The 11th Canadian Conference on Earthquake Engineering

Canadian Association for Earthquake Engineering

ADVANCING TSUNAMI DETECTION: THE OCEAN NETWORKS CANADA TSUNAMI PROJECT

Tania L. INSUA
Ocean Analytics Program Manager, Ocean Networks Canada, Canada
tinsua@uvic.ca

Kate MORAN
President and CEO, Ocean Networks Canada, Canada
kmoran@uvic.ca

Scott MCLEAN
Innovation Centre Director, Ocean Networks Canada, Canada
sdmclean@uvic.ca

Teron MOORE
Innovation Centre Business Analyst, Ocean Networks Canada, Canada
tmoore@uvic.ca

Martin HEESEMANN
Staff Scientist, Ocean Networks Canada, Canada
mheesema@uvic.ca

Benoît PIRENNE
User Engagement Director, Ocean Networks Canada, Canada
bpirenne@uvic.ca

Dawei GAO
School of Earth and Ocean Sciences MSc student, University of Victoria, Canada
daweigao@uvic.ca

Jay HOEBERECHTS
School of Earth and Ocean Sciences MSc Student, University of Victoria, Canada
jaymph@gmail.com

Peter SALOMONSSON
Computer Science MSc Student, University of Victoria, Canada
pbjs@uvic.ca

Yvonne COADY
Professor, Computer Science Department, University of Victoria, Canada
ycoady@gmail.com

Lucinda LEONARD
Assistant Professor, School of Earth and Ocean Sciences, University of Victoria, Canada
lleonard@uvic.ca

Kelin WANG
Professor, Pacific Geoscience Centre, Geological Survey of Canada and University of Victoria, Canada
Kelin.Wang@NRCan-RNCan.gc.ca

ABSTRACT: The Ocean Networks Canada (ONC) Tsunami project leverages the assets of ONC's sensor array and data collection infrastructure, and its supercomputing infrastructure to perform high-speed data analyses that support advanced tsunami detection and modelling for the coast of British Columbia. The Tsunami project comprises several sub-projects that are defined and integrated in this article. These projects include the development of bathymetry and topography data fusion software, new source models for the area and the wave propagation and inundation maps based on these, a high frequency radar and a new system for detection of tsunami waves based on GNSS signals. The real-time detection software developed by ONC is detailed in a separate article from this conference.

1. Introduction

The coast of British Columbia has a rich history of tsunamis that is present in the oral history of the local First Nations (Nuu-chah-nulth First Nations communication during IdeaFest 2015, Ludwin et al. 2005). The occurrence of a great earthquake in 1700 due to the rupture of the Cascadia subduction megathrust off the west coast is recognized in First Nations oral histories and in the coastal and offshore paleoseismic sedimentary record; the impact of this tsunami that crossed the Pacific was recorded in historical documents in Japan (e.g. Satake et al., 2003).

Recent studies indicate there is a 40-80% probability over the next 50 years that a significant tsunami will impact the British Columbia (BC) coast, generating run-up higher than 1.5 m (Leonard et al., 2014). The probability for more damaging run-up higher than 3 m varies between 10 and 30% in 50 years. These probabilities consider local and far-field events, earthquakes and large submarine landslide sources, and are based on historical, paleotsunami and paleoseismic data as well as modelling and empirical relations between source and tsunami (Leonard et al., 2014). Modelling by Cherniawsky et al. (2007) using a simple source model indicates that a megathrust earthquake on the Cascadia subduction zone could produce run-up exceeding 10-15 m in some areas.

There are several water level stations currently operating that can record tsunamis offshore Canada's west coast. Some of these sensors are designated for tsunami warning while others are part of the Permanent Water Level Network (PWLN) (IOC, 2011). These systems are operated by the Canadian Hydrographic Service (Fisheries and Oceans Canada) and the Water Survey of Canada (Environment Canada). In addition to the land stations of the Canadian National Seismograph Network, seismic data are continuously collected by several broadband ocean bottom seismographs on the cabled ocean observatories offshore Vancouver Island (IOC, 2011). These data are transferred directly to the Incorporated Research Institutions for Seismology (IRIS). The tsunami detection system in the Pacific operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) is designed for far-field tsunamis with sources around the Pacific Rim distant from BC (e.g. Rabinovich et al., 2006). The National Tsunami Warning Centre (NTWC) at Palmer, Alaska issues the alerts that are locally disseminated by Emergency Management British Columbia (EMBC), the agency responsible for issuing tsunami warnings to local authorities and the public (IOC, 2011). However, the detection system is not designed to provide rapid response for a near-field tsunami generated by the Cascadia megathrust, which requires less than 20 minutes of warning between the start of an event and the wave impact on the western shoreline of Vancouver Island (Cherniawsky et al., 2007).

