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REAL-TIME GROUND MOTION FROM THE NEW STRONG MOTION SEISMIC NETWORK IN BRITISH COLUMBIA, CANADA

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SUMMARY

Canada's chief vulnerability to earthquakes is concentrated in a few urban regions. The south-west coast of the province of British Columbia is subject to the hazard posed by the Cascadia subduction zone with the associated earthquake scenarios of shallow crustal events, deeper subcrustal events and magnitude 9 megathrust earthquakes.

The Geological Survey of Canada operates a new real-time ground motion reporting network of accelerographs in British Columbia. As of January 2006, one hundred instruments have been deployed, most concentrated in and around the urban centres of Vancouver and Victoria.

The instruments combine several functions, serving as continuously recording strong motion accelerographs, and, at the same time, as sensors which automatically detect events and report real-time ground motion parameters such as peak ground acceleration (PGA), velocity (PGV), and spectral intensity (SI). Instruments form a network using various physical means of communications, including wired, wireless and satellite Internet links. Standard Internet protocols are employed to convey ground motion reports.

The network thus does not depend on the existence of a seismic data centre to analyze full waveform data, generate an alarm and subsequently disseminate ground motion maps. Instead, ground motion parameters from an instrument are relayed directly to disaster response agencies and lifeline and critical infrastructure operators. A prototype client system, which depicts peak ground motion values on a thematic map, is in operation with the Ministry of Transportation in British Columbia.

The reliability of alarms from this network as well as the quality of the generated shake maps depend primarily on station density. Since the instruments are inexpensive to own, deploy, and operate, dense arrays have become a realistic proposition.

1. INTRODUCTION

Modern rapid earthquake information systems usually combine observed ground motions with those predicted by earthquake source data and simple propagation models such as attenuation relations [Wu et al., 1999, Wald et al.1999, Atkinson, 2005]. However, there is frequently a strong bias towards the latter simply due to a lack of adequate instrument coverage [Gee et al. 2004, National Research Council, 2006].

Canada's principal high seismic hazard area stretches along the Pacific coast of the province of British Columbia [Rogers, 1998], where seismic risk is concentrated in a few urban areas (figure 1). In 2001 the Geological Survey of Canada (GSC) began a program to restore its ground motion monitoring capability in the south-western part

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of British Columbia, which at that time consisted of about thirty-five partially vintage (analogue) strong motion seismographs without telemetry [Rosenberger et al., 2004, Rogers et al., 1999].

2. NEW INSTRUMENTATION

The GSC adapted the paradigm that station density was more important than sensitivity of an individual instrument -- in particular, when the bulk of the new instruments would be spatially distributed according to seismic risk, i. e. would be deployed in an urban environment with high background noise.

We chose to design a compact, "all in one" instrument, which acquires 18 bit, 100 sps, digital acceleration data from three orthogonal sensors. The commercial version of this instrument is available with a RMS noise floor of either 500ug or 50ug and a range of +-3g and +-2g respectively. The instrument is designed to have a permanent Internet connection and achieves absolute (UTC) time synchronization with less than 10 ms error using network time servers [Mills, 1997].

Full waveform data are acquired continuously into a ring-buffer of 36 hour capacity. An integrated single board computer (SBC) provides signal-processing capacity to compute derivative data such as velocity and a spectral intensity estimate [Katayama et al.,1998] continuously and in real time [Kanamori et al., 1999]. Continuously computed values of short time and long time average ratios are used in a noise adaptive triggering scheme (STA/LTA trigger). Once triggered, peak values of acceleration (PGA), velocity (PGV) and spectral intensity (PSI) are determined over an observation time interval and if peak spectral intensity exceeds a pre-set threshold, waveform data are additionally stored in non volatile (flash) memory.

Parametric data from an event, such as PGA, PGV and PSI are reported in a time stamped message to one or several computers over the Internet using a standard protocol (UDP, Syslog). An encrypted and authenticated TCP/IP tunnel connection is used to re-configure the instrument or to offload data from the ring-buffer and from non-volatile event memory.

The physical means to connect the instrument to the Internet are not limited to classic wired Ethernet. Instruments in the current network are routed to the Internet through Ethernet over power-line bridges, spread-spectrum radio links, satellite and wireless local area connections. Ethernet to cellular-data to Internet routers are also readily available, but are currently not employed in the Canadian network.

