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Performance comparison between current automated earthquake location methods, Autoloc and Antelope

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Abstract

The two methods of automatic earthquake location currently in use (as of May 2010) by the Canadian Hazards Information Service, Autoloc and Antelope, are compared to solutions produced daily by seismologists in an effort to evaluate the performance of both algorithms. The one year evaluation period extends from May 7, 2009 to May 6, 2010. Results show that both algorithms have their strengths and weaknesses that are specific to their current usage. In general Autoloc outperforms Antelope in terms of earthquake event detection across magnitudes of 2.0 and greater, while Antelope appears to possess a superior ability to identify seismic phase arrival times and thus is more accurate in its automated locations of earthquakes. Currently magnitude assessment is difficult for Antelope due to limitations in its design, however, for Autoloc current overall automated magnitudes for earthquakes >2.0 are underestimated by -0.3 magnitudes, improving to 0.04 as magnitude increases to 4.5. Potential exists in combining the strengths of both algorithms either as a single entity or by using both in tandem for improved hazard awareness.

Introduction

Automation of earthquake location is a necessity for the Canadian National Seismic Network (CNSN). With a growing network of 146 CNSN, 76 POLARIS and many other research and international stations contributing to daily records of ground motion data, it is an extremely difficult task to monitor the entirety of Canada for potentially hazardous earthquakes with manual methods, even more so if timely alerts are desired 24 hours-a-day. While seismologists have the experience and ability to identify, associate and make judgments regarding details of an earthquake to produce a location and magnitude of such an event with a high degree of confidence, they also require rest and may have a delayed response when events occur to make such decisions. Thus automated procedures are used giving a limited skill set derived from physical laws, signal properties and seismologist experience to process these large amounts of data and identify, associate and locate earthquakes around the clock in near real-time. In such a way automated systems provide a first-alert to the occurrence of an earthquake and can provide an initial location and magnitude of the event for the purposes of timely emergency and situational response by daughter processes and agencies. These locations may then be reviewed and verified later by seismologists manually.

EarthquakesCanada currently uses two automated earthquake algorithms in day-to-day operations of the CNSN, called Autoloc and more recently Antelope (Boulder Real Time Technologies, BRTT, http://www.brtt.com). Beginning in 1997 Autoloc has been used as the prime algorithm for automatically identifying and locating earthquake events in Canada and has been linked with several day-to-day operational systems including the automated earthquake alert service, AENEAS. As alerts are sent to third parties and affect the function of critical infrastructure in a time critical manner, it is necessary to determine Autoloc's accuracy of identifying, locating and measuring earthquakes.

Since the mid-2000's, the Pacific office of *EarthquakesCanada* has employed an integrated seismic monitoring and analysis package called Antelope. Developed by BRTT and marketed by Kinemetrics, Inc. (http://www.kinemetrics.com/p-145-Antelope.aspx), the package is in an open development project in use by many seismic and hazard monitoring groups worldwide. Included as part of the Antelope package is the ability to automatically identify and locate events in the region monitored, in this case the Pacific coast of Canada. This alternate method of automated event location provides the opportunity to not only evaluate Autoloc's effectiveness but also compare it to an independent algorithm designed to perform the same function. This comparative study of Autoloc's and Antelope's performance is the focus of this report, studying the results of automated reports delivered by each system daily over the course of 2009 through to 2010.

Dataset

The dataset for this study consists of two alerting system outputs (one for each auto-location routine, Autoloc and Antelope) and the National Earthquake Database (NED) during the time period from May 7, 2009 to May 6, 2010. Currently the Antelope automated location system is only in use by the Pacific Geological Center (PGC) in Sydney, BC. As this arm of CHIS actively monitors earthquake only those earthquakes occurring west of the Canadian Cordillera, this region will be the focus of the comparative 1 year study. During the study period, there were 1833 earthquakes with magnitudes greater than 2.0 reviewed by the PGC Seismologists and placed within the NED. The locations and times of the events in the NED are hereafter determined to be the definitive locations and times to which the automated solutions will be compared.

