The Web-enabled Awareness Research Network (WARN) Project

Detection Methods for Earthquakes and Tsunamis

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Abstract

The Web-enabled Awareness Research Network (WARN) implements the data acquisition, event detection and correlation aspects of an integrated geo-hazard alert system. The intent of the project is to lead to the delivery of early warning to urban areas, coastal communities and key infrastructure operators.

Figure 1 provides the overview of a generic alert system top-level architecture and situates WARN in this context. WARN relies on the existence of sensors installed both underwater and on land. WARN also relies on data acquisition performed by Ocean Networks Canada's Oceans 2.0 data management system. Event detection/correlation are the key parts of WARN. The Ocean Networks Canada (ONC) infrastructure is host to the various sensors required to perform the detections. The sensors include, but are not limited to, accelerometers (installed off- and on-shore), coastal radars to detect incoming near-field tsunami waves, and bottom pressure recorders to complete the network. This infrastructure can be expanded geographically both on land and underwater.

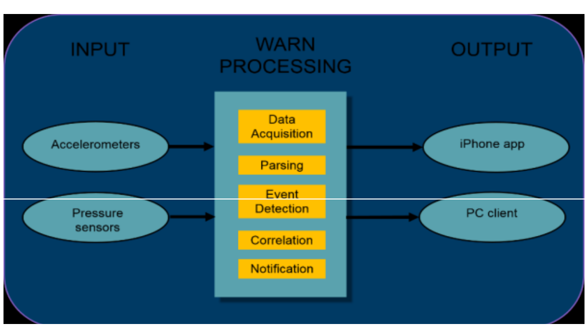

Figure 1 – WARN overview

Earthquake detection is performed by detecting the initial P-wave that is disseminated by the earthquake and which arrives before the destructive S-waves. By correlating the P-wave detection at 3 or more accelerometers, the epicentre location can be estimated. The magnitude of the earthquake is also estimated. Both the epicentre and magnitude solutions undergo automatic quality checks to help prevent false alarms.

Tsunami detection is performed by analyzing the water pressure readings from highly sensitive Bottom Pressure Recorders (BPRs). The residual and tidal pressure is removed from the data and then it is analyzed by various software filters to detect changes in pressure within a range of frequencies that might be attributed to a tsunami wave. Another filter helps to avoid false alarms caused by seismic waves that cause the sensors to vibrate. An event is declared only if a tsunami is detected on 3 BPRs.

Earthquake and tsunami events are reported to those users who have subscribed to these events. Notification methods include e-mail, push notification to a special ONC WARNAlert iPhone app, and push notification to the client's computer via HTTP.

This paper describes the earthquake and tsunami detection algorithms used by Ocean Networks Canada, explains how event notifications are sent out and how they are interpreted by the client software, and gives examples of actual detections.

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Keywords- earthquake, tsunami, BPR, accelerometer, seismic, EEW, TEW

I. INTRODUCTION AND CONTEXT

Ocean Networks Canada (ONC — see oceannetworks.ca) is a not-for-profit organization that manages the NEPTUNE [1], VENUS [2], Cambridge Bay [3], and Bay of Fundy [3] cabled ocean observatories, extending the Internet underwater all the way to a vast array of instruments and sensors[4]. Those sensors are provided with power and communication capabilities, ensuring 24/7 operations, a high data rate and quasi real-time data. The Software Engineering department of ONC is in charge of the development and maintenance of the organization's data management and archiving system, known as Oceans 2.0[5]. The group has been successful in setting up a software system that acquires data from large sensor networks, archives them and makes them available to a varied audience of scientists, the public and various government and non-governmental agencies. Ocean Networks Canada is located at the University of Victoria in Victoria, British Columbia.