Ocean Networks Canada (ONC), a not-for-profit society established by the University of Victoria, operates several cabled ocean observatories offshore Vancouver Island, in the Strait of Georgia, and in the Arctic and Atlantic. Currently, ONC is developing a new generation of ocean observing systems (referred to as Smart Ocean Systems™), advanced undersea observation technologies, data networks and analytics.

The ONC Tsunami project is a Smart Ocean Systems™ initiative in collaboration with IBM Canada and the University of Victoria. The Tsunami project addresses the need for a near-field tsunami detection system for the coastal area of British Columbia. The NEPTUNE cabled ocean observatory, operated by ONC off the west coast of British Columbia, can be used to detect near-field tsunami events with existing instrumentation including seismometers and bottom pressure recorders (Thomson et al., 2011, Taylor et al. 2012, Figure 1). The incorporation of new sensors such as high-frequency coastal radar will provide the ability to directly detect, measure and profile incoming tsunami waves (Dzvonkovskaya et al., 2009; Gurgel et al., 2011).

Three major challenges are identified for the implementation of a near-field tsunami detection and forecast system on the BC coast: 1) limited availability of bathymetric and topographic data, which is proprietary in some cases; 2) inadequate definition of fault mechanics and rupture scenarios and the need for real-time source definition in the case of a Cascadia megathrust earthquake; and 3) the need for benchmark testing of existing tsunami wave models, using relevant local case conditions, to compare and refine techniques and results (Insua and Moran, 2014). Another important need is the development of new technology (hardware and software) for near-field tsunami detection.

The Tsunami project is designed to conduct high-speed analyses of sensor data in the case of a near-field tsunami accompanying a Cascadia megathrust earthquake and to combine these data with cutting edge technology and tsunami model algorithms to simulate the inundation impact onshore. This project leverages the assets of ONC's sensor array, data collection infrastructure and supercomputing infrastructure to perform high-speed data analyses that support advanced tsunami detection and modelling for the coast of British Columbia.