During the same period the number of automated final location messages with magnitudes greater than 1.0 produced by all operational variations of Autoloc totalled: 18,736

In comparison, the total number of automated final location email alerts produced and sent via: rt@seis.pgc.nrcan.gc.ca, by Antelope totalled: 498

Autoloc location process

The Autoloc procedure uses the automated real-time detection lists (RDL) produced by single stations to generate events. The RDLs use continuously computed long term averages (LTA) and short term averages (STA) to generate detections in multiple frequency bands. To reduce sharp signal onsets adversely affecting the LTA, the LTA is computed with a 10 sample lag behind the STA. When the STA exceeds a given threshold above the LTA for a predetermined length of time, a detection is declared and the continuous calculation of the LTA is stopped. Upon the STA returning once more to a predetermined level the detection is stopped and the calculation of the LTA is reinstated. If this occurs in the individual frequency bands in such a way that satisfies the system that the detection is an earthquake signal, the detection information is written to the RDL. These individual station RDLs are then made available to Autoloc. Currently four frequency bands between 1.0 and 20 Hz are monitored in this manner to produce RDLs. These bands are:

1/ 1.0 – 3.0 Hz
2/ 3.0 – 6.0 Hz
3/ 6.0 – 12 Hz
4/ 12 – 20 Hz

As each individual station is unique in its seismic noise characteristics, so are the detection thresholds for each band on a specific station.