Presently, data from over 200 online instruments are available from Oceans 2.0. Data can be previewed through a number of tools such as video viewers and plotting tools and can be downloaded through search interfaces and web services. Data are available in a variety of formats and can be subjected to a number of preprocessing steps on behalf of the user. Formats are often specific to the scientific disciplines of our users. Oceans 2.0 has deployed a fairly complete instrument vs. data products/data formats matrix to translate and deliver data to suit user needs.

The WARN module within Oceans 2.0 provides potential subscribers with early notifications of tsunamis and earthquakes as part of the Ocean Networks Canada's Smart Oceans B.C. initiative [6]. It utilizes existing Oceans 2.0 data acquisition infrastructure while incorporating some new instruments and new event detection algorithms and software. Tsunami detection uses data from pressure sensors such as the existing Bottom Pressure Recorders (BPRs) for far-field tsunamis and a planned WERA (WavE RAdar) NorthernRadar system [7] for near-field events. Earthquake detection uses Accelerometers, providing p-wave detection data. While WARN was implemented as a research/prototype with limited sensors and select early adopters for now, it is being designed to be expandable to greater numbers and types of instruments and subscribers.

While British Columbia is not known for frequent, damaging earthquakes, there is a 25-40% probability of a magnitude 8.0 or greater earthquake somewhere on the Cascadia Subduction Zone in the next 50 years[8]. This fault runs from offshore northern Vancouver Island to offshore northern California. Also, there is a 40 – 80% probability of a tsunami with a run-up exceeding 1.5m on the outer Pacific coast of Canada in the next 50 years, and 10 – 30% probability of run-up exceeding 3m in the same timeframe[9]. So an earthquake and tsunami warning system for the coast of British Columbia could potentially save many lives and reduce property damage significantly. The methods used by ONC could also be used at other earthquake hazard sites anywhere in the world.

II. EARTHQUAKE DETECTION

Earthquake detection is done using a number of accelerometers located on land on northern Vancouver Island, and in the future also on the seafloor west of Vancouver Island. Accelerometers normally only output a characteristic amplitude value known as the Japanese Meteorological Agency's (JMA) instrumental intensity, which is not used at the moment. Instead, WARN's driver software, which runs on a computer co-located with the accelerometer, analyzes the accelerometer data on all three axes and looks for the signature of an earthquake's primary wave (P-wave). The P-wave is the initial compressional wave produced by the earthquake[10]. This P-wave does not typically cause damage but travels faster than the secondary wave (S-wave), which arrives at a specific location later and is the source of potential damage. If a P-wave is detected, the driver outputs the time of detection of the P-wave. Then the driver analyzes the first few seconds of motion and determines the maximum displacement of the vertical component of the shaking, *Pd*, and the maximum period of the vertical component, *Tau*. The P-wave detection time, *Pd* and *Tau* values are sent out by the driver to the Oceans 2.0 software running at the University of Victoria.

The P-wave time, *Pd*, and *Tau* are analyzed by two algorithms to determine the epicentre and time of origin, and two different algorithms to determine the magnitude - see Figure 2.

The epicentre is determined provided at least three accelerometers have reported a P-wave detection. The P-wave detection times are analyzed by triangulation using a Direct Grid Search algorithm, knowing the relative detection times of the P-wave at each of the sensors, plus the location of the sensors. Before declaring the epicentre the quality of the solution is first checked by "reverse engineering" the data to compare the theoretical P-wave arrival time at each sensor based on the computed epicentre, to the actual arrival times. If the quality of the solution is considered high enough, an earthquake is declared by the Earthquake Correlator and the results are passed to the Event Notification component [11, 12].

If the quality is not high enough the software waits until a fourth accelerometer reports detection of a P-wave. Then the Direct Grid Search runs again. In addition another algorithm called Linearized Least Squares also analyzes the four P-wave times (it requires at least 4 readings before it can run). If the epicentres from the two algorithms are less than 80 km apart, the mean value is reported as the epicentre. Knowing the distance from the epicentre to the sensors and the detection time, the time of origin of the earthquake is also estimated and reported.

