# Ocean Networks Canada Society

# Earthquake Early Warning System

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# Introduction

This section is intended to provide an overview of the project.

## 1.1. Project Administration

### Project team

*Table 1. A summary of the full project team, including all current and former staff, who have contributed to the success of this project. Staff are listed in accordance to their level of involvement (from top to bottom) within specific roles, followed by relevant supervisors.*

| Role | Name | Title |
|---|---|---|
| **Project Sponsor** | Benoit Pirenne | Director, User Engagement |
| **Stakeholder Manager** | Teron Moore | Public Safety Program Manager |
| **Science Consulting** | Andreas Rosenberger | Science Consultant, Arescon Research Ltd. |
| | Martin Heeseman | Senior Staff Scientist |
| **Project Manager** | Jessica Robinson | Project Manager |
| *(former)* | Ivan Rincon | Program Manager, PMO |
| **Field Operations** | Ryan Key | Project Engineer |
| | Degnan Hembroff | Project Engineer |
| | Chad Gunderson | Senior Marine Equipment Specialist |
| | Brian Kaltenberger | Marine Equipment Specialist |
| | Chris Sanii | Marine Equipment Specialist |
| | John Dorocicz | Project/Software Engineer |
| *(former)* | Evan Poulton | Project Engineer |
| | Marc Christensen | Co-op student |
| | Dirk Brussow | Project Engineer |
| | Jeb Dexter | Project Engineer |
| | William Glatt | Marine Equipment Specialist |
| *(former)* | Ian Beliveau | Project Engineer |
| | Kevin Bartlett | Marine Equipment Specialist |
| | Albert Ruskey | Project Engineer |
| | Philippe Janicki | Co-op student |

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|---|---|---|
| | Grant Tingstad | Co-op student |
| | Alex Brown | Co-op student |
| | Allan Stenlund | Co-op student |
| *(former)* | Paul Macoun | Field Services Manager |
| | Jeff Bosma | Testing and Development Manager |
| | Ian Kulin | Director, Marine Operations |
| | Adrian Round | Director, Observatory Operations |
| **System Operations Specialist** | Seann Wagner | Observatory Systems Analyst |
| *(former)* | Martin Hoffman | Systems and Operations Manager |
| | Shane Kerschtien | Observatory Systems Manager |
| **Data Stewardship and Operations Support** | Reyna Jenkyns | Data Stewardship Manager |
| | Nadia Kreimer | Data Steward |
| | George Parker | Data Steward |
| | Christine Adams | Data Steward |
| *(former)* | Ross Timmerman | Data Steward |
| | Meghan Tomlin | Data Steward |
| | Karen Douglas | GIS Specialist |
| | Mark Rankin | GIS Specialist |
| **Data Team** | Michael Morley | Data Manager |
| | Angela Schlesinger | Scientific Data Specialist |
| | Jeannette Bedard | Data Specialist |
| *(former)* | Marlene Jeffries | Data Manager |
| **Software Development** | Eli Ferguson | Software Developer |
| | Tim Choo | Software Developer |
| *(former)* | Mitozcelle Valenzuela | Senior Software Developer |
| | Tim Lavallee | Senior Software Developer |
| | Yingsong Zheng | Senior Software Testing Engineer |
| | Patrick Conley | Software Developer |
| | Tony Lin | Software Developer |
| | Ben Biffard | Senior Scientific Programmer |

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|---|---|---|
| | Becky Croteau | Software Developer |
| | Michael Thorne | Software Developer |
| *(former)* | Alex Lam | Software Developer |
| | Yan Chen | Senior Software Developer |
| | Kiersten Mort | Software Developer |
| *(former)* | Conner McConkey | Software Developer |
| *(former)* | Johanna MacLeod | Software Developer |
| | Jonathan Cheng | Software Developer |
| *(former)* | Nick Houghton | Software Developer |
| *(former)* | Emil Jafarli | Software Developer |
| *(former)* | Helen He | Software Developer |
| | Melissa MacArthur | Senior Software Developer |
| | Nathan Hogman | Software Developer |
| | Nick Allen | Software Developer |
| | Ryan Hotte | Software Developer |
| *(former)* | Mac Button | Software Developer |
| *(former)* | Joshua Stelting | Co-op student |
| *(former)* | Stephen Tredger | Co-op student |
| *(former)* | Kyle Gering | Co-op student |
| *(former)* | Kyle Newman | Co-op student |
| | Wenli Huang | Co-op student |
| *(former)* | Murray Leslie | Software Testing Engineer |
| *(former)* | Daisy Qi | Software Testing Engineer |
| | Eric Guillemot | Associate Director, Software Engineering |
| **System Analysis** | Bob Crosby | System Analyst |
| *(former)* | Megumi Patchett | Research Analyst Intern |
| *(former)* | Ziming Wang | Research Analyst Intern |
| **Permit Officer** | Karen Hamilton | PMO Administrator |
| **Administrative Support** | Marja Blase | Office Administrator |
| *(former)* | Scott Trivers | Operations Support Specialist |

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|---|---|---|
| *(former)* | Ryan Rutley | Operations Support Specialist |
| | Nathan Deis | Junior Operations Support Specialist |
| | Polly Tordova | Purchaser |
| | Matthew Uganecz | Operations Support Manager |
| | Lyuba Goundareva | Corporate Services Coordinator |
| | Corrine Aarsen | Corporate Services Administrator |
| *(former)* | Janet Powers | Office Administrator |
| *(former)* | Emily Boulter | PMO Assistant Intern |
| *(former)* | Scott McLean | Director, Innovation |
| **Financials** | Brigitte Boutin | Chief Finance and Operating Officer |
| | Sandy Bligh | Chief Finance Officer |
| | Kimberly Vincent | Finance Manager |
| *(former)* | Beverley Goodridge | Finance Manager |
| *(former)* | Joyce Coleman | Finance Manager |
| | Caroline Robinson | Accounting Clerk |
| *(former)* | Janet Stear | Senior Accounting Coordinator |
| | Ellen Sark | Accounting Clerk |
| | Lana Benger | Accounting Coordinator |
| *(former* | Leslie Chiang | Accounting Coordinator |
| *(former)* | Binghui (Kelly) Yu | Accounting Coordinator |
| *(former)* | Niranjala Storm | Accounting Coordinator |
| **First Nations Engagement** | Maia Hoeberechts | Associate Director, Learning and Community Engagement |
| | Monika Pelz | Education Coordinator |
| | Pieter Romer | Indigenous Community Liaison |
| *(former)* | Jessica Brown | Indigenous Community Liaison |
| | Dave Riddell | Post-Secondary Education Coordinator |

## 1.2. Background

In March 2016, the Government of the Province of British Columbia awarded $5M to Ocean Networks Canada to develop an integrated earthquake early warning system (EEWS) for southwestern British Columbia. The earthquake early warning system was developed to provide timely detection of earthquake events that occur in or near the Cascadia Subduction Zone near Vancouver Island.

In its implementation of the project, ONC expanded and enhanced its current network of seismic sensors by deploying instrumentation in offshore and land-based areas near and on Vancouver Island, close to the subduction zone. ONC integrated its existing seismic network along with networks owned and operated by other agencies (Natural Resources Canada, Pacific Northwest Seismic Network).