The instrument is designed to fit into almost any local area network configuration. It can operate without problems from behind a firewall or network address translating (NAT) router. Several of our instruments operate in security sensitive environments and have passed an external network security audit as well as the test of time: We have not had a single security related incident over the course of three and one half years of operation.

3. THE INSTRUMENT NETWORK

The capability of an instrument to compute and report ground motion parameters is crucial for the network design and operation:

The communication bandwidth required by an instrument is extremely low in normal operation, on average less than 25 bits/sec since there are no full waveform data transmitted. The instrument has thus no measurable impact on the local network. In British Columbia this network does not generate any communications costs at the instrument locations. All GSC instruments are hosted on third party Internet connections, including private, residential DSL/Cable, and satellite connections, without charge.

We use a so-called relay server to maintain tunnelled connections to the instruments and to re-distribute event reports sent from an instrument. As illustrated in figure 2, the use of a relay facilitates the communication with instruments that are on private networks which are screened by a firewall or a network address translation router. The instruments actively establish a connection to the relay. An application wanting to communicate with an instrument can pick up the connection at the relay server. All connections are authenticated and encrypted.

A total of three relay servers is used in our network. Two additional relays are located outside the high seismic hazard area and serve as back-up systems in the event of a large earthquake affecting the coastal region. Two relays are additionally equipped with a GPS clock and provide time to most instruments via the network time protocol (NTP) service.

Physically a relay is nothing but CD-Rom based software, which boots any standard PC-style hardware into a single purpose application. This has proven to be a secure and reliable way to organize communications and scales well with large numbers of instruments. One relay can handle several hundred instruments. It does not require any routine maintenance.

3.1 Network performance, an example

On January 15, 2006 many people in the southern parts of Vancouver Island, British Columbia, Canada woke up to a Mw 3.9 Earthquake, which occurred at 4:30 a.m. PST (12:30 UTC), 20 km northwest of the city of Victoria, near the town of Bamberton, at a depth of about 50 km. Thirty instruments are deployed in the southern Vancouver Island area, 18 of those are located in the greater Victoria area (figure 3).

The box in figure 4 shows instrument reports as they were logged arriving at one of three computers which then relayed the messages to client systems. Time-stamps were assigned by both the relay at the time of reception and the reporting instrument at the time the message was emitted. Latency is less than a second for most messages.

The instruments report twice: A first message reports that the instrument has triggered, then after a post-trigger observation time has passed, a second message with the observed peak ground motion values is issued. Our instruments report acceleration in fractions of the earth's acceleration, g, computed values of velocity and spectral intensity are referenced to g as well. The instruments "PGC01NA" (14.2 km from the epicentre) and "SDN01NA" (16.6 km from the epicentre) are less than 6 km distant from one another (figures 3 and 5). "PGC01NA" is located in the seismic vault of the Pacific Geoscience Centre while "SDN01NA" is in the noisier environment of the town of Sidney's municipal hall. Just from looking at the time-stamps of the reports from both instruments it can be seen that the PGC instrument obviously triggered on the P-wave arrival, while "SDN01NACN" triggered on the larger amplitude S-wave. This is to be expected since the trigger-threshold of the Sidney instrument is adapted to the noisy site, the P-arrival did not reach that threshold.

The largest peak acceleration value of about 1% g is reported by one of the Victoria urban instruments (VCT03NA, 20.5 km from epicentre) which also reports the largest peak spectral intensity value of about 0.001 [*9.81 m/s] (0.4 cm/sec^2 in Katayama (1998) units). This instrument is installed in a private residence located on a known amplification site [Monahan et al., 1998, Molnar et al., 2004].

Figure 5 shows vertical component waveforms on a time-distance plot. The tremendous variability in amplitudes is due to the radiation pattern of the source and, to a large extent, to site amplification. For example, instrument SOK01NA at almost twice the distance (23km) from the epicentre displays a five times larger peak acceleration amplitude than instrument PGC01NA (11 km). Attenuation functions based on an isotropic source model fail to predict this kind of variability.

4. CLIENT SYSTEMS

The ground motion reports generated from a large number of instruments in this network need to be presented in a visualization which is suited for non-expert use. Based on the number of reporting stations and the strength of shaking reported, some additional tasks may have to be performed automatically. We currently operate two prototype systems which perform those tasks and which we refer to as clients of the network.