The magnitude of the earthquake is estimated using two methods. One method uses the *Tau* (period) values reported by the accelerometers. The magnitude is proportional to the *Tau* on a logarithmic scale. The other method uses the *Pd* or maximum vertical displacement reported by each of the sensors. The magnitude is proportional to Pd but inversely proportional to the distance between the epicentre and the sensor on a logarithmic scale. If the magnitude values computed using the two methods are different by more than a threshold value, the detection is rejected until additional sensors report.

The epicentre coordinates, time of origin, and magnitude are passed to the Event Notification component.

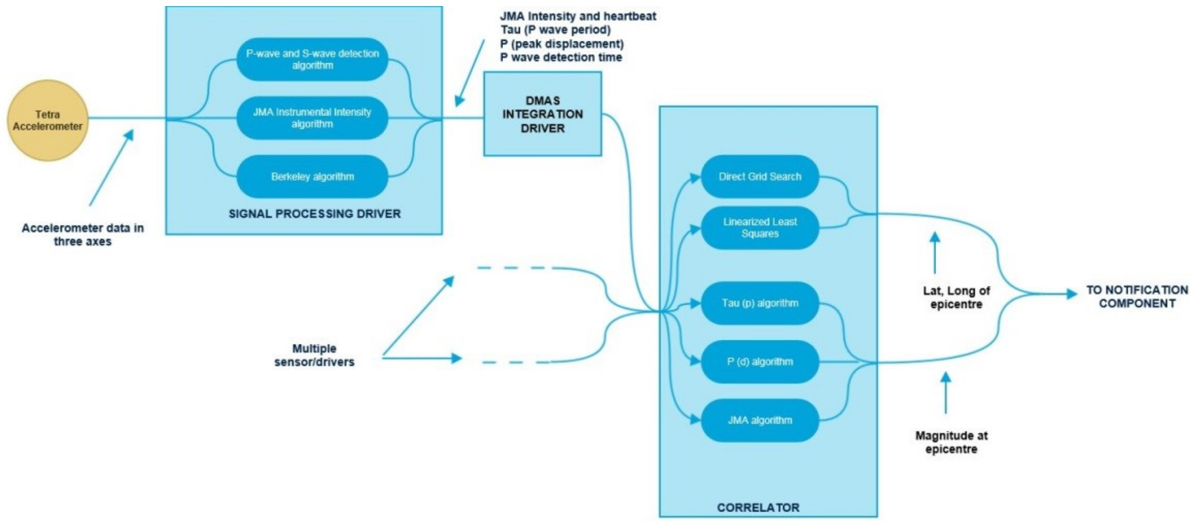

Figure 2 – earthquake detection process

The time from detection at the final sensor until event notifications are sent out after all processing has been completed is less than one second.

III. TSUNAMI DETECTION

Tsunami detection is done using cabled Bottom Pressure Recorders (BPRs) which are located on the seafloor at various locations west of Vancouver Island at depths of up to 2660m (8730 ft). These are highly sensitive instruments that can measure the weight of the water above them and can detect changes in the water depth of as little as 1mm in some cases. Although tsunamis can be quite large at the shoreline, they are much smaller in the deep ocean.

For each of the BPRs configured for WARN, the following processing occurs for every data sample received, and a new sample is received from every BPR every second. See Figure 3.

First the effects of the fixed depth and the effects of the tides must be removed. The "detider" algorithm analyzes the most recent pressure readings as well as samples of pressure from each of the past 3 hours. The data are analyzed using a third-order polynomial curve fitting algorithm in order to predict the next sample. The difference between the predicted value and the actual value (the "pressure residual") is the output of the detider. Typically those values are close to 0 but when a tsunami arrives a large non-zero signal is seen.

There are four algorithms that take the detider output as their input, and they run in parallel [13,14]. Their purpose is to determine whether a tsunami should be declared by this particular BPR. Note that WARN requires more than one BPR to detect a tsunami, but more about that later.