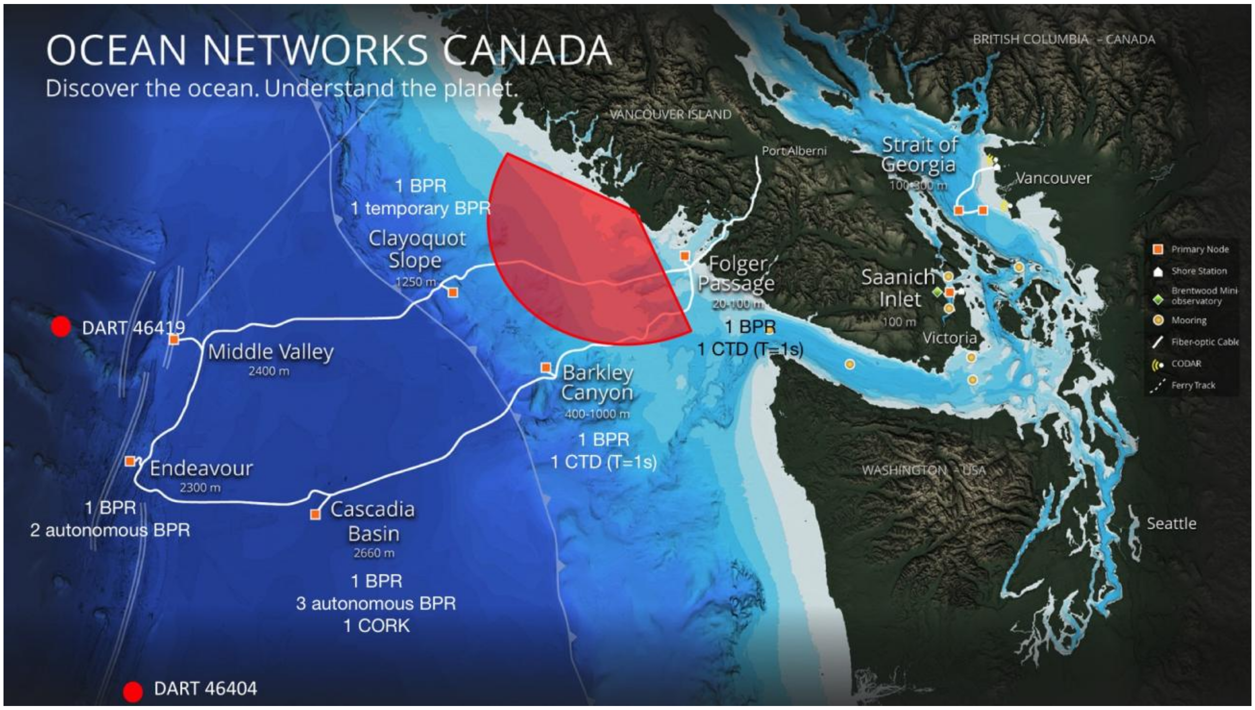

Fig. 1 – NEPTUNE observatory and DART (Deep-ocean Assessment and Recording of Tsunamis) sensors available for tsunami detection offshore British Columbia (red shape indicating high-frequency WERA RADAR). BPR: bottom pressure recorder; CTD: Conductivity-Temperature-Depth sensor, CORK: Circulation Obviation Retrofit Kit sensor

2. Major active components of the Tsunami Project

The Tsunami project comprises several sub-projects that cover tsunami detection, tsunami forecast, and inundation mapping that will help to build resilience in British Columbia communities. Some of these projects are currently active and they are the gateway for future developments. Here we provide an overview of the major components and recent advances. Another article in this same conference provides detailed information about the real time detection for tsunamis implemented as part of the Web-enabled Awareness Research Network (WARN) project.

2.1. Bathymetry and topography data fusion

One of the major limitations for tsunami inundation forecasting in the area of British Columbia is the availability of bathymetry and topography data as well as their combination following international standards.

Tsunami inundation prediction requires a representation of the Earth's surface in the form of a digital elevation model (DEM). To create a DEM, existing digital bathymetric and topographic data are utilized; this dataset is generally not extensive enough to provide a simple grid based on the raw elevation points. The existing data points are used as input to calculate a model. Where the data density is higher, subsampling may be used; where it is lower, an interpolation algorithm can calculate values at the grid points or even extrapolate in areas with little or no data. The resulting DEM is a gridded surface model of the Earth at the resolution of the grid spacing. The aim of this project is to design, and then implement, a prototype system to provide the required Digital Elevation Models (DEMs) along with uncertainty estimates.

The combination of datasets usually generates major discontinuities and artefacts at the borders of datasets from different sources that usually also have different resolutions. The fusion of datasets from different sources can be challenging and the methodology used needs to avoid the creation of artefacts during the fusion process.

The processing of high-density data with the Combined Uncertainty and Bathymetry Estimator (CUBE) provides grids with uncertainty (QPS, 2014; Calder and Wells, 2007). These grids can be used in conjunction with two other approaches that can provide lower resolution datasets with uncertainty values and fuse datasets while minimizing artefacts. The two major techniques currently being implemented in this software are: the three-step approach and overlapping tiles.

Elmore and Steed (2008) recommended a three-step approach (TSA) for the fusion of gridded and sounding archival datasets. This solution is based on creating DEMs from archival soundings with associated uncertainty (Ryan et al., 2009). In this project we are also examining an alternate overlapping tiles approach to storing and blending datasets (Ryan et al., 2009). The TSA uses archived datasets with the intention of fusing them into a gridded DEM with associated uncertainty. The archival data points can be soundings or gridded DEM. The sounding data require associated horizontal uncertainty values and the gridded data are assumed to have associated vertical uncertainty. The resulting DEMs have low resolution, produced from sparse data. This method is not designed to process high-density data. High-density data can be gridded utilizing other methods, for example CUBE (Calder and Wells, 2007). However, high-quality data sets can be used as an input to TSA to estimate the archival data measurement error.

