bottom pressure data and tsunami detection in real time, a Pressure Acoustically Coupled Tsunameter (PACT) was developed for the German-Indonesian Tsunami Early Warning System (GITEWS). In this paper, the technical specifications of PACT are described. PACT combines pressure sensor, on-board tsunami detection, and acoustic communication in a single, compact instrument which resembles the proven PIES design, thus minimizing deployment and recovery effort. The automatic tsunami detection is performed identical to the DART® algorithm. The entire PACT system was successfully tested during a 6-month at-sea deployment under realistic conditions. The first deployments of PACT off Indonesia as a part of GITEWS are planned for April 2009.

Acknowledgments

The development of PACT was founded by the Federal Ministry for Education and Research (BMBF) as a part of the German-Indonesian Tsunami Early Warning System (GITEWS). The bottom unit was developed by Michael Busack and co-workers from OPTIMARE Sensorsysteme AG, Bremerhaven. The HAM.NODE acoustic modems were developed by Markus Motz and co-workers from develogic GmbH, Hamburg. We acknowledge the technical advice of the University of Rhode Island and MARUM, who also supported at-sea test opportunities at the DOLAN mooring.

References

[1] GITEWS website: http://www.gitews.org/
[2] DART website: http://nctr.pmel.noaa.gov/Dart/index.html
[3] C. Meinig, S.E. Stalin, A.I. Nakamura, F. González, and H.G. Milburn. “Technology developments in real-time tsunami measuring, monitoring and forecasting.” *Oceans 2005 MTS/IEEE, 19–23 September 2005*, Washington, D.C., 2005.
[4] Optimare. “Operating manual Pressure Acoustic Coupled Tsunameter (PACT), Rev. Nov 30th, 2008.” Technical Manual, OPTIMARE Sensorsysteme AG, Bremerhaven, 2008.
[5] Develogic. “User manual HAM.NODE Hydro Acoustic Modem with multi node capability, Rev. C3, Nov 16th, 2008,” Technical Manual, develogic GmbH, Hamburg, 2008.
[6] PIES website: http://www.po.gso.uri.edu/dynamics/IES/index.html
[7] G.F. Chaplin, and D.R. Wattts. “Inverted echo sounder development.” *IEEE Oceans '84 Conf. Rec.*, 1, 249-253, Int. of Electr. and Electr. Eng., New York, 1984.
[8] University of Rhode Island. “Inverted Echo Sounder user’s manual, revised.” Report, University of Rhode Island, Narragansett, 2006.
[9] K. Tracey, M. Wimbush, and R. Watts. “PIES bibliography.” Graduate School of Oceanography, University of Rhode Island, 2009. Weblink: http://www.po.gso.uri.edu/dynamics/IES/iesbibupdated.pdf
[10] H.O. Mofjeld. “Tsunami detection algorithm.” PMEL/NOAA, (no date supplied). Weblink: http://nctr.pmel.noaa.gov/tda_documentation.html
[11] C. Meinig, S.E. Stalin, A.I. Nakamura, and H.B. Milburn. “System for reporting high resolution ocean pressures in near real time for the purposes of tsunami monitoring.” United States Patent 7289907, Application No. 11/133,324, 2007.
[12] DAMOCLES website: http://www.damocles-eu.org/
[13] DOLAN website: http://www.marum.de/en/DOLAN.html
[14] J. Behrens. “Advisory report on deep ocean wave gauges – Overview.” Tsunami Project Documentation Document No. 021, Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, 2008.