The first algorithm is called Direct Amplitude Thresholding and is very simple. It checks each detided pressure sample and reports if any sample (absolute value) crosses over a threshold.

The second algorithm is called STA/LTA, which stands for Short Term Average over Long Term Average. This algorithm improves the signal-to-noise ratio; the output is compared with a threshold [15].

The third algorithm is called Kurtosis. It computes the kurtosis value of the detided data, which is a statistical parameter that measures the "peakedness" of the signal. The output is compared with a threshold [15].

The final algorithm is a "not-a-tsunami" detector called a Seismic Wave Detector. Knowing that earthquakes cause shaking of the seafloor, which will cause the BPRs to shake and effectively create their own signals similar to what would be caused by ocean waves, this detector distinguishes between false alarms caused by seismic seafloor waves and tsunami waves on the ocean surface. The first step is to use a digital high pass filter to distinguish seismic waves from tsunamis, since they have a higher frequency signature. The output signal is improved using an STA/LTA method. The output of that is compared with a threshold.

For any single BPR, a tsunami is declared if the tsunami detection algorithms exceed their thresholds within a certain time window ***and*** the Seismic Detector *does not* detect a seismic wave at the same time. This is the function of the Watcher in Figure 3.

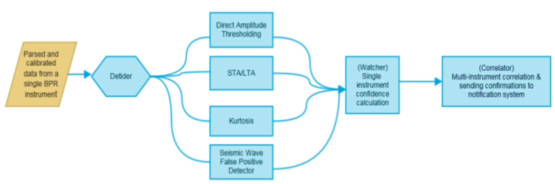

Figure 3 - tsunami detection process

See plots showing the detection of the March 2011 Tohoku, Japan tsunami (processed after the fact) in Figure 4.

The above process is repeated on each of the BPRs. Note that the BPRs are spaced far apart which means they detect the tsunami at different times.

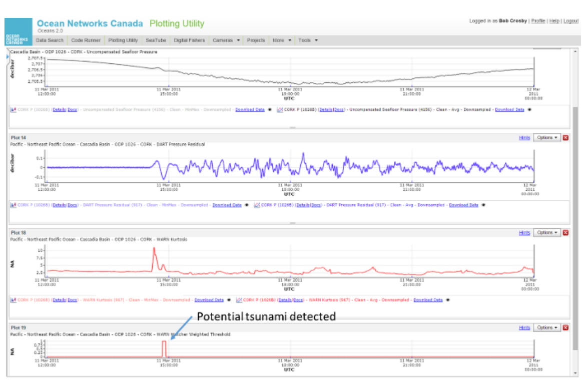

Figure 4 - detection of Tohoku, Japan tsunami on one BPR (some algorithm outputs not shown)

The Correlator watches for a tsunami declaration from at least 3 BPRs. The correlation has two conditions - 1) the BPRs that have reported must be at least 15km apart from each other (to help rule out false alarms), and 2) the arrival time of the tsunami at each BPR must occur within a certain time window relative to all other reporting BPRs. If all of these conditions are met the Correlator passes on the detection timestamp, the height of the tsunami wave at the time of detection, and the maximum height over a certain time window after detection, to the Event Notification software. The time from detection at the third BPR until the tsunami is reported externally is less than one second.

IV. EVENT NOTIFICATION

The Event Notification component allows ONC staff to define and activate event detection, to manually test events, and to allow others to subscribe to certain events and to decide how they wish to be notified. For WARN the two events that are most important are WARN Earthquake Detection and WARN Tsunami Detection.

At the moment there are three ways that a user can be notified of an event:

- by server notification, where we directly call the subscriber's URL by HTTP and the subscriber has written software to accept our call and take some action.
- by e-mail. This method is mainly useful for test purposes as it cannot be relied upon to be fast enough in most cases.
- by Apple Push notification [16], which will notify anyone running the WARNAlert iPhone application. Note that this "app" was developed for demonstration purposes and may not be released to the public.