Through improvements in its epicentre and magnitude determination software, ONC allows for timely notifications of earthquake events to be delivered to various stakeholders within the Province. The aim of the earthquake early warning system is to contribute towards the future development of a comprehensive earthquake early warning system within the Province that provides the means for early detection of multiple types of earthquake events and provides notification tools for the public.

The work performed by ONC over the course of the project implementation phase included: sensor installation off-shore, sensor installation on Vancouver Island on NRCan sites, sensor installation on Vancouver Island in new locations, implementation and installation of p-wave detection software and computers at all sites, improvement of epicentre and magnitude determination software, improvement of notification software, introduction of redundant computer centres, setup of system control and data quality monitoring for the facility, and overall tests of the system.

The implementation of the earthquake early warning system under this contract provides a fast (<3 seconds on average) first estimate of the event's epicentre location and magnitude estimate after a 4th site has detected the primary wave. For a subduction zone area event offshore, this translates to about a minute of warning time for recipients of the notification in Victoria or Vancouver. This allows for reactions to the event according to pre-programmed disaster mitigation workflow specific to each recipient.

With a focus on Cascadia subduction events, ONC's earthquake early warning system is in a position to qualify earthquakes included in the detection zone (Figure 3). This area corresponds to the system's best sensitivity and to events that will provide a significant warning time given the instrument locations.

Out of scope for detection (and therefore warning) would be areas that are to the south or to the north of Vancouver Island, or are too close to Victoria or the lower mainland. The integration of the Pacific Northwest Seismic Network sensors operationally would allow for a significant extension of the coverage area, mostly to help detect events occurring in Washington State or Oregon with potential impact on southwestern British Columbia.

## 1.3. Location

Figures 1-3 indicate the location of the sensors.


*Figure 1: A high-level view of the final earthquake early warning system network, where fully installed stations are indicated by a green symbol.*

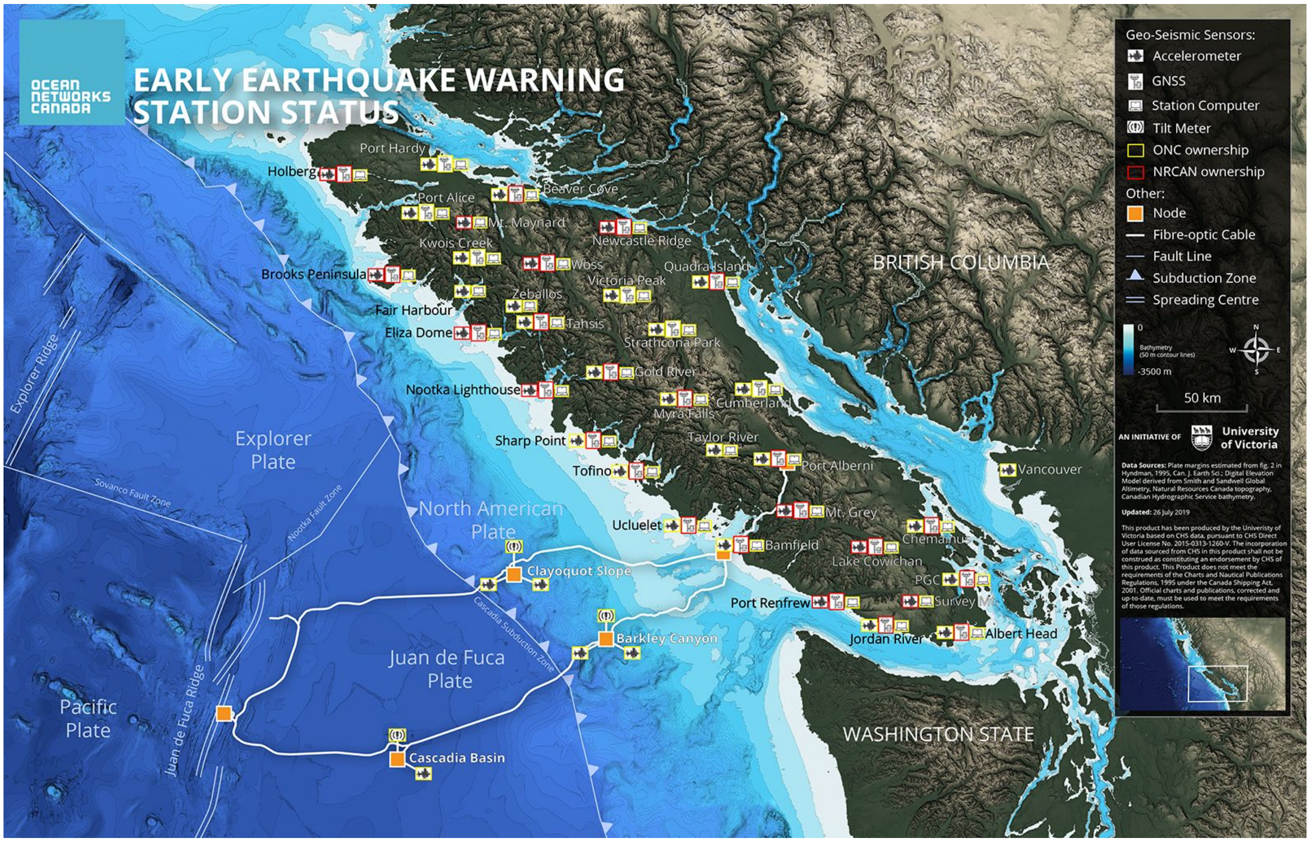


*Figure 2. A detailed view of the final earthquake early warning system station components, where instruments are indicated by a corresponding symbol identified in the legend at the top right hand corner. Icons are bordered by either a yellow (ONC-owned) or red (Natural Resources Canada-owned) box to indicate ownership.*


*Figure 3. The current earthquake early warning system detection zone. Events that occur outside of this boundary are rejected and will not result in a notification. Please note that this map does not include the zone of Washington State and Oregon that the addition of detection data from the Pacific Northwest Seismic Network would allow us to detect earthquakes in.*

## 1.4. Summary

### 1.4.1. Station Installation

Over the course of three years, ONC has installed 36 land-based and eight seafloor stations, with a total number of approximately 107 devices. These stations are equipped with core components that include accelerometers, Global Navigation Satellite Systems (GNSS) and central processing units in order to measure ground shaking, provide accurate geospatial positioning and perform key calculations, respectively. The land-based subsystems comprise joint Natural Resources Canada (NRCan) and ONC components, and also include ONC-only managed sites.