From the RDLs Autoloc performs a series of post processes on the identified segment of data in an attempt to discern the type of seismic phase detected, the algorithm then begins to build seismic events based upon individual time of detections, their phases, the probabilities that surrounding stations also detected the event and cross referencing these probabilities with the station RDLs. Using this method Autoloc identifies specific probable seismic phases and computes trial locations and magnitudes. A quality factor is then evaluated for the solution using a combination of the number of phases, the stations used and the overall fit to the data. These trial events are then updated as new (or late) station information becomes available until the event is closed, where upon a final message to the CNSN system is delivered with the event location, estimated magnitude and stations/phases used. An example of such a message is provided in Figure 1.

```
GEOLOGICAL SURVEY OF CANADA AUTOMATIC POSSIBLE SEISMIC EVENT LOCATIONS
LOCALISATIONS AUTOMATIQUES D'EVENEMENTS SEISMIQUES POSSIBLES, COMMISSION GEOLOGIQUE DU CANADA
    Date      Time       Latitude Longitude    Depth    Ndef Nsta Gap     Mag1  N    Mag2  N    Mag3  N  Author          ID
       rms   OT_Error       Smajor Sminor Az       Err   mdist  Mdist      Err        Err        Err     Quality

2009/05/07 04:38:03.8     72.9213  -72.8288     10.0 f    14   14 232   MN 2.6  2  mb 3.0  1             CAN_NDC
                                                                         +-0.2      +-0.0                a i uk

173 KM E OF POND INLET, N.W.T.            173 KM E DE POND INLET, T.N.-O.            QUALITY 22 + 4
ULF mag:  3.4 (av of 1):  GIFN   3.4
QUALITY 22 + 4, Lg matches at  GIFN  QILN  RES   SRLN
                        Mn:    2.9   3.0   2.3   2.8  av:   2.7
BAFFIN BAY SEISMIC ZONE.                  PAS DANS UNE ZONE SEISMIQUE               velocity 1

Sta    Dist  EvAz      Phase       Date      Time     TRes  Azim  AzRes  Slow  SRes Def   SNR       Amp   Per   Mag1   Mag2 Arr ID
GIFN    4.06 228.0 a   Sg      2009/05/07 04:39:59.0   7.9                          ---             4.1   0.1
SRLN    5.58 223.4 a   Pn      2009/05/07 04:39:30.6   4.5  33.5   -4.5  13.7   4.8 TAS  88.0       0.7   0.1
SRLN    5.58 223.4 a   Sg      2009/05/07 04:40:31.6   4.2                          ---   9.0       2.8   0.1
SRLN    5.58 223.4 a   TraceMa 2009/05/07 04:41:13.4  19.6                          ---            11.5   0.6 MN 2.8
RES     6.39 296.4 a   Pn      2009/05/07 04:39:38.9   1.1  95.2  -12.2  13.7  -1.5 TA-  30.0       0.4   0.1
RES     6.39 296.4 a   Sg      2009/05/07 04:40:45.4   3.1                          ---   5.0       1.0   0.2
RES     6.39 296.4 a   TraceMa 2009/05/07 04:41:20.5   2.2                          ---             2.3   0.4 MN 2.3
QILN    7.81 223.3 a   Pn      2009/05/07 04:39:59.8   0.9  30.5   -3.5  13.6   4.9 TAS   3.0       2.0   0.2
QILN    7.81 223.3 a   Sg      2009/05/07 04:41:24.5   2.2                          ---             2.7   0.2
STLN    8.82 240.5 a   Pn      2009/05/07 04:40:15.1   1.1  41.5  -11.5  13.6  -0.4 TAS  31.0       1.5   0.1
STLN    8.82 240.5 a   Sg      2009/05/07 04:41:47.9   6.5                          ---   6.0       0.9   0.2
WAGN    9.12 227.7 a   Pn      2009/05/07 04:40:16.8  -1.7  32.1  -38.1  13.6   4.9 T-S  28.0       1.0   0.1
WAGN    9.12 227.7 a   Sg      2009/05/07 04:42:00.5   2.0                          ---             2.1   0.2
FRB     9.33 168.2 a   Pn      2009/05/07 04:40:22.6   1.4 352.2   -3.2  13.6   4.9 TAS  16.0       0.6   0.2
FRB     9.33 168.2 a   Sg      2009/05/07 04:42:04.7   3.0                          ---   5.0       1.7   0.2
BULN    9.56 237.1 a   Pn      2009/05/07 04:40:23.4  -1.0  38.0    9.0  13.6  -1.8 TAS  21.0       0.5   0.1
BULN    9.56 237.1 a   Sg      2009/05/07 04:42:06.4   6.9                          ---   4.0       0.8   0.2
SEDN   11.79 224.2 a   Pn      2009/05/07 04:40:52.8  -2.1  27.1    0.9  13.6   5.0 TA-  32.0       1.0   0.2
JOSN   11.94 224.6 a   Pn      2009/05/07 04:40:55.9  -0.9  27.2 -177.2  13.6   5.0 T--   8.0       0.5   0.2
YBKN   11.95 235.8 a   Pn      2009/05/07 04:40:53.9  -3.2  34.1   12.9  13.6  -0.2 TAS   4.0       0.7   0.2
COKN   16.17 252.0 a   P       2009/05/07 04:41:51.4  -1.3  38.4   15.6  13.2   5.3 TA-   8.0       1.6   0.4
WHFN   16.28 248.3 a   P       2009/05/07 04:41:52.0  -2.0                          T--             1.1   0.4
GDLN   16.42 245.7 a   P       2009/05/07 04:41:54.0  -1.8                          T--             0.2   0.1
FCC    16.46 221.7 a   P       2009/05/07 04:41:56.0  -0.4  22.2   14.8  13.2   5.3 TA-   4.0       0.4   0.2
GALN   17.99 263.8 a   P       2009/05/07 04:42:12.4   3.3                          ---             0.1   0.2
SCHQ   18.31 168.9 a   P       2009/05/07 04:42:20.9   1.4                          ---             0.5   0.3 mb 3.0
SILO   19.16 201.8 a   P       2009/05/07 04:42:25.1   4.5  10.8  -43.8  12.2   6.3 ---   5.0
INK    19.80 287.2 a   P       2009/05/07 04:42:39.9   3.0  49.4  124.6  11.8   6.8 ---   4.0       0.8   0.2
```

Figure 1: Example of an Autoloc finalized earthquake location message.

Since the Autoloc algorithm uses probabilities to determine the suitability of associating individual station RDL detections together to build events, many poor quality and even false events are created during the process due to spurious phase associations and/or too few phases. This is reflected in the significant quantities of Autoloc event messages provided earlier, with most of these having relatively low quality factors compared to the equivalent numbers for Antelope seen previously. Yet a significantly large event may still have several individual Autoloc location messages associated with it, each with a high quality, as the solution is revised with phases arriving later at more distant stations being added.

Currently there are two instances of the Autoloc procedure in day to day operational use by the CNSN. The first uses a combination of stations across Canada for both location and magnitude and location-only purposes and serves as the main automated system for the country (Figure 2a). The second instance is a tailored subset of the CNSN stations specifically for locating earthquakes occurring in and around the Vancouver Island and lower mainland region (VILM) of British Columbia (Figure 2b).