One system which continuously receives trigger-messages and ground motion parameters is installed at the Pacific Geoscience Centre in Sidney, BC, Canada. It consists of a simple PC running a program which parses incoming trigger-messages and either discards reports with small spectral intensity values or, if peak SI is over a certain threshold, adds the trigger data to a queue like structure. Triggers already in the queue, which are 90 seconds older than the present one (with respect to their timestamps), are removed from the queue and finally the total count of triggers currently queued is taken. If the result is greater than a preset threshold (currently 5) the client system issues an alarm.

In essence this very simple algorithm implements a very robust voting scheme: Within 90 seconds, the maximum time a shear-wave would need to traverse south-western British Columbia, a minimum number of instruments need to vote that a sufficiently strong event has actually happened to set things in motion. The system then sends an e-mail to a mailing list and attaches automatically generated maps which depict symbols of different size and colour depending on reported PGA and PSI at instrument locations. This client system will also automatically collect full waveform data from all instruments bracketing the event time.

A total of eleven instruments triggered and reported ground motion parameters during the Bamberton earthquake on January 15, 2006. Only one (VCT03NA) reported a peak spectral intensity greater than the pre-set threshold of 0.001 [*9.81 m/s]. Only this report was queued and since it was the only report in the queue over the next 90 seconds no alarm was issued, as would be expected for a small event like this.

A second client system was developed in co-operation with the Ministry of Transportation, British Columbia (MoT(BC)). In 2005, MoT(BC) initiated a specific program to instrument Lifeline Bridges and critical areas of high seismicity to provide measurements of ground shaking and record the response of the structures during earthquakes. The user interface of this second client system is shown in figure 6. This interface is to a large degree platform independent. It can run on desktop computers with different operating systems and employs the same basic report queuing scheme but also displays triggers as they arrive on several GIS generated maps as circles with sizes varying with reported PGA and colour according to reported PSI. Symbols are removed from the map after 90 seconds unless more than a certain number of trigger messages arrived during this time interval. Then all symbols are retained and newly arriving ones are added to the map, until a user intervenes.

The map can be printed at any time and, in a major earthquake, represents the first snapshot of ground-motions as they are recorded. The use of a GIS system to generate base maps opens the opportunity to tailor different thematic maps for emergency responders, life-line, and critical infrastructure operators. The MoT(BC) will be using this data to identify structures subject to the greatest potential damage following a significant earthquake. Because the map is GIS based, the Ministry will be able to overlay it with their bridge inventory, their Disaster Response Routes or other critical data sets needed for post earthquake response.

Other client systems can be set up using the same building blocks. A system which would use the first message transmitted from an instrument rather than waiting for ground motion parameters could serve as an early warning system. Such a system would simply analyze the proximity in time of messages arriving from an array which is optimized to trigger on P-wave arrivals in a particular source scenario, and issue an alarm when a certain number of triggers arrives within a time appropriate for the source/array geometry.

5. CONCLUSIONS

The key observation is that this network can function without the existence of an elaborate and sophisticated data centre. Data analysis for basic ground motion parameters is performed in a classical distributed computing scheme using the instrument's embedded computing resources. Parametric ground motion can be presented directly as decision support information for non-expert users. Peak spectral intensity values correlate well with damage to structures [Elenas, 2002] and since these are in-situ measurements, rather than ground motion estimates, they already reflect the source characteristics, propagation, and local amplification effects, no corrections are required.

As long as the infrastructure of the Internet can be used to route parametric data to client systems, no further communication links are needed. The bandwidth requirements for an initial route from the instrument to the Internet are minimal, which opens a wide range of communication technologies. Bridging from cellular or satellite based communication systems is not necessarily associated with high costs due to the low overall data volume.

Relay servers are used to distribute the information to a larger number of clients and limit the amount of data traffic from an individual instrument; they also provide the hinge for TCP/IP tunnels for direct control of the instruments. However, they are not required in a basic network.

For a reasonably well defined earthquake source scenario it would be possible to deploy an array of instruments which provides P-wave early warnings to different client systems.