*Table 2. EEWS station summary, including offshore sites and both ONC owned and ONC/NRCan shared land-based sites.*

| Station Code | Location Name | Coordinates | | | Instruments S/N | Status | | Ownership |
|---|---|---|---|---|---|---|---|---|
| | | Latitude (°) | Longitude (°) | Elevation (m) | | Seismic | Geo-detic | |
| AL2H | Albert Head | 48.38981 | -123.48739 | 29 | • Nanometrics Titan SMA (S/N 000619)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016127 Trimble<br>• Antenna Chokering TRM59800 SN 5112354071 | Completed | Completed | ONC-NRCan |
| BAMF | Bamfield | 48.83533 | -125.13514 | 9 | • Nanometrics Titan SMA (S/N 000637)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3015944 Septentrio<br>• Antenna Chokering B3/E6 SN 5120 | Completed | Completed | ONC-NRCan |
| BCOV | Beaver Cove | 50.54427 | -126.84264 | 36 | • Nanometrics Titan SMA S/N 000349)<br>• Septentrio PolaRx5 UNAVCO GNSS<br>• Receiver SSID 3016104 Septentrio Antenna Chokering B3/E6 SN 5122 | Completed | Completed | ONC-NRCan |
| BPEB | Brooks Peninsula | 50.15662 | -127.77188 | 730 | • Nanometrics Titan (S/N 002582)<br>• Nanometrics Centaur (S/N 1036)<br>• Septentrio PolaRx5 GNSS Receiver SSID | Completed | Completed | ONC-NRCan |

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|---|---|---|---|---|---|---|---|---|
| | | | | | 3016170<br>• Septentrio Antenna Chokering B3/E6 SN 5117 | | | |
| SC04 | Chemainus | 48.9233 | -123.70432 | 15 | • Nanometrics Titan SMA (S/N 000635)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016004<br>• Septentrio Antenna Chokering B3/E6 SN 5148 | Completed | Completed | ONC-NRCan |
| CMBR | Cumberland | 49.59497 | -125.01135 | 328 | • Nanometrics Titan SMA (S/N 000636)<br>• Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018552<br>• Septentrio Antenna Chokering B3/E6 SN 5158 | Completed | Completed | ONC |
| ELIZ | Eliza Dome | 49.87311 | -127.12162 | 150 | • Nanometrics Titan (S/N 1109)<br>• Nanometrics Centaur (S/N 2598)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016090<br>• Septentrio Antenna Chokering B3/E6 SN 5133 | Completed | Completed | ONC-NRCan |
| FAHB | Fair Harbour | 50.22639 | -127.20324 | 10 | • Nanometrics Titan SMA (S/N 000842) | Planned | N/A | ONC |
| GLDR | Gold River | 49.68181 | -126.12726 | -11 | • Nanometrics Titan SMA (S/N 000844)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016119<br>• Septentrio Antenna Chokering B3/E6 | Completed | Completed | ONC-NRCan |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | SN 5141 | | | |
| HOLB | Holberg | 50.64019 | -128.13314 | 547 | • Nanometrics Titan (S/N 000945)<br>• Nanometrics Centaur (S/N 1873)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016155<br>• Septentrio Antenna Chokering B3/E6 SN 5130 | Completed | Completed | ONC-NRCan (hardware update required by NRCan) |
| JORD | Jordan River | 48.43303 | -124.05387 | 96 | • Nanometrics Titan SMA (S/N 000618)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3015949<br>• Septentrio Antenna Chokering B3/E6 SN 5144 | Completed | Completed | ONC-NRCan (comms to be set up by ONC) |
| KWOI | Kwois Creek | | | | • Nanometrics Titan SMA (S/N 000782)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3018540<br>• Septentrio Antenna Chokering B3/E6 SN 5166 | In progress | In progress | ONC |
| CLRS | Lake Cowichan | 48.82032 | -124.1309 | 174 | • Nanometrics Titan (S/N 000943)<br>• Nanometrics Centaur (S/N 1867)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016152<br>• Septentrio Antenna Chokering B3/E6 SN 5134 | Completed | Completed | ONC-NRCan |
| MGRB | Mount Grey | 48.99973 | -124.69705 | 1310 | • Nanometrics Titan (S/N 001110) | Completed | Completed | ONC-NRCan |

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|---|---|---|---|---|---|---|---|---|
| | | | | | • Nanometrics Centaur (S/N 2082)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3015935<br>• Septentrio Antenna Chokering B3/E6 SN 5121 | | | |
| MAYB | Mount Maynard | 50.40253 | -127.17368 | 1481 | • Nanometrics Titan (S/N 001119)<br>• Nanometrics Centaur (S/N 2570) | Complete | N/A | ONC-NRCan (hardware updated required by NRCan) |
| MYRA | Myra Falls | 49.5509 | -125.57053 | 626 | • Nanometrics Titan SMA (S/N 000357)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016053<br>• Septentrio Antenna Chokering B3/E6 SN 5145 | Completed | Completed | ONC-NRCan |
| BACME.W1 | NEPTUNE - Barkley Canyon Mid East | 48.314654 | -126.058199 | -897 | • Nanometrics TitanEA (S/N 000143) | Completed | N/A | ONC |
| BACND.Z1 | NEPTUNE - Barkley Canyon Node | 48.34594 | -126.15802 | -643 | • RBRconcerto Tilt Meter ACC.BPR 63056 | Completed | N/A | ONC |
| NCBC.W1 | NEPTUNE - Barkley Canyon Upper Slope | 48.42661 | -126.174726 | -395 | • Nanometrics TitanEA (S/N 000646) | Completed | N/A | ONC |
| CBC27.W1 | NEPTUNE - Cascadia Basin | 47.756685 | -127.731932 | -2661 | • Nanometrics TitanEA (S/N 000788) | Completed | N/A | ONC |
| CBC27.Z1 | NEPTUNE - Cascadia Basin | 47.756717 | -127.731602 | -2656 | • RBRconcerto Tilt Meter ACC.BPR 63057 | Completed | N/A | ONC |
| CQS64.W1 | NEPTUNE - Clayoquot Slope | 48.699718 | -126.872618 | -1318 | • Nanometrics TitanEA (S/N 000787) | Completed | N/A | ONC |
| NC89.W1 | NEPTUNE | 48.670473 | -126.847701 | -1259 | • Nanometrics | Completed | N/A | ONC |

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|---|---|---|---|---|---|---|---|---|
| | - Clayoquot Slope Bullseye | | | | TitanEA (S/N 000647) | | | |
| NC89.Z1 | NEPTUNE - Clayoquot Slope Bullseye | 48.67086956 | -126.8481413 | -1259 | • RBRconcerto Tilt Meter ACC.BPR 63055 | Completed | N/A | ONC |
| NCSB | Newcastle Ridge | 50.40301 | -126.0559 | 1296 | • Nanometrics Titan (S/N 1113)<br>• Nanometrics Centaur (S/N 2506)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016122<br>• Septentrio Antenna Chokering B3/E6 SN 5127 | Completed | Completed | ONC-NRCan |
| NTKA | Nootka Lighthouse | 49.5924 | -126.6166 | 12 | • Nanometrics Titan (S/N 001121)<br>• Nanometrics Centaur (S/N 2600)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3015941<br>• Septentrio Antenna Chokering B3/E6 SN 5140 | Completed | Completed | ONC-NRcan |
| PTAL | Port Alberni | 49.25632 | 49.25632 | 92 | • Nanometrics Titan SMA (S/N 000845)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016071<br>• Septentrio Antenna Chokering B3/E6 SN 5147 | Completed | Completed | ONC-NRCan |
| PALI | Port Alice | 50.42978 | -127.4881 | 21 | • Nanometrics Titan SMA (S/N 00353) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID | Completed | Completed | ONC |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 3018383 Septentrio Antenna Chokering B3/E6 SN 5155 | | | |
| PHRD | Port Hardy | 50.70615 | -127.514717 | 149 | • Nanometrics Titan SMA (S/N 000617)<br>• Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018538<br>• Septentrio Antenna Chokering B3/E6 SN 5177 | Completed | Completed | ONC |
| PTRF | Port Renfrew | 48.54423 | -124.41304 | 185 | • Nanometrics Titan (S/N 000969) Nanometrics Centaur (S/N 2100) Septentrio PolaRx5 GNSS Receiver SSID 3016110 Septentrio Antenna Chokering B3/E6 SN 5123 | Completed | Completed | ONC-NRCan |
| QUAD | Quadra Island | 50.13247 | -125.33072 | 5 | • Nanometrics Titan SMA (S/N 000836)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016107<br>• Septentrio Antenna Chokering B3/E6 SN 5126 | Completed | Completed | ONC-NRCan |
| SHPB | Sharp Point | 49.3476 | -126.25979 | 26 | • Nanometrics Titan (S/N 001117)<br>• Nanometrics Centaur (S/N 2562)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016106<br>• Septentrio Antenna Chokering B3/E6 SN 5131 | Completed | Completed | ONC-NRCan |