All messages are sent using CAP (Common Alerting Protocol)[17] format, which is the same format used to send severe weather and other emergency alerts. In addition, a “heartbeat” message will be sent to all server notification subscribers on a regular basis. After analyzing the most recent accelerometer and BPR samples, the heartbeat indicates whether Oceans 2.0 and WARN is currently capable of detecting and reporting earthquakes and tsunamis. This can be used by clients to verify their service level agreement. All messages are “pushed”, not “pulled”. All CAP messages use a digital signature with private and public keys so that only alerts sent from Ocean Networks Canada will be acted on by the clients. See Figure 5.

At this time it is necessary to obtain permission from ONC in order to subscribe to events.


```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<alert xmlns="urn:oasis:names:tc:emergency:cap:1.2">
  <identifier>ED17:1435011404469</identifier>
  <sender>onc-0039</sender>
  <sent>2015-06-22T22:20:03+00:00</sent>
  <status>Test</status>
  <msgType>Alert</msgType>
  <scope>Public</scope>
  <info>
    <category>Geo</category>
    <event>Earthquake</event>
    <urgency>Expected</urgency>
    <severity>Unknown</severity>
    <certainty>Observed</certainty>
    <eventCode>
      <valueName>Event</valueName>
      <value>earthquake</value>
    </eventCode>
    <effective>2015-06-22T22:16:44+00:00</effective>
    <parameter>
      <valueName>OriginTime</valueName>
      <value>2015-06-22T22:16:13+00:00</value>
    </parameter>
    <parameter>
      <valueName>NumberOfSensors</valueName>
      <value>3</value>
    </parameter>
    <parameter>
      <valueName>Epicentre</valueName>
      <value>48.902, -128.691</value>
    </parameter>
    <parameter>
      <valueName>Magnitude</valueName>
      <value>7.0</value>
    </parameter>
    <area>
      <areaDesc>NORTHEAST PACIFIC</areaDesc>
    </area>
  </info>
</alert>
(plus additional information for digital signing)
```


Figure 5 – earthquake CAP message

V. CLIENT SOFTWARE

The PC and iPhone client software behave in a similar fashion. Both devices parse the incoming CAP message to extract the details of the earthquake or tsunami alert or heartbeat. If it’s an earthquake alert, the distance from the epicentre to the device is computed using Vincenty’s formulae[18]. Knowing the distance and the magnitude, the estimated intensity of the shaking at the client's location is determined and is given in units of the Modified Mercalli Intensity (MMI). And given the distance, the origin time, and the typical propagation velocity of an S-wave, the "time to shaking" is determined. This is the basic functionality of the client API which we provide. Users who implement their own version of the client software are free to do whatever they choose with this information, such as to give a visual or audible indication or operate a relay to control equipment. See Figure 6.

In the case of the WARNAlert iPhone app, an audible alarm is provided which is always at maximum volume. The details of the event are provided, and in the case of an earthquake, a countdown shows the time to shaking. A map also shows the epicentre and an expanding circle to indicate the approximate current location of the S-wave. Users can choose the estimated level of shaking at which they wish to be notified, and they can also choose whether or not to be notified for test simulations.

```
Cap signature is valid

  2015-08-11 16:56:04 UTC WARN declared an
earthquake -
  Status:   TEST
  Origin time:   2015-08-11 16:55:24 UTC
  Epicentre:   (48.90,-128.69)
  Magnitude:  7.0

  Location 1- University of Victoria, Victoria, B.C.
  Shaking Expected:   2015-08-11 16:57:14 UTC
  Intensity:          3.8
  Distance to Epicentre:   399.1 km

  Location 2- B.C.Place stadium, Vancouver, B.C.
  Shaking Expected:   2015-08-11 16:57:17 UTC
  Intensity:          3.8
  Distance to Epicentre:   409.5 km

  Location 3- Tofino, B.C.
  Shaking Expected:   2015-08-11 16:56:21 UTC
  Intensity:          4.7
  Distance to Epicentre:   205.5 km

  Number of sensors detected:   3
```