The combination of all the bathymetry and topography data available for British Columbia into one large dataset represents a computational challenge. A manageable solution is the partition of the area into tiles 5% larger than required. In this way the tiles will have an overlapping border that allows calculations to cross tile edges. Data can be added to a tile and the merged dataset re-gridded while maintaining smooth transitions between different tiles (Ryan et al., 2009).

Assessment of the data uncertainties for this project is initially based on a Monte-Carlo approach (Calder, 2006) to simulate multiple virtual datasets from the archive data to provide an estimate of the error magnitude. This approach allows the user to decide which dataset is hierarchically more important when no other information is available. The calculation of the uncertainty is also important for an understanding of the limitations in the wave propagation model output since different grid sizes are known to affect the calculation of wave-generated currents (NTHMP, 2015). The objective of this project is to develop new software that will automatically generate the best DEM possible with the datasets available for the area following the requirements of the user.

2.2. Source modelling and wave propagation

In predicting local coastal inundations caused by tsunami waves generated by a nearby subduction earthquake, the source model, or fault rupture scenario, presents the most critical information. For long-term tsunami risk analysis and real-time tsunami warning, multiple scenarios of megathrust rupture encompassing different fault geometries, slip magnitudes, and along-fault slip distributions are needed.

As part of the Tsunami project, we are developing a suite of ~20 source rupture models of the northern Cascadia subduction zone. These models are based on the best available knowledge of the geologic/tectonic structure of the subduction zone and the physics of seismic rupture processes.

These source models are developed in four steps, of which currently two are being accomplished. First, a new digital geometric model of the northern Cascadia megathrust will be developed. Existing megathrust models for Cascadia are confined to south of the Nootka Fault zone (NFZ). Recent geophysical observations have shown unambiguously that the segment of the plate boundary north of the NFZ where the Explorer plate subducts beneath North America is also capable of tsunamigenic megathrust rupture. The new fault model includes the Explorer segment on the basis of the latest structural knowledge from analysis of recorded seismic waves. This model also accounts for different scenarios of fault branching near the deformation front based on existing geophysical imaging data. Second, a 2D finite element thermal model is under development for the Explorer segment to define the downdip extent of the seismogenic rupture. The thermal structure of northern Cascadia south of the NFZ is one of the best studied in the world (e.g., Gao and Wang, 2014). This experience can be readily applied to the Explorer segment where the subducting plate is younger and the subduction rate is lower. Third, a suite of rupture scenarios will be developed using a 3D dislocation model (Wang et al., 2013). The slip distribution scenarios are constrained by the knowledge of rupture mechanics and observations of recent large tsunamigenic earthquakes such as those at the Sumatra, Chile, and Japan subduction zones. Fourth, the models will be refined through comparison with paleoseismic and paleotsunami observations and modern geodetic observations. For comparison with geodetic observations, the effect of mantle viscoelastic relaxation needs to be taken into account. This effort will be based on the use of a 3D spherical-Earth finite element model (Wang et al., 2012).

Currently the first source models are being tested for wave propagation with the FUNWAVE model (Kirby et al., 1998). This model combines the source model with DEMs of the area that are used as nested grids to provide information about the estimated time of arrival of the wave, wave height for different locations and inundation maps when topographic information is available as well as the phase speeds and particle kinematics. FUNWAVE has a fully non-linear Boussinesq approximation as described in Wei et al. (1995) for the wave propagation equations in coastal areas. This numerical model was benchmarked against other models as part of the U.S. National Tsunami Hazard Mitigation Program (NTHMP, 2015), proving to be one of the most robust models available.

2.3. Tsunami detection and integration of Global Navigational Satellite System signals

The inclusion of GNSS (Global Navigational Satellite System) data is recommended as a key component of a real-time tsunami detection system in British Columbia (ONC, 2014). These data could more accurately identify the tsunami source, and provide key input for the prediction of tsunami inundation. The integration of real-time positional data available from Natural Resources Canada's GNSS network into the Tsunami project will allow for timely and accurate predictions of tsunami inundation in the event of a tsunamigenic subduction earthquake.