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|---|---|---|---|---|---|---|---|---|
| PGC5 | Sidney - PGC | 48.64983 | -123.45206 | 15 | • Nanometrics Titan SMA (S/N 000640) Septentrio PolaRx5 GNSS Receiver SSID 3016100 Septentrio Antenna Chokering B3/E6 SN 5118 | Completed | Completed | ONC-NRCan |
| STRA | Strathcona Park | 49.90003 | -125.64718 | 513 | • Nanometrics Titan SMA (S/N 000840)<br>• Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018555<br>• Septentrio Antenna Chokering B3/E6 SN 5159 | Completed | Completed | ONC |
| SYMB | Survey Mountain | 48.55929 | -123.79893 | 945 | • Nanometrics Titan (S/N 000895)<br>• Nanometrics Centaur (S/N 1801) | Completed | N/A | ONC-NRCan |
| TAHB | Tahsis | 49.892871 | 126.677409 | 464 | • Nanometrics Titan (S/N 001097)<br>• Nanometrics Centaur (S/N 2648)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016070<br>• Septentrio Antenna Chokering B3/E6 SN 5143 | Completed | Completed | ONC-NRCan |
| TLRR | Taylor River Rest Area | 49.29472 | -125.30028 | - | • Nanometrics Titan SMA (S/N 000819) | Planned | N/A | ONC |
| TFNO | Tofino | 49.15434 | -125.90772 | -8 | • Nanometrics Titan SMA (S/N 000642)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016109<br>• Septentrio | Completed | Completed | ONC-NRCan |

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|---|---|---|---|---|---|---|---|---|
| | | | | | Antenna Chokering B3/E6 SN 5125 | | | |
| UCLU | Ucluelet | 48.92457 | -125.54198 | 8 | • Nanometrics Titan SMA (S/N 000643)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016064<br>• Septentrio Antenna Chokering B3/E6 SN 5132 | Completed | Completed | ONC-NRCan |
| ERMD | Vancouver - ProTrans | 49.19781 | -123.11988 | 5 | • Nanometrics Titan SMA (S/N 000834) | Completed | N/A | ONC |
| VICP | Victoria Peak | 50.00632 | -126.10854 | 1572 | • Nanometrics Titan SMA (S/N 000839)<br>• Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018534<br>• Septentrio Antenna Chokering B3/E6 SN 5156 | Completed | Completed | ONC |
| WOSB | Woss | 50.16078 | -126.57039 | 961 | • Nanometrics Titan (S/N 000904)<br>• Nanometrics Centaur (S/N 1896)<br>• Septentrio PolaRx5 GNSS Receiver SSID 3016069<br>• Septentrio Antenna Chokering B3/E6 SN 5128 | Completed | Completed | ONC-NRCan |
| ZEBA | Zeballos | 49.98961 | -126.85058 | 42 | • Nanometrics Titan SMA (S/N 000843) | Completed | N/A | ONC |

### 1.4.2. Data, Algorithm and Software Development

Raw acceleration data from a three-axis, strong motion accelerometers (Nanometrics Titan and RBR tiltmeter) are collected at each individual earthquake early warning accelerometer-only site. The primary data integrated into the earthquake early warning system are the derived parameters that are computed by middleware as close to the instruments as possible. These parameters are:

- JMA Intensity Amplitude
- Maximum Peak Displacement Amplitude
- Maximum Predominant Period
- Peak Displacement Amplitude
- Predominant Period
- P-wave Arrival Time
- P-wave Detection Ratio
- S-wave Arrival Time
- S-wave Detection Ratio

An Oceans 2.0[1] driver connects to this middleware to receive the data streams. Upon driver start up, the version of the middleware is sent and archived as provenance information. Currently, the JMA Intensity Amplitude reports every second and serves as a heartbeat, while other parameters are transmitted only in the case of an event. The computed parameters are parsed and archived in the database in near real-time.

Land-based stations comprise an accelerometer and a GNSS receiver, where the middleware developed by ONC is hosted on a Compulab fitlet at each site; this server processes the raw acceleration data. Furthermore, the land-based stations include displacement data from Septentrio GNSS (GPS) systems. Recent research shows that incorporating real-time displacement data from GNSS provides more robust estimates and more precise updates while a larger magnitude (>M6) earthquake unfolds. The algorithms have thus been extended to process GNSS data and the data from a co-located seismometer through a Kalman Filter into an unbiased displacement time-series (Bock et al. 2011, Melgar et al. 2013, Li, 2015, Niu and Xu, 2014). Specifically, inclusion of these data provides the system with two additional magnitude parameters—peak displacement and peak ground displacement—ultimately adding another layer of computational sophistication. The GNSS raw output data is processed using three separate instances of Natural Resources Canada's Precise-Point-Positioning (PPP) software (Integer, Float, and Orbit solutions). These data provide more reliable magnitude estimates in the early stages of a developing earthquake, and the magnitude estimates are continuously updated over the total duration of the earthquake (Crowell et al., 2013). Assuming the magnitude can be determined from the GNSS data, it will be selected as the estimated event magnitude value. If the magnitude cannot be computed using the GNSS data, the maximum

[1] Oceans 2.0 is the name of Ocean Networks Canada's integrated data management system.

value determined between the two seismic magnitude parameters ($\tau_P$, peak displacement) is used instead to report the estimated event magnitude.

Detection data from all of the land and underwater stations are fed into an earthquake associator algorithm at ONC. Within the earthquake associator, two independent algorithms are used to estimate the earthquake epicentre from at least four detections at different sites in the network: linearized least squares (LLS) and direct grid search (DGS). Both the LLS and DGS algorithms are required for accurate epicentre determination, where both of the epicentres must be within 80 kilometres of each other. Similarly, two independent algorithms have been implemented to estimate the magnitude from the seismic data as well. Earthquakes estimated to have a smaller magnitude (<M5) are computed using an algorithm that is based on the frequency content of the early seismic signal (Wurman, Allen, and Lombard, 2007; Lockman and Allen, 2007). Conversely, larger magnitude earthquakes are computed with an algorithm that is based on the initial displacement amplitudes (Kuyuk and Allen, 2013).