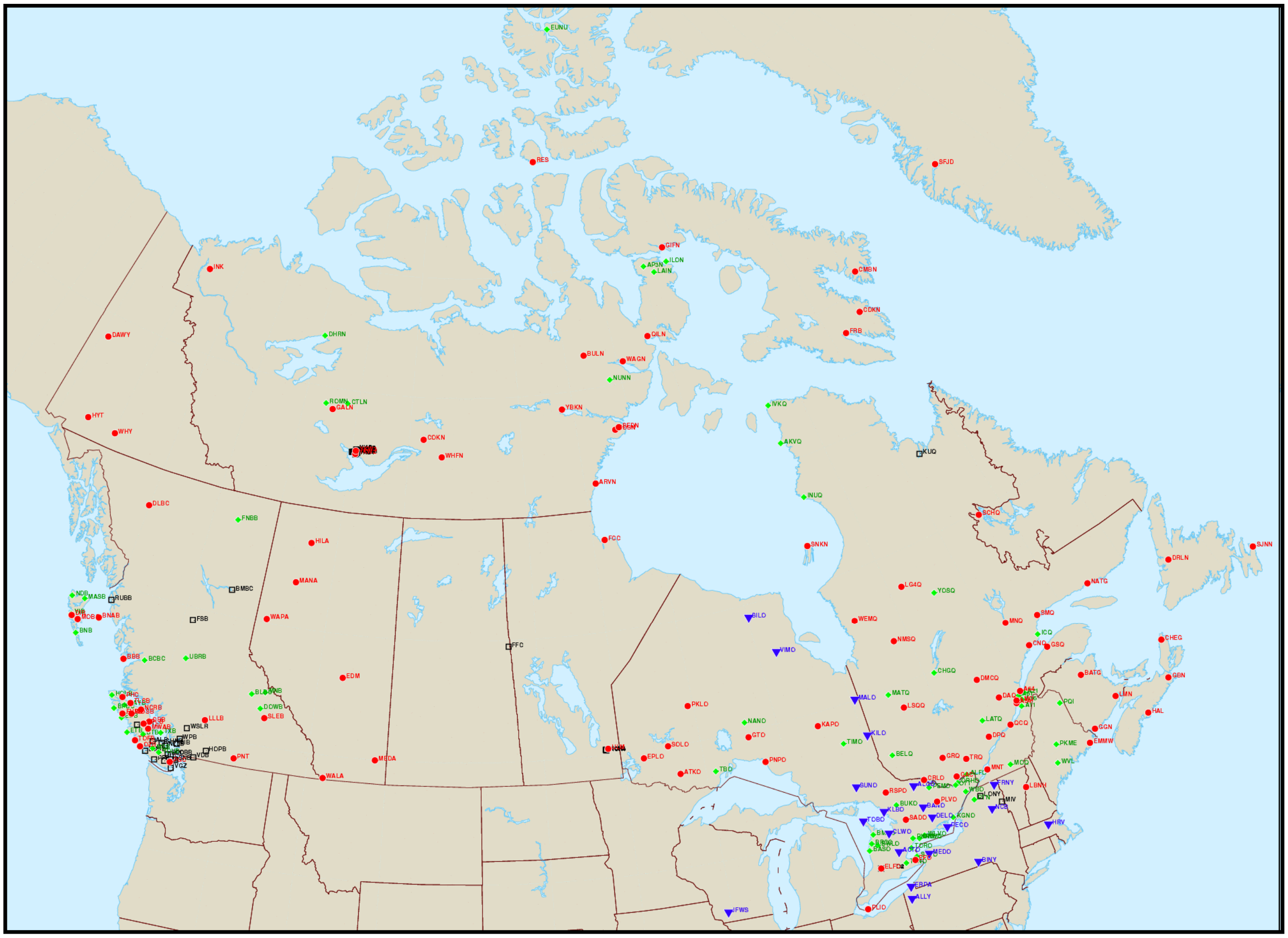


Figure 2a: Station map showing the CNSN and POLARIS stations used for the Canada-wide application of Autoloc. Red stations are used both for location and magnitude estimation. Blue stations are used for location purposes only. Green stations are available but are not used for either location or magnitudes. Black stations provide waveform data, but do not produce real-time detection lists (RDLs).