6. FIGURES

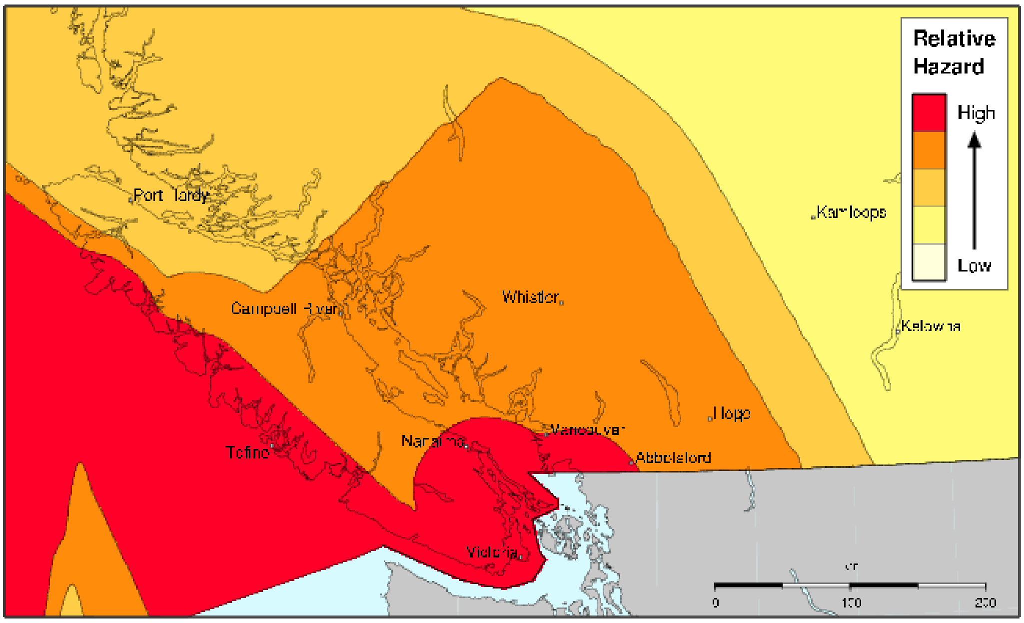

Figure 1: The 2005 seismic hazard map for Southwest British Columbia. The dark red area represents peak ground acceleration of 0.6g with a probability of exceedence of 2% in 50 years.

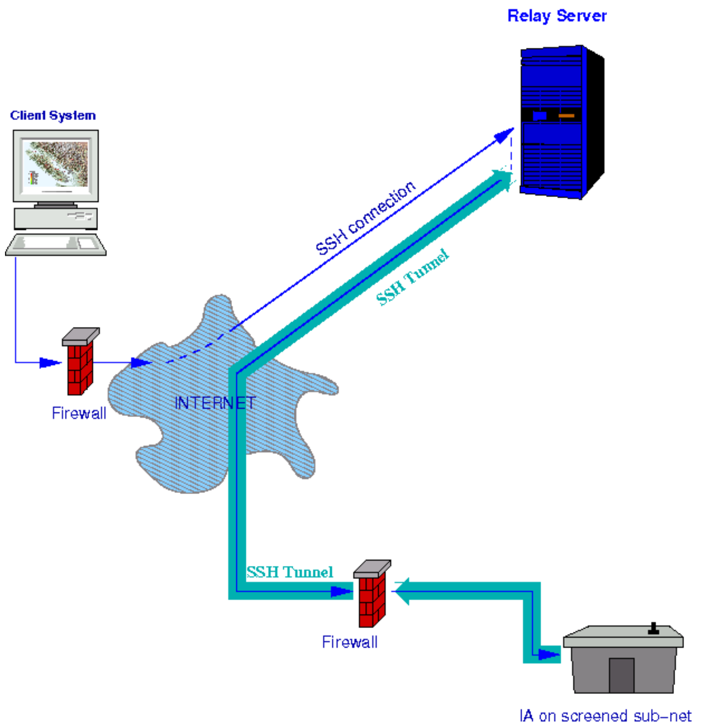

Figure 2: Basic building blocks of the network. A Relay maintains authenticated and encrypted tunnel connections with an instrument. Client systems connect to a unique port on the Relay and are forwarded to a specific instrument.