Currently, the system utilizes two associator instances located at the University of Victoria and in Kamloops, British Columbia. This geographical separation is intentional in order to maintain full operational capability even during potential widespread devastation specifically affecting the Victoria location.

Upon the successful detection of an earthquake event by the associator, the earthquake early warning system software suite provides a notification message to subscribers using the common alerting protocol (CAP) message format that allow real-time notification updates. The CAP notification contains a geocode field describing the estimated earthquake epicentre location as well as its magnitude estimate. The CAP standard is defined by Public Safety Canada (https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/mrgnc-prprdnss/capcp/index-en.aspx).

The message includes the number of sensors contributing to the epicentre and magnitude estimates as a means to indicate and measure notification accuracy. The CAP message also includes an encrypted signature that guarantees the origin of the message and will prevent the system to be spoofed by malevolent actors.

ONC also provides an application programming interface (API) to use the CAP messages. The simple functions it provides include: CAP message signature verification; calculation of distance to the epicentre given a pair of coordinates; calculation of time-of-arrival of the shaking at the given coordinates; and calculation of the estimated level of shaking at the given coordinates.

The last two calculations make assumptions regarding, and are adapted to, the nature of the rocks in south-western British Columbia.

### *1.4.2.1. Integration of Detection Data from PNSN*

Earthquake parameters (e.g., p-wave arrival times, peak displacement, $\tau_p$) derived from land-based stations managed by the Pacific Northwest Seismic Network (PNSN) are integrated into the ONC earthquake early warning system.

Pacific Northwest Seismic Network data are sent to ONC from a computer at the University of Washington to an ONC computer in Victoria using an Apache ActiveMQ message broker that parses the data into a format that can be used by ONC's earthquake associator algorithm. When a Pacific Northwest Seismic Network message is detected from a new device, the device metadata is automatically added into the Oceans 2.0 database. Metadata such as network, station, location, channel codes are captured in the device name, while latitude and longitude are also populated. Device elevation, manufacturer and accelerometer model are captured in the metadata accordingly, extracted with an IRIS (Incorporated Research Institutions for Seismology) Web API query. Three sensors are also included: P-wave detection time, $\tau_{P,}$ and peak displacement, all of which are used by the associator to determine an earthquake epicenter and magnitude. After the data is associated, it gets archived allowing ONC to play back earthquakes detected using the Pacific Northwest Seismic Network data.

### *1.4.2.2. ONC-NRCan Collaboration*

Among its various mandates, Natural Resources Canada is to deliver nationwide seismic and geodetic information. More specifically, the Pacific GeoScience Centre (PGC), the Geodetic Service of Canada (GSC) and the Canadian Hazard Information System (CHIS) are three departments that have contributed actively in the development of the Cascadia earthquake early warning system. The contributions from these departments have been multifaceted, including support via software, expertise, administration and installation resources. The Pacific GeoScience Centre has provided advice on earthquake science, systems and administrative support, office space, and testing facilities. Geodetic Service of Canada has supported understanding, calibration, and installation of geodetic instruments (GNSS) together with dedicated software integral to earthquake detection. The Canadian Hazard Information System has contributed instrumentation and auxiliary/ancillary equipment, provided data and site access, committed equipment and supplies, and offered various levels of field support. The established relationship and ongoing collaboration with Natural Resources Canada has been a critical success factor credited to the current state of the earthquake early warning system.

Throughout the duration of this three-year project, Natural Resources Canada was actively involved with the upgrade and amalgamation of their geodetic reference and seismic stations. In a collective effort to promote system integration, pool resources, reduce redundant efforts, utilize current infrastructure, decrease administration, curtail capital costs and expedite timelines, ONC and Natural Resources Canada developed an approach that relied on collaborative efforts. There were 20 Natural Resources Canada stations with existing geodetic instrumentation, where 10 also included seismic equipment. ONC participated and assisted with a variety of office and field activities to upgrade the infrastructure, add seismic instrumentation to these geodetic-only sites, and add new seismic/geodetic stations. Additional network equipment, power systems, secondary communication channels, ancillary equipment and battery backups were also added to compensate for the additional load in a variety of combinations at each of these sites.

To integrate the existing NRCan stations with ONC requirements, a second router/firewall has been added to each station. This provides an additional secure network intended to isolate Natural Resources Canada network devices from ONC devices, while providing filtering to the Internet connection. Raw acceleration data streams were enabled for dual-streaming to ONCs associator and NRCNatural Resources Canada's data storage facility for 27 sites.

The architecture of the system is such that it allows for the combination of multiple sensor networks to achieve an integrated earthquake detection capability. The focus of this project being the Cascadia events, and considering that the Cascadia subduction zone extends south to northern California, it would make sense to adopt and integrate data from networks in Washington State and Oregon.

The Pacific Northwest Seismic Network, run from the University of Washington, is composed of about 300 accelerometers distributed across the two states and uses instruments from the same manufacturer and with very similar sensitivity to the ones we have installed in British Columbia. Considering the homogeneity of the equipment and the benefits of a common regional focus, it made sense to seek data exchange between our two networks. To that effect, an agreement was drafted to explore and test data exchange between us. The integration was implemented but not tested. Conversely, an integration of the ONC network with those of Smart Infrastructure Monitoring Program or the University of Britich Columbia was considered but not actively pursued (those networks sense different regions), as this integration would have diluted the Cascadia focus and would have implied dealing with very different instruments with different sensitivities and response. Integrating with those networks will make more sense when a comprehensive alerting system that integrates other types of earthquakes will be considered.

A basic map of the final status of ONC-Natural Resources Canada shared sites is shown in Figure 2.

#### *1.4.2.3. EEWS Event detection, Location, Performance*

The following table shows earthquake events detected by the earthquake early warning system from September 2018 through to 16 July 2019. There were 18 detections of real earthquake events in this time.

*Table 3. Earthquake events detected by ONC's earthquake early warning system.*

| Earthquake | Date | Magnitude | Location | # of SItes that contributed to the detection |
|---|---|---|---|---|
| 1 | 22-Oct-2018 | 6.6 | 218 km SW of Port Hardy | 8 |
| 2 | 22-Oct-2018 | 6.8 | 197 km SW of Port Hardy | 9 |
| 3 | 22-Oct-2018 | 4.3 | 201 km SW of Port Hardy | 5 |
| 4 | 22-Oct-2018 | 4.6 | 235 km SW of Port Hardy | 14 |
| 5 | 19-Nov-2018 | 3.8 | Olympic Peninsula, Washington | 7 |
| 6 | 09-Dec-2018 | 5.4 | 215 km W of Tofino | 11 |
| 7 | 28-Dec-2018 | 2.3 | 96 km W of Gold River | 4 |
| 8 | 19-Jan-2019 | 4.0 | 209 km W of Port Hardy | 6 |
| 9 | 11-Feb-2019 | 4.2 | 186 km W of Port Hardy | 9 |
| 10 | 01-Mar-2019 | 2.0 | 59 km W of Gold River | 8 |
| 11 | 30-Mar-2019 | 2.9 | 64 km W of Gold River | 14 |
| 12 | 08-May-2019 | 3.4 | 79 km S of Port Alice | 5 |
| 13 | 20-May-2019 | 2.5 | 25 km SE of Neah Bay, WA | 9 |
| 14 | 21-May-2019 | 3.4 | 16 km NNE of Ocean Shores, WA | 12 |
| 15 | 25-May-2019 | 2.7 | Olympic Nat. Park, WA | 5 |
| 16 | 03-Jul-2019 | 1.9 | 15 km S of Tofino | 7 |
| 17 | 04-Jul-2019 | 6.2 | 196 km WSW of Bella Bella | 4 |
| 18 | 12-Jul-2019 | 4.6 | Three Lakes, WA | 6 |