Figure 6 - client earthquake notification example

Given the location of the limited number of current accelerometers, figure 7 gives an example of the amount of warning time we can give to the coastal cities in British Columbia and northwestern Washington. This assumes that the epicentre is on the Nootka Fault, an area with fairly frequent earthquake activity. The warning times will of course vary by epicentre. These warning times are theoretical and assume good quality detections by the nearest 3 sensors. Additional accelerometers, as planned, will improve the warning times and will also make the system less sensitive to epicentre location.

Figures 5, 6, and 7 relate to the same event.

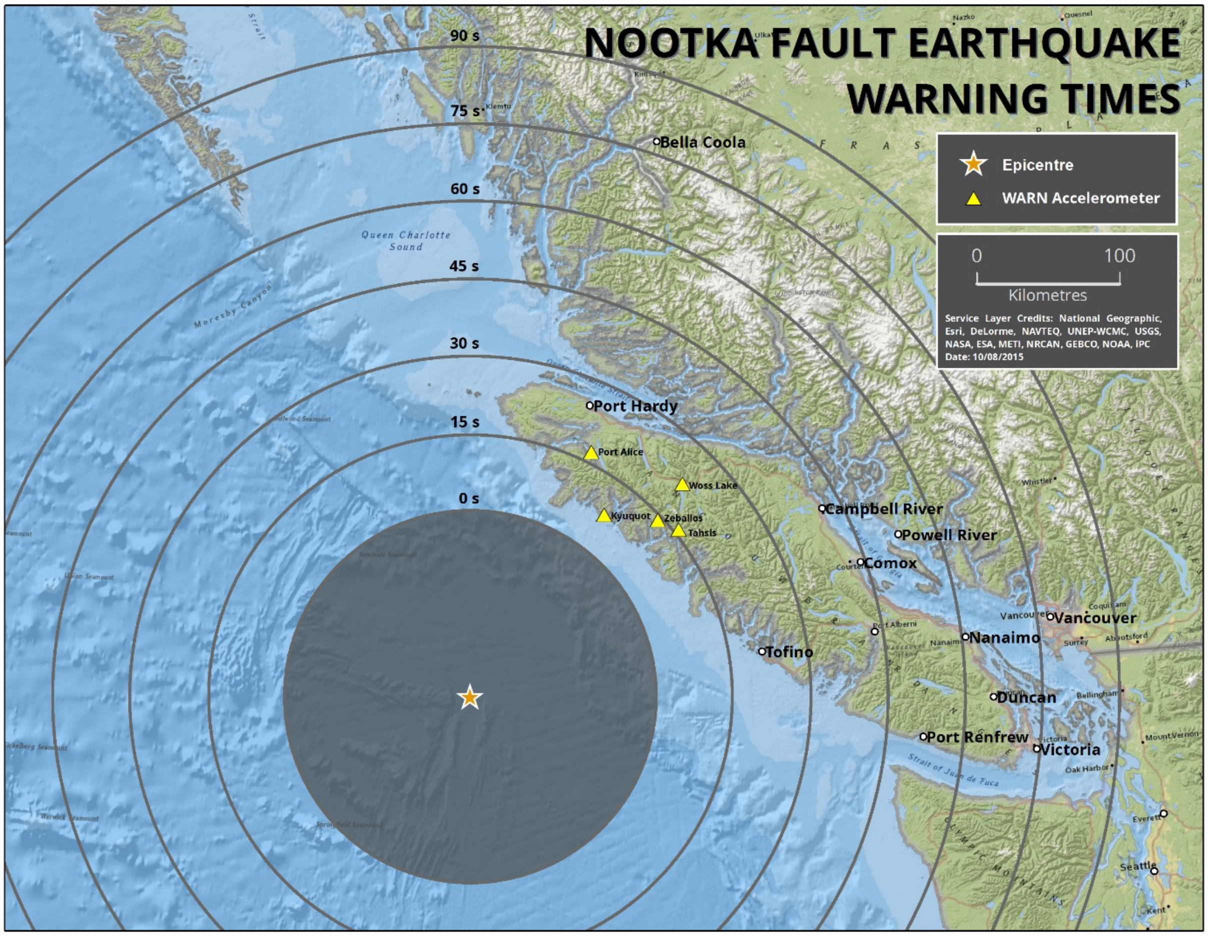

Figure 7 – earthquake warning times for an example epicentre, given the current 5 sensors

VI. ACTUAL EVENT DETECTIONS

a. Tsunami

There have been no tsunamis near Vancouver Island since the TEW (Tsunami Early Warning) section of WARN was deployed in November, 2014. However 2 of the BPRs used by WARN were in place on the seafloor during the March 11, 2011 Tohoku, Japan earthquake and tsunami and their data was archived. When we reprocessed that data through the system with the WARN software in place, we can clearly see a strong tsunami signal on both of them about 9 hours after origin, with a maximum wave height of 13cm in deep water – see Figure 8. If WARN had been running at the time, we would have reported a tsunami on both BPRs. In fact, based on the actual arrival time of the tsunami at coastal cities [19], assuming we had a third