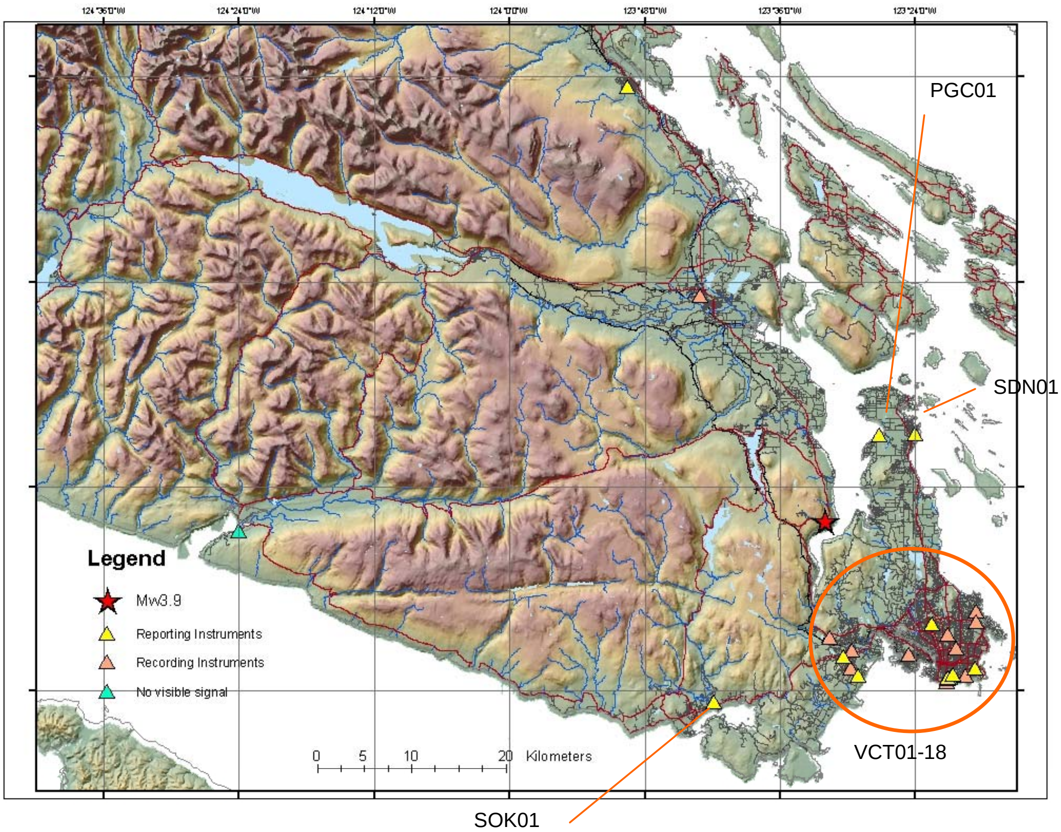

Figure 3: Southeast tip of Vancouver Island and the greater Victoria area (circle). The epicentre of the Mw 3.9 Earthquake is marked with a red star. Instruments which recorded the event are shown as orange triangles. Yellow triangles mark instruments which additionally detected the event and reported ground motion parameters.