The average difference for the earthquake early warning system computed earthquake origin time compared to the United States Geological Survey (USGS) reported time was six seconds, with a maximum difference of 31 seconds. The average difference between the earthquake early warning system computed epicentre location and the USGS reported epicentre location was <100 km, ranging between 0.5 to 334 kilometres. These differences increase in areas where the earthquake early warning system has poor network coverage.

Differences between preliminary magnitude estimates from the ONC earthquake early warning system and the USGS estimates range between 0.01 and 4.5 magnitudes. These differences can be associated with fine-tuning of the ONC algorithms that were still under development at this phase of the project. More recently, and following such adjustments, these differences have decreased significantly. More site-specific adjustments will be required to improve magnitude and epicenter estimates during the commissioning phase.

The most successfully detected events were the Sovanco earthquake series from 22 October 2018 (see supplementary video simulation). A series of events that rapidly followed after one another were detected and correctly reported by the earthquake early warning system. The first event was reported 44 seconds after the calculated origin time. The estimated warning time for Victoria and Vancouver was 84 seconds based on an epicenter distance of 460 kilometre. The ONC earthquake early warning system reported magnitude (Mw) estimates ranged between 6.2 to 6.75, which align with the USGS reported magnitudes.

#### ***1.4.2.4. Data Latency***

Accelerometer data have an average latency of 1.5 to three seconds to the associator that is located on a server at the University of Victoria. ONC also has a backup server located in Kamloops, British Columbia, where a second data stream is associated. The corrected GNSS data have an average latency of four to six seconds to the associator. Magnitude parameters arrive four to five seconds after a P-wave detection. The more P-waves are detected at the individual sites, the more accurate the information that can be derived, if only at the expense of a slightly slower calculation. No earthquake early warning system event notifications are sent out until at least four seconds after an earthquake.

#### ***1.4.2.5. Station/Site performances***

A total number of 24 land and eight subsea stations were used for the event detections reported here. On average all sensors were online 90 percent of the time (between September 2018 and July 2019).

#### ***1.4.2.6. Associator Testing***

Testing the capability of the associator to estimate the correct epicentre of an earthquake event and calculated P-wave travel-times using ray-tracing to stations in the earthquake early warning system was carried out successfully. Potential earthquakes originating within the subduction slab were simulated with a fixed hypo-central depth of 20 kilometres. A succession of only the first four, six, and ten arrivals for an earthquake event association to simulate the progression of time as more and more stations detect the event was simulated. The condition number for the matrix inversion of the linearized least squares (LLS) algorithm serves as a first proxy for the quality of a solution, an example of which is shown in Figure 1. High condition numbers amplify errors in the input data and affect epicentre locations as well as magnitude estimates since those depend on epicentral distances.

The distance between the true epicentre and the solution computed with both the DGS and the LLS algorithms, is shown in Figure 2 after the first 10 P-wave arrivals have been detected. Areas with dark red colors represent the fact that the use of the first 10 stations has a relatively short baseline in the direction of sources in that area and consequently has limited range resolution.

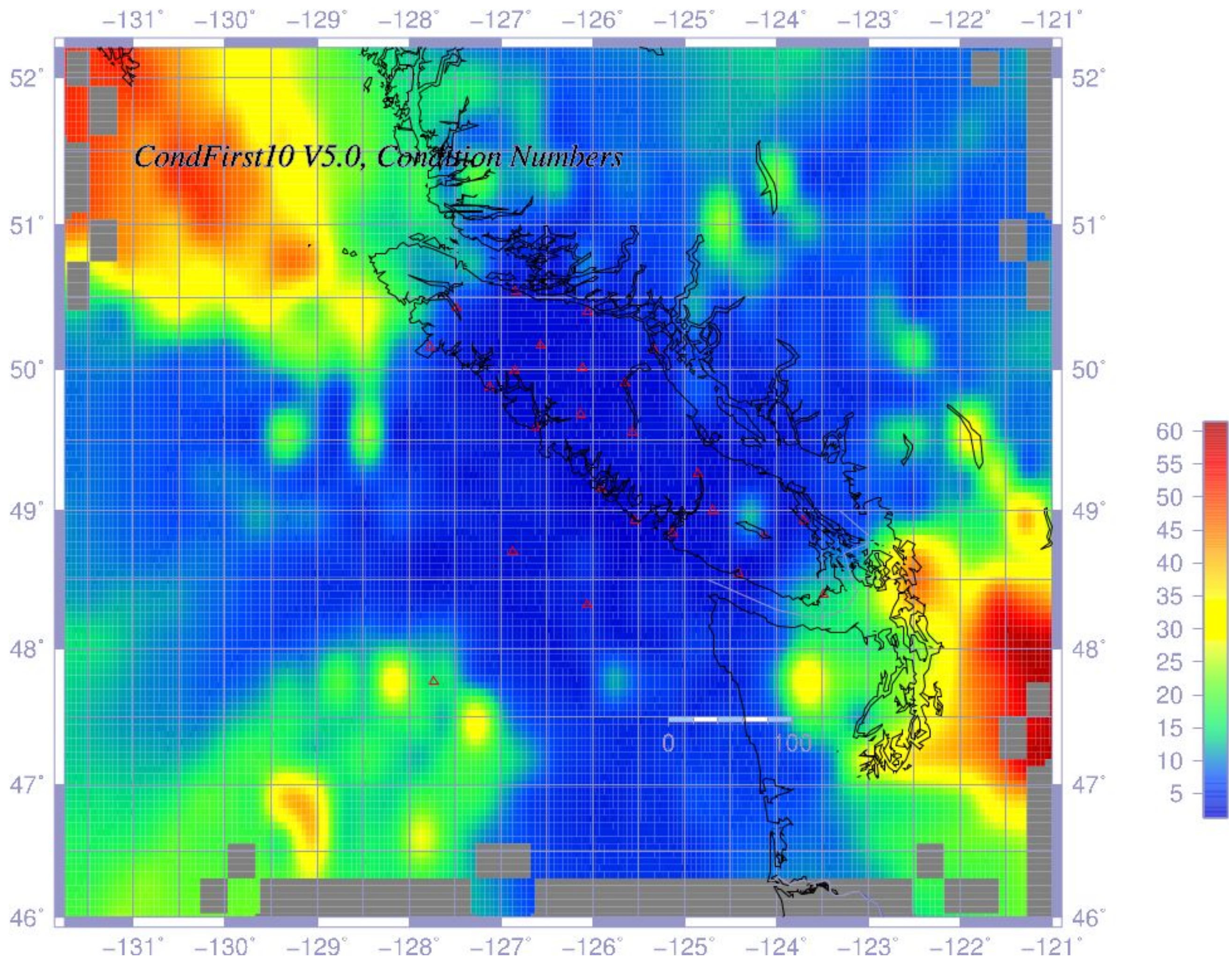


*Figure 4. The linearized least squares algorithm's condition number is a proxy for the reliability of the epicentre location. Here, the first 10 stations have detected an event located anywhere in the geographic region. Grey areas mark the regions where no solution was obtained. Condition number of >30 represent areas of detection/association difficulties using only 10 stations. Red triangles mark the location of incorporated seismic stations.*