BPR running WARN software and it was located further west than the other two BPRs (such as at our Endeavour site), we could have given approximately 33 minutes warning to Tofino and 74 minutes warning to Port Alberni, a city that received significant tsunami damage in a 1964 Alaska earthquake. In addition we detected a strong seismic signal from the Tokoku earthquake 11 minutes after origin. This was detected by the seismic detection algorithm and prevented a tsunami false alarm.

An unexpected side effect of the seismic detection algorithm in the tsunami detection code was that at least 30 earthquakes seem to have been detected from all around the Pacific Rim including an M7.1 in Fiji, M4.3 west of California, M6.7 near Alaska, M 7.1 in Indonesia, M6.3 near Japan, and an M7.3 in Nepal. WARN has been configured to send an e-mail from each detecting BPR each time one of these events occurs, and we compare the results with USGS (United States Geological Service) data.

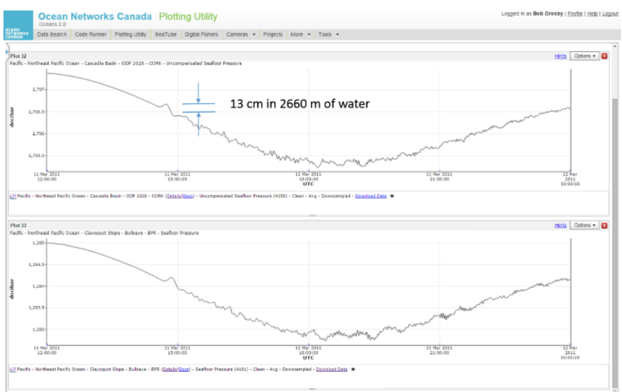

Figure 8 – reprocessed data from Tohoku, Japan tsunami March 2011 at 2 BPRs

b. Earthquake

The initial sensors that were deployed – Tetra Accelerometers – did not detect any earthquakes. They are currently being replaced by more sensitive Nanometrics TitanSMA strong motion accelerometers. Small but relatively frequent earthquakes in the Nootka Fault region west of Vancouver Island are expected to be detected after that. Hopefully I will have some results to report when this paper is presented at Oceans '15.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