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Jan 14 17:47:10: VCT04NACN *** Triggered Sun Jan 15 01:47:10 2006 , waiting for data ...
Jan 14 17:48:10: VCT04NACN Sun Jan 15 01:47:10 2006 -Event parameters PGA 1.0575e-02, PGV 4.6893e-04, PGD 4.2060e-04, kSI 5.7849e-04
Jan 14 20:05:58: WHS01NACN *** Triggered Sun Jan 15 04:05:58 2006 , waiting for data ...
Jan 14 20:06:58: WHS01NACN Sun Jan 15 04:05:58 2006 -Event parameters PGA 1.9865e-02, PGV 7.7274e-04, PGD 4.2796e-04, kSI 1.0538e-03
Jan 14 23:29:49: VCT08NACN *** Triggered Sun Jan 15 07:29:49 2006 , waiting for data ...
Jan 14 23:30:49: VCT08NACN Sun Jan 15 07:29:49 2006 -Event parameters PGA 1.6838e-02, PGV 1.2673e-03, PGD 4.0877e-04, kSI 2.4747e-03
Jan 15 04:29:54: PGC01NACN *** Triggered Sun Jan 15 12:29:54 2006 , waiting for data ...
Jan 15 04:29:58: SDN01NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:58: VCT14NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:58: VCT17NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:59: VCT03NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:04: VCT11NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:30:04: SOK01NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: VCT01NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: VCT04NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: LDY01NACN *** Triggered Sun Jan 15 12:30:04 2006 , waiting for data ...
Jan 15 04:30:11: VNC19E3CN *** Triggered Sun Jan 15 12:30:11 2006 , waiting for data ...
Jan 15 04:30:58: SDN01NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 9.8580e-03, PGV 4.9888e-04, PGD 4.4868e-04, kSI 6.5753e-04
Jan 15 04:30:58: VCT17NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 5.8614e-03, PGV 4.3085e-04, PGD 3.9501e-04, kSI 5.7685e-04
Jan 15 04:30:58: VCT11NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 1.0618e-02, PGV 5.5440e-04, PGD 4.8871e-04, kSI 5.9432e-04
Jan 15 04:30:58: VCT14NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 1.3837e-02, PGV 6.4166e-04, PGD 4.9910e-04, kSI 6.8502e-04
Jan 15 04:30:59: VCT04NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 5.1100e-03, PGV 4.6578e-04, PGD 3.7877e-04, kSI 7.2124e-04
Jan 15 04:30:59: VCT03NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 1.0279e-02, PGV 5.0312e-04, PGD 3.8180e-04, kSI 1.0052e-03
Jan 15 04:30:59: VCT01NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 6.1010e-03, PGV 5.3726e-04, PGD 4.4226e-04, kSI 5.8064e-04
Jan 15 04:31:11: VNC19E3CN Sun Jan 15 12:30:11 2006 -Event parameters PGA 3.6962e-03, PGV 4.5077e-04, PGD 3.1260e-04, kSI 6.7338e-04
Jan 15 04:31:24: PGC01NACN Sun Jan 15 12:29:54 2006 -Event parameters PGA 3.3991e-03, PGV 8.2866e-05, PGD 3.9088e-05, kSI 1.6015e-04
Jan 15 04:31:29: SOK01NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 1.3690e-02, PGV 6.5612e-04, PGD 4.5142e-04, kSI 6.7652e-04
Jan 15 04:31:34: LDY01NACN Sun Jan 15 12:30:04 2006 -Event parameters PGA 4.8901e-03, PGV 4.7656e-04, PGD 4.4859e-04, kSI 6.4765e-04
Jan 15 10:28:39: BWN01NACN *** Triggered Sun Jan 15 18:28:39 2006 , waiting for data ...
Jan 15 10:30:09: BWN01NACN Sun Jan 15 18:28:39 2006 -Event parameters PGA 6.1532e-03, PGV 4.7546e-04, PGD 3.8555e-04, kSI 5.9018e-04
Jan 15 11:01:48: VCT16NACN *** Triggered Sun Jan 15 19:01:48 2006 , waiting for data ...
Jan 15 11:02:48: VCT16NACN Sun Jan 15 19:01:48 2006 -Event parameters PGA 7.1192e-03, PGV 6.3187e-04, PGD 3.8531e-04, kSI 8.3782e-04
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Figure 4: Trigger-messages and ground motion parameter reports as they were logged during the January 15, 2006 event. The highlighted blocks pertain to the event. Close proximity in time distinguishes the set from spurious triggers, which occur frequently in a noisy urban environment. Note that the initial trigger occurred 8 seconds after the earthquake origin time of 12:29:46 UTC.