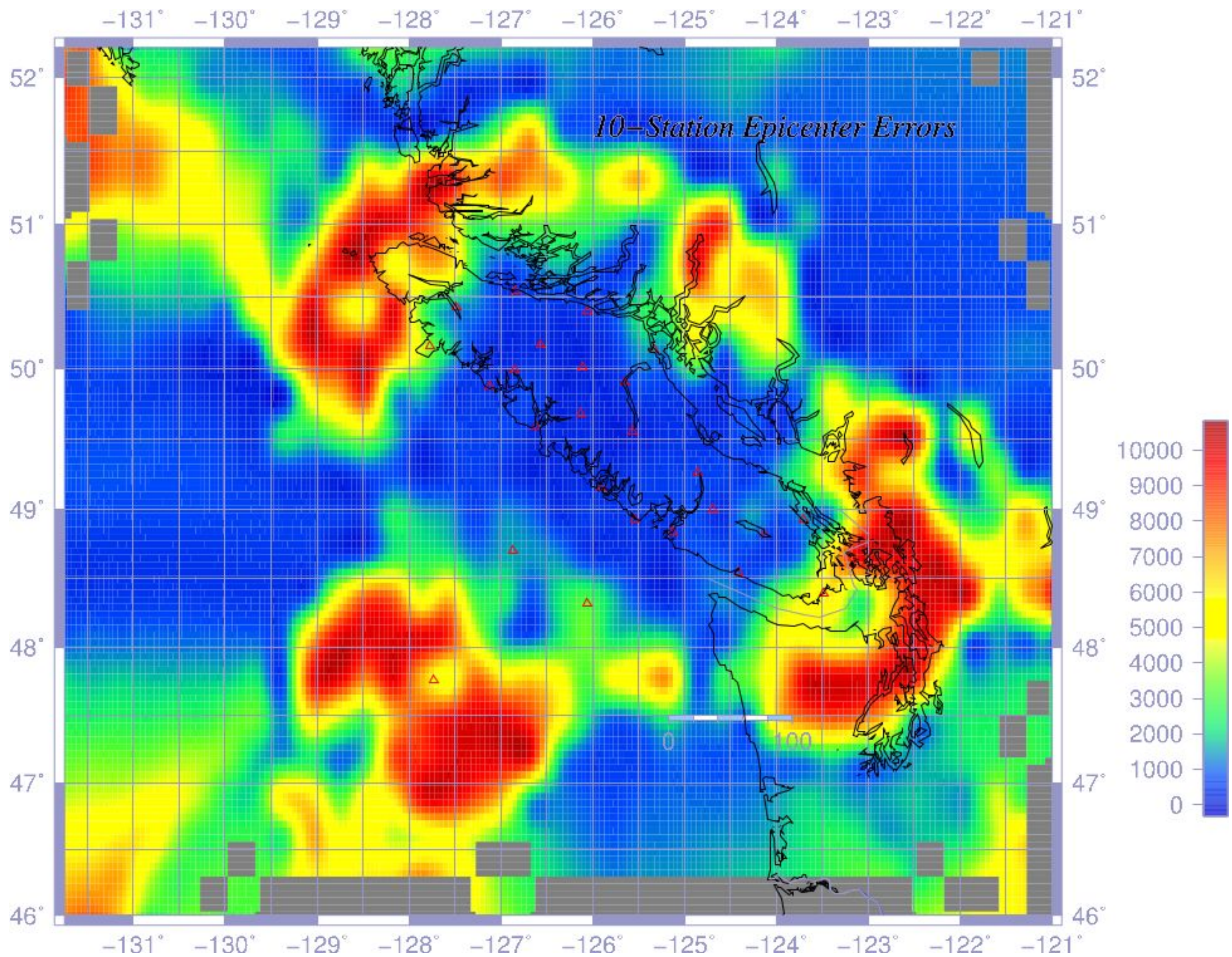


*Figure 5. The distribution of errors in epicentre locations from the combined algorithms after the first 10 stations have detected P-wave arrival (scale in meters). The dark red regions mark errors of >10km. Red triangles mark the location of incorporated seismic stations.*

## 1.4.3. System Testing with End-users

ONC, with the support and approval of Emergency Management BC, worked with volunteer end-users from a variety of sectors to support the testing of ONC's earthquake early warning notifications and helped identify "last-mile" implementation requirements. End-user pilot projects have been approved in various sectors, including light rail, marine transport, health, first responders/local government, utilities, public alerting, and Indigenous communities. This process mirrors that of the ShakeAlert earthquake early warning system under development by the USGS and state partners in the USA. In fact, many end-users were invited to participate in ShakeAlert's™ sector-specific EEW Symposia. Where possible, we aligned our approach with that of our southern neighbours, given that consistency of public safety systems is critical.

### *1.4.3.1. End-user Workshop*

On 19 April 2017, ONC conducted a full-day workshop with a broad cross section of potential earthquake early warning end-users. The plenary group was split into three smaller groups to review three specific topics related to the implementation of earthquake early warning in different contexts. These groups spent time discussing the benefits and limitations, implementation considerations, and development/testing requirements of the earthquake early warning system.

From this workshop, potential pilot projects were identified, and eight were undertaken.

- Protrans - Canada Line (Transit - Light Rail)
- Fortis (Utility)
- Pelmorex (Public Alerting)
- District of Oak Bay (Local Government – Urban and First Responder)
- Pacheedaht First Nation (Local Government – Rural)
- BC Ferries (Transit – Marine)
- Health Emergency Management BC (Health/Hospital)
- Translink (Transit – Light rail, Bus, Marine)
- Emergency Management BC (Emergency Management)

### *1.4.3.2. End-user Pilots*

Earthquake early warning end-user testing took place in the following stages:

1. Technical discussion
2. Software Application Programming Interface integration
3. Initial testing and performance reporting
4. EEW workshop and training
5. Full systems test

### *Technical discussion*

ONC initiated connections with the pilots' technical point of contact, as well as with technically knowledgeable staff within the organization, and directed them on how to connect and receive the earthquake early warning notification. Installing ONC's client software and allowing a computer server to receive a notification was the minimum criteria for testing; however, some end-users explored the integration of test notifications into automated systems (automatic doors, elevators and staff announcements, etc.).