The spatial pattern, magnitude, and timing of continuously-recording GNSS stations displaced by a near-field earthquake can be inverted to calculate the source characteristics and to predict the 3-D displacement field of the ocean bottom (Blewitt et al., 2009). With a sufficiently dense network, this technique can accurately provide the initial conditions for tsunami modelling. Alternatively, the displacements of GNSS stations can be compared with the pre-computed predictions of earthquake rupture models in order to rapidly select and scale the best-fit tsunami source model and corresponding inundation predictions. Natural Resources Canada scientists who have laid the groundwork for the incorporation of GNSS data for tsunami early warning (e.g., Henton et al., 2014) are collaborating in this initiative. This project is currently in early stages that include an evaluation of the available data streams, and of the suitability of various available software and techniques for the accurate and robust estimation of coseismic station displacements (e.g., Plag et al., 2012). Natural Resources Canada provides up to 1 Hz positional data for its continuous GNSS stations analyzed with various softwares, with typical uncertainties on the order of a few centimetres and a latency of less than 10 seconds. Fingerprinting techniques are currently under development for rapid comparison of the GNSS displacement field with those predicted from a suite of pre-computed tsunami source models, and selection and scaling of the most appropriate tsunami source-inundation model pair. This method incorporates the a priori tsunami source models produced in another part of this project (see previous section on source modelling). The integration of this type of signal in the case of a near-field tsunami can help to better define the pre-calculated scenario that needs to be dimensioned and reported to the emergency management agencies.

Coastal GNSS stations also have the potential to provide accurate real-time measurements of tsunami amplitude, in order to provide early warning of far-field tsunamis (e.g., from Alaska). Such data collected on the west coast of Vancouver Island could also be used to improve the accuracy of near-field tsunami inundation forecasts in advance of the first wave's arrival at more distant locations such as significant populations on southern and eastern Vancouver Island, and mainland British Columbia. This technique is currently under evaluation to build on recent studies that demonstrate the accuracy of coastal GNSS stations as “tide gauges” (Larson et al., 2013; Löfgren and Haas, 2014).

Therefore this project has a double objective. On the one hand it will allow integration of real-time positional data available from the GNSS network into the Tsunami project, to allow for timely and accurate predictions of tsunami inundation in the event of a near-field tsunamigenic earthquake. On the other hand, it is setting ground for the development of new technology for wave measurements. Both of these objectives are integrated with the capability of detecting and forecasting tsunamis based on ocean observatory systems for British Columbia.

2.4. WERA High-Frequency Radar

High-frequency (HF) radar systems are capable of measuring surface ocean currents with high spatial and temporal resolution. Numerical experiments have demonstrated that HF radar systems can be used as tsunami warning systems for coastal regions with wide continental shelves (Gurgel et al., 2011). Post-event processing of data from the 2011 Tohoku-Oki tsunami shows that HF radar systems are capable of detecting tsunami waves based on radial velocity for the first time (Lipa et al., 2011; Hinata et al., 2011).

New research on HF RADAR systems has indicated their capability to detect tsunami waves on their way to shore in a radius up to 300 km (Grilli et al., 2015). The Tohoku-Oki tsunami in 2011 was detected between 10 and 45 minutes earlier on the HF radar than on coastal tide gauges (Lipa et al., 2011).

As part of this project a new high-frequency Wellen radar (WERA) was installed at the Long Beach Airport, Tofino, British Columbia in March 2015 (Figure 2). This system is currently operating at a transmitting frequency of 13.5 MHz. The Tofino WERA is composed of twelve 3 m RX antennas spaced 10.1 m apart and four 5.1 m TX antennas arranged in a rectangle of 11.1 m by 5.5 m. Once fully operational, this system operates at 33.3 seconds/sample and the output will be integrated over 2 min time intervals.