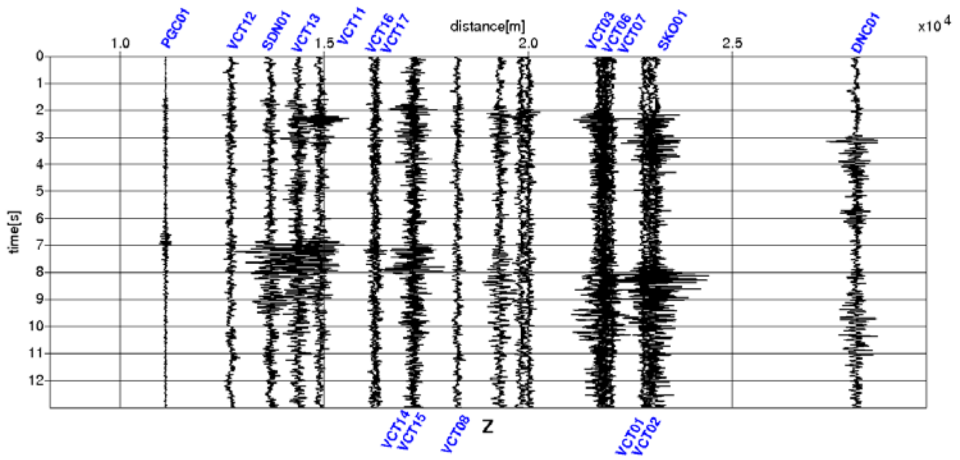

Figure 5: Vertical component data vs. epicentral distance from the January 15, 2006 event. Amplitude variability is due to radiation pattern and local site amplification.

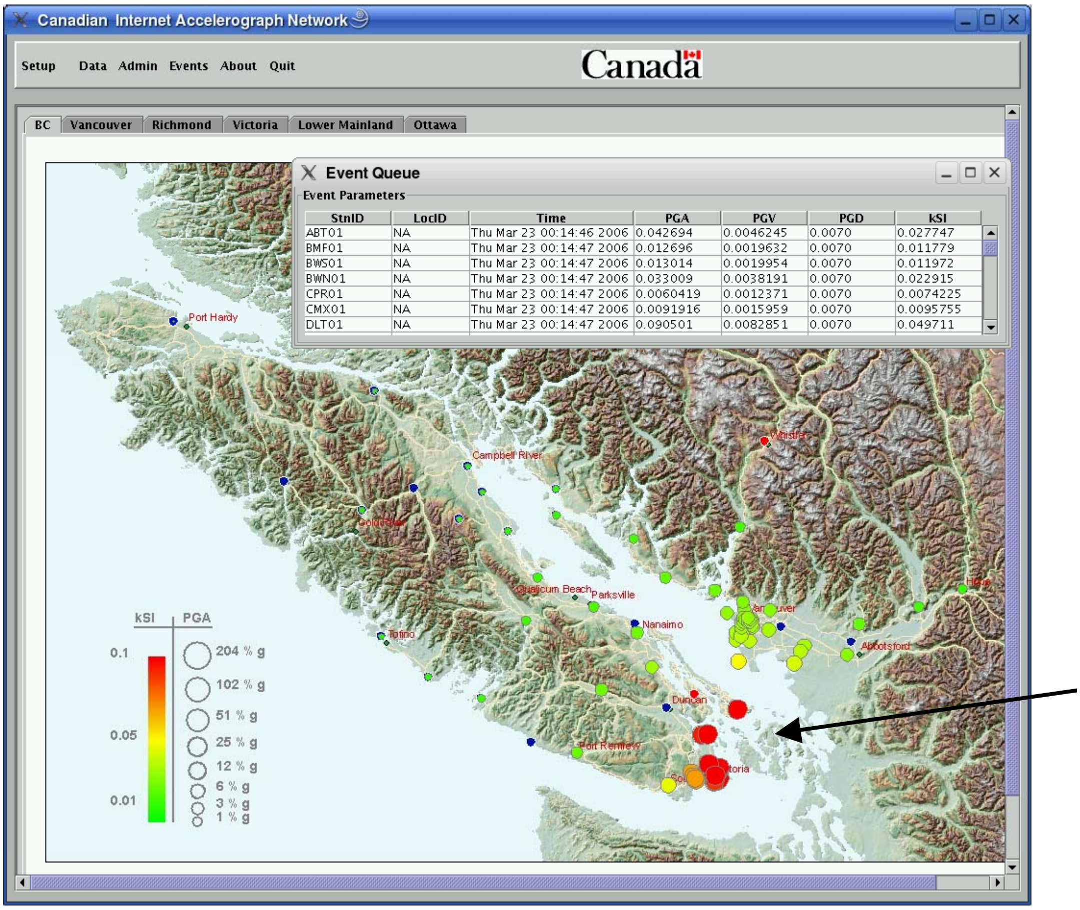

Figure 6: A desktop client developed jointly with the Ministry of Transportation. Ground motion parameters are displayed in real time. The map displays data from a simulated earthquake northeast of Victoria (the arrow indicates the approximate epicentre). An additional window shows the queue of event reports. Maps of different scales can be selected. This interface can also be used to retrieve and view full wave-form data.

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