1. *C*. Barnes, M. M. R. Best, B. Bornhold, S. K. Juniper, B. Pirenne, P. Phibbs, "The NEPTUNE Project - a cabled ocean observatory in the NE Pacific: Overview, challenges and scientific objectives for the installation and operation of Stage I in Canadian waters" underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007. Symposium on, pp. 308–313, IEEE April 2007.
2. R. Dewey, P. Macoun, A. Round, J. Vervynck, V. Tunnicliffe, "The VENUS Cabled Observatory: Engineering Meets Science on the Seafloor", IEEE Oceans 2007, pp. 1-7.
3. M. Hofmann, R. Flagg, R. Key, K. Moran, S. McLean, S. K. Juniper, B. Pirenne, "Cabled Observing Stations for Remote Locations" IEEE Oceans 2013.
4. B. Pirenne, "The role of Information Communication Technologies (ICT) for seafloor observatories: acquisition, archival, analysis, interoperability", in Seafloor Observatories, Praxis, Springer Verlag, in press.
5. B. Pirenne, E. Guillemot, "Oceans 2.0: a Data Management Infrastructure as a Platform", EGU General Assembly 2012, held 22-27 April, 2012 in Vienna, Austria., p.13346
6. B. Pirenne, A. Rosenberger, E. Guillemot, R. Jenkyns, "The Web-enabled Awareness Research Network (WARN) project Early Earthquake and Tsunami warning at Ocean Networks Canada", IEEE Oceans 2014.
7. See: http://www.aslenv.com/WERA.html
8. Goldfinger, C., Nelson, C.H., Morey, A.E., Johnson, J.E., Patton, J.R., Karabanov, E., Gutiérrez-Pastor, J., Eriksson, A.T., Gràcia, E., Dunhill, G., Enkin, R.J., Dallimore, A., and Vallier, T., 2012, "Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone" - U.S. Geological Survey Professional Paper 1661–F, 170 p. (Available at http://pubs.usgs.gov/pp/pp1661f/).
9. L. J. Leonard, G. C. Rogers, S. Mazzotti, "Tsunami hazard assessment of Canada", 2013. DOI 10.1007/s11069-013-0809-5, p.1
10. Rosenberger, A., "Real-time Ground-Motion Analysis: Distinguishing P and S Arrivals in a Noisy Environment", Bull. Seism. Soc. Am., 2010, 100, 1252-1262
11. Rentsch, S.; Buske, S.; Luh, S. & Shapiro, S. A. , Fast location of seismicity: A migration-type approach with application to hydraulic fracturing, Geophysics, 2007, 72, S33-S40
12. Gillette, M. D. & Silverman, H. F. "A linear closed-form algorithm for source localization from time-differences of arrival", IEEE Signal Process. Lett., 2008, 15, 1-4
13. Mofjeld, H. Real-Time Tsunami Detection in the Open Ocean: Tsunami Detection Algorithm 1998, URL http://nctr.pmel.noaa.gov/tda_documentation.html
14. Mofjeld, H. O.; Whitmore, P. M.; Eble, M. C.; Gonzalez, F. I. & Newman, J. C. , Seismic-wave contributions to bottom pressure fluctuations in the North Pacific - Implications for the DART Tsunami Array, ITS 2001 Proceedings, 2001
15. Küpperkoch, L.; Meier, T. & Diehl, T. Borman, P. (Ed.), New Manual of Seismological Observatory Practice 2 (NMSOP-2), Chapter 16 Deutsches GeoForschungsZentrum GFZ, 2012, URL http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:43230:9.
16. See https://developer.apple.com/library/ios/documentation/NetworkingInternet/Conceptual/RemoteNotificationsPG/Chapters/ApplePushService.html
17. See: http://en.wikipedia.org/wiki/Common_Alerting_Protocol
18. See https://en.wikipedia.org/wiki/Vincenty%27s_formulae
19. S. Narayanan, "Chart-related Operational Services Update", 2012 Mariner's Workshop, Feb. 21-22, 2012 Montreal, Canadian Hydrographic Service, p.16