Fig. 2 – WERA system installed in Long Beach Airport, Tofino, British Columbia

Three different major methods were used in the past for the detection of tsunamis with HF radar: 1) direct observation of current velocities based on signals from two radar systems combined; 2) analysis of the radial components from a single radar system and 3) frequency shifts in the Doppler spectrum of the radar echo (Murata et al., 2010; Lipa et al., 2011). The distance, and therefore the time before coastal arrival, at which the wave is detected are highly dependent on the bathymetry and extension of the continental shelf in the area (Lipa et al., 2011). These approaches have the limitation of detecting tsunami currents only down to a certain velocity (10-15 cm/s) therefore limiting the use of this technology to near-shore areas with an extended shelf. A new algorithm developed by Grilli et al. (2015) is able to detect tsunami currents as low as 5 cm/s therefore allowing more effective detection. This algorithm takes advantage of the correlations between HF radar signals at two different locations shifted in time proportionally to the propagation time from the tsunami source (Grilli et al., 2015).

During the first testing after deployment the system demonstrated the capacity of detecting wave heights up to 100 km offshore Tofino (Figure 3).

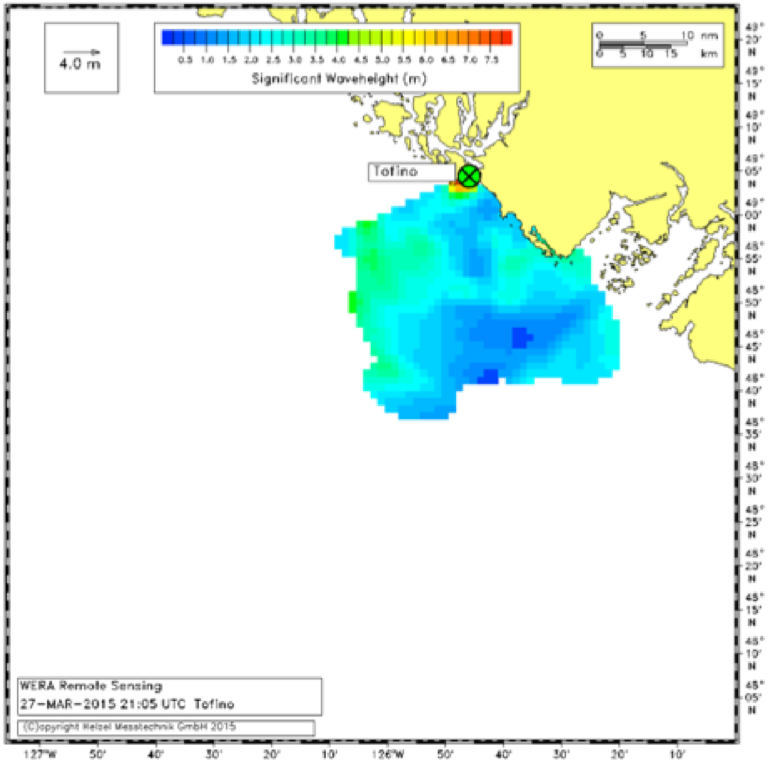

Fig. 3 – WERA system coverage on the first test

Data are currently being received and stored for this system. New algorithms for automatic detection of tsunamis are currently being developed for the WERA and will be integrated into the tsunami detection system of this project.

3. Summary

The ongoing tsunami initiative for British Columbia is combining efforts from different local, provincial and federal agencies and universities at a national and international level to leverage the infrastructure and data available in the area for near-field tsunami detection and forecast. The components presented in this article constitute some of the major initiatives currently under development for tsunami science and real-time detection on the west coast of Canada.

The first results from some of these projects are expected in 2015 and they will provide a basis for further development. This is part of an extended project that will take place over several years and will evolve based on research advances.

The capabilities under development will aid real-time tsunami detection and the provision of alerts to emergency managers as well as helping local communities to strengthen their resilience to geohazards. This research will also be used to develop new tsunami detection systems that can be implemented for the benefit of society.

4. Acknowledgements

The authors would like to thank Emergency Management B.C., IBM Canada, Western Economic Diversification and Transport Canada for their support on this project. We would also like to thank Dr. Jeffrey Harris for his assistance on the implementation and running of the wave propagation model in the Ocean Networks Canada Systems and the Ocean Networks Operations team, in particular Jarrett Little, Ian and Tori Kulin and Lucy Hurlbut for the deployment and images of the WERA system. Data used in this work were provided by Ocean Networks Canada.

5. References

BLEWITT, G., HAMMOND, W.C., KREEMER, C., PLAG, H-P., Stein, S. and Okal, E. "GPS for real-time earthquake source determination and tsunami warning systems." *Journal of Geodesy* 83, no. 3-4 (2009): 335-343.