### *Software API integration*

ONC's API client code was installed on the selected workstation(s).

### *Initial testing and performance reporting*

Tests of connections were performed to ensure the expected data transport behaviour was observed.

### *EEW workshop/training*

Earthquake early warning training workshops were delivered to a number of engaged user groups. The workshops gave an overview of earthquake early warning technology and how it can be applied in various contexts. Training included interested participants from various departments of the users' organization, including operations staff, safety officers, facilities managers, and others interested in earthquake safety. Background information on the technology and its application in other jurisdictions, along with information on the potential benefits and limitations of the system were presented along with scenario-based table-top exercises to explore the use of earthquake early warning within different contexts. Pre- and post-workshop surveys were delivered to allow for feedback and further commentary from participants.

### *Full systems test*

Coinciding with ShakeOut 2018, a full systems test was carried out, giving end-user test participants an opportunity to practice what they might do with 60 seconds warning before their ShakeOut drill.

The Canada Line in Vancouver took the opportunity to demonstrate a test of the integration of EEW into their light rail system's Operations and Control Centre in Richmond, British Columbia. This included a test of earthquake response procedures that take immediate actions upon receipt of an earthquake early warning notification prior to the onset of ground shaking. The exercise also included an all-staff earthquake drill with evacuation and business continuity planning.

## 1.4.4. Designs, Approvals and Reports

Copies of these documents are available in an electronic folder located here: https://drive.google.com/open?id=1BZSK_xnE_LVnKL04SoQUETPM5erjikDL

## 1.5. Budget

| Total Approved Project Budget | Amount (CAD) |
|---|---|
| Provincial Government Share | $5,000,000 |
| Local/Federal Government / Other Funding Source Share | $2,000,000 |

| Total Eligible Project Costs Paid | Amount (CAD) |
|---|---|
| Provincial Government Share | TBS |
| Local/Federal Government / Other Funding Source Share | $1,995,000 |

## 1.6. Schedule

Project timeline

- April to May 2016: Project planning and refinement of project scope. Project Plan signed by EMBC and ONC for May 31, 2016.
- June 2016 to July 2019: Acquisition and installation of seismic and deformation sensors in offshore areas and land based areas on Vancouver Island.
- June 2016 to January 2019: Enhancement of seismic and deformation data analysis capabilities.
- June 2016: Delivery of quarterly project status update report to EMBC.
- June 2016: A total of 3 offshore sensors installed on the NEPTUNE array.
- September 2016 to June 2019: Seismic network integration and data sharing. Deliverable - EEW Commissioning guideline document for the integration of sensors into the EEW system on March 8, 2019.
- September 2016: Delivery of quarterly project status update report to EMBC.
- December 2016: Delivery of quarterly project status update report to EMBC.
- March 2017: Delivery of quarterly project status update report to EMBC.
- April 2017: A total of 14 land-based sensors installed on Vancouver Island.
- June 2017: Delivery of quarterly project status update report to EMBC.
- September 2017 to January 2019: EEW notification system development. Deliverables - Testing framework for the EEWS and test of notification system with beta-users by Jan 31, 2019.
- September 2017: A total of 6 offshore sensors installed on the NEPTUNE array.
- September 2017: Delivery of quarterly project status update report to EMBC.
- December 2017: Delivery of quarterly project status update report to EMBC.
- March 2018: Delivery of quarterly project status update report to EMBC.
- April 2018: A total of 16 Land-based sensors installed on Vancouver Island.
- April 2018 to July 2019: Monitoring of the EEWS.
- June 2018: Delivery of quarterly project status update report to EMBC.
- September 2018: Delivery of quarterly project status update report to EMBC.
- September 2018: A total of 8 offshore sensors installed on the NEPTUNE array.

- December 2018: Delivery of quarterly project status update report to EMBC.
- March 2019: Delivery of quarterly project status update report to EMBC.
- March 2019: 52 Land-based sensors installed on Vancouver Island.
- June 2019: Delivery of quarterly project status update report to EMBC.
- July 2019: Delivery of project completion report to EMBC.

## 1.7. Procurement

ONC adheres to strict procurement guidelines in accordance to the University of Victoria's policies. Copies of these procedures are outlined in the supplemental documents provided in the electronic folder accessible here: https://drive.google.com/open?id=1BZSK_xnE_LVnKL04SoQUETPM5erjikDL.

# Proof of Expenditure

A summary of all expenditures is included with the supplemental file folder located here: https://drive.google.com/open?id=1BZSK_xnE_LVnKL04SoQUETPM5erjikDL.

# Conclusion

ONC is proud to have built a system that notifies of Cascadia area-related earthquake events occurring near Vancouver Island. The earthquake early warning system is leading edge, in that it uses a modern system architecture, leverages the most recent advances in the combination of accelerometer and GNSS receiver data, and seamlessly combines earthquake detection using underwater as well as land-based sensors.

The system was installed with support from Natural Resources Canada whose Canadian Hazard Information System division allowed us access to some of their pre-existing sites for instrumentation upgrade and integration into the new network. Moreover, Natural Resources Canada's Geodetic Service supported the integration of GNSS data by providing codes that help improve magnitude estimates. Thanks to ONC's efforts in preparing new sites, upgrading existing ones, optimizing codes and adding redundancies, the system is now operating and delivering test-labelled notifications to keen industry users pending the completion of a formal commissioning phase. Commissioning will help establish the overall performance of the system in terms of its ability to correctly determine actual event parameters and avoid false detections while offering timely notifications.

# References

Bock, Y.; Melgar, D. & Crowell, B. W., Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers, *Bull. Seism. Soc. Am.,* **2011**, *101*, 2904-2925

Crowell, B. W.; Melgar, D.; Bock, Y.; Haase, J. S. & Geng2, J.,Earthquake magnitude scaling using seismogeodetic data, *GRL,* **2013***, 40*, 6089–6094

Kuyuk, H. & Allen, R., A Global Approach to Provide Magnitude Estimates for Earthquake Early Warning Alerts, *Geophys. Res. Lett.,* **2013***, 40*, 6329–6333

Li, X., Real-time high-rate GNSS techniques for earthquake monitoring and early warning *Technische Universität Berlin,* **2015**

Lockman, A. B. & Allen, R. M., Magnitude-Period scaling relations for Japan and the Pacific Northwest: Implications for Earthquake Early Warning, *BSSA,* **2007***, 97*, 140-150

Melgar, D.; Bock, Y.; Sanchez, D. & Crowell1, B. W., On robust and reliable automated baseline corrections for strong motion seismology, *JGR,* **2013***, 118*, 1177–1187

Niu, J. & Xu, C., Real-Time Assessment of the Broadband Coseismic Deformation of the 2011 Tohoku-Oki Earthquake Using an Adaptive Kalman Filter, *SRL,* **2014***, 85*, 836-843

Wurman, G.; Allen, R. & Lombard, P., Toward earthquake early warning in northern California *JGR,* **2007***, 112*

# Appendix

Below is a collection of various earthquake early warning system stations exhibiting both seismic and GNSS instrumentation. All sites are either tied-into a grid powered system or remotely run on an off-grid solar array where data are streamed through a satellite communication system, or shared using current cellular networks.