CALDER, Brian. "On the uncertainty of archive hydrographic data sets." Oceanic Engineering, IEEE Journal of 31.2, 2006: 249-265.

CALDER, B., WELLS, D. CUBE User Guide V1.13. January 2007, [Online]. Available: http://ccom.unh.edu/sites/default/files/publications/Calder_07_CUBE_User_Manual.pdf

CHERNIAWSKY, Josef Y., TITOV, Vasily V., WANG, Kelin and LI, Jing-Yang. "Numerical simulations of tsunami waves and currents for southern Vancouver Island from a Cascadia megathrust earthquake." *Pure and Applied Geophysics* 164, no. 2-3, 2007: 465-492.

DZVONKOVSKAYA, Anna, GURGEL, K-W., POHLMANN, Thomas, SCHLICK, Thomas and XU, Jiangling. "Tsunami detection using HF radar WERA: A simulation approach." In *Radar Conference-Surveillance for a Safer World, 2009. RADAR. International*, IEEE, 2009: 1-6.

ELMORE, Paul and STEED, Chad A. “Algorithm design study for bathymetry fusion-review of current state-of-the-art and recommended design approach.” *Naval Research Lab Stennis Space Center M.S. Marine Geosciences Division,* No. NRL/FR/7440--08-10162, 2008.

GAO, X. and WANG, K. “Strength of stick-slip and creeping subduction megathrusts from heat flow observations.” *Science* 345, 1038, 2014; DOI: 10.1126/science.1255487

GRILLI, Stéphan T., GROSDIDIER, Samuel and GUÉRIN, Charles-Antoine. "Modelling of Tsunami Detection by High Frequency Radar Based on Simulated Tsunami Case Studies in the Mediterranean Sea." *ISOPE 2015 International Conference*, Kona, HI, June 2015

GURGEL, Klaus-Werner, DZVONKOVSKAYA, Anna, POHLMANN, Thomas, SCHLICK, Thomas and GILL, Eric. "Simulation and detection of tsunami signatures in ocean surface currents measured by HF radar." *Ocean Dynamics* 61, no. 10, 2011: 1495-1507.

HENTON, J.A., DRAGERT, H. and LU, Y. “Real-time GNSS positioning along Canada’s active coastal margin”, *2014 AGU Annual Fall Meeting*, San Francisco, December 2014.

HINATA, Hirofumi, FUJII, Satoshi, FURUKAWA, Keita, KATAOKA, Tomoya, MIYATA, Masafumi, KOBAYASHI, Takashi, MIZUTANI, Masahiro, KOKAI, Takahiro and KANATSU, Nobuyoshi. "Propagating tsunami wave and subsequent resonant response signals detected by HF radar in the Kii Channel, Japan." *Estuarine, Coastal and Shelf Science* 95, no. 1, 2011: 268-273.

INSUA, Tania L., and MORAN, Kate. "Detecting Near-Field Tsunamis off the Coast of British Columbia." *Eos, Transactions American Geophysical Union* 95, no. 37 (2014): 336-336.

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISION (IOC) “Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS) Twenty-fourth session”. *Reports of Governing and Major Subsidiary Bodies. UNESCO, 2011*

KIRBY, James T., WEI, Ge, CHEN, Qin, KENNEDY, Andrew B. and DALRYMPLE, Robert A. *Funwave 1.0: Fully Nonlinear Boussinesq Wave Model-Documentation and User's Manual*. University of Delaware, 1998.

LARSON, K.M., LÖFGREN, J.S., and HAAS, R. “Coastal sea level measurements using a single geodetic GPS receiver.” *Advances in Space Research,* 51, 2013: 1301-1310

LEONARD, Lucinda J., ROGERS, Garry C., and MAZZOTTI, Stephane. "Tsunami hazard assessment of Canada." *Natural Hazards* 70 2014: 237-274.

LIPA, Belinda, BARRICK, Donald, SAITOH, Sei-Ichi, ISHIKAWA, Yoichi, AWAJI, Toshiyuki, LARGIER, John and GARFIELD, Newell. "Japan tsunami current flows observed by HF radars on two continents." *Remote Sensing* 3, no. 8 2011: 1663-1679.

LÖFGREN, J.S., and HAAS, R. “Sea level measurements using multi-frequency GPS and GLONASS observations.” *EURASIP Journal on Advances in Signal Processing* 50, 2014: 1-13

LUDWIN, Ruth S., DENNIS, Robert, CARVER, Deborah, MCMILLAN, Alan D., LOSEY, Robert, CLAGUE, John, JONIENTZ-TRISLER, Chris, BOWECHOP, Janine, WRAY, Jacilee and JAMES, Karen. "Dating the 1700 Cascadia earthquake: great coastal earthquakes in Native stories." *Seismological Research Letters* 76, no. 2, 2005: 140-148.

MURATA, Yasuhiro, NAGAKURA, Toshiro and KOKAI, Takahiro. "Tsunami early detection: enhanced resolution of HF oceanographic radar." *Coastal Engineering Proceedings* 1, no. 32, 2011: currents-4.

NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM (NTHMP), Annual meeting, http://nws.weather.gov/nthmp/2015annualmeeting/index.html, Portland, 2015

OCEAN NETWORKS CANADA (ONC), “A tsunami detection initiative for British Columbia”. Workshop report, 2014. http://www.oceannetworks.ca/science/getting-involved/workshops/tsunami-workshop-2014

PLAG, H-P., BLEWITT, Geoff and BAR-SEVER, Yoaz. "Rapid determination of earthquake magnitude and displacement field from GPS-observed coseismic offsets for tsunami warning." *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International*, IEEE, 2012: 1182-1185

QPS hydrographic and marine software solutions. CUBE Algorithm. December 2014. [Online]. Available: https://confluence.qps.nl/display/KBE/CUBE+Algorithm

RABINOVICH, Alexander B., THOMSON, Richard E. and STEPHENSON, Fred E.. "The Sumatra tsunami of 26 December 2004 as observed in the North Pacific and North Atlantic oceans." *Surveys in Geophysics,* 27, no. 6, 2006: 647-677

RYAN, William BF, CARBOTTE, Suzanne M., COPLAN, Justin O., O'HARA, Suzanne, MELKONIAN, Andrew, ARKO, Robert, WEISSEL, Rose Anne, FERRINI, Vicki, GOODWILLIE, Andrew, NITSCHE, Frank, BONCZKOWSKI, Juliet and ZEMSKY, Richard. "Global multi-resolution topography synthesis." *Geochemistry, Geophysics, Geosystems* 10, no. 3, 2009.

SATAKE, Kenji, WANG, Kelin and ATWATER, Brian F. “Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions”. Journal of Geophysical Research 108(B11), 1535, 2003.

TAYLOR, S. Martin, MCLEAN, Scott, MORAN, Kate, THOMSON, Richard and LINTERN, Gwyn. "Ocean Networks Canada near-field Tsunami research facility." In *Oceans, 2012-Yeosu, IEEE*, 2012: 1-5.

THOMSON, Richard, FINE, Isaac, RABINOVICH, Alexander, MIHÁLY, Steve, DAVIS, Earl, HEESEMANN, Martin and KRASSOVSKI, Maxim. "Observation of the 2009 Samoa tsunami by the NEPTUNE-Canada cabled observatory: Test data for an operational regional tsunami forecast model." *Geophysical Research Letters* 38, no. 11, 2011: 1-5.

WANG, Kelin, HU, Yan and HE, Jiangheng. "Deformation cycles of subduction earthquakes in a viscoelastic Earth." *Nature* 484, no. 7394, 2012: 327-332.

WANG, Pei-Ling, ENGELHART, Simon E., WANG, Kelin, HAWKES, Andrea D., HORTON, Benjamin P. NELSON, Alan R., and WITTER, Robert C. "Heterogeneous rupture in the great Cascadia earthquake of 1700 inferred from coastal subsidence estimates." *Journal of Geophysical Research: Solid Earth* 118, no. 5, 2013: 2460-2473.

WEI, Ge, KIRBY, James T., GRILLI, Stephan T. and SUBRAMANYA, Ravishankar. "A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves." *Journal of Fluid Mechanics* 294, 1995: 71-92.