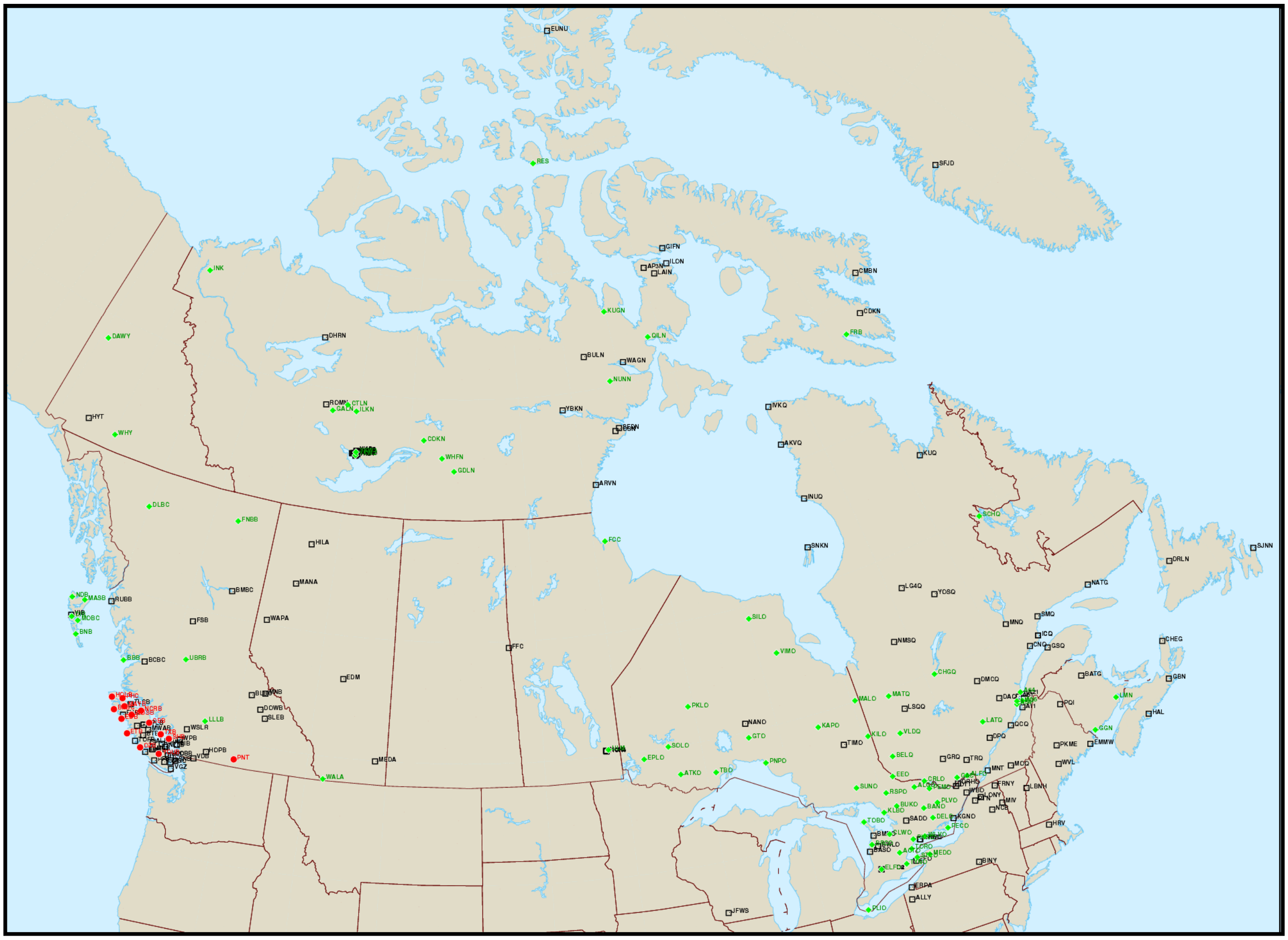


Figure 2b: Stations used (shown in red) for the PGC application of Autoloc designated for the Vancouver and Lower Mainland region of British Columbia (VILM). As such only stations within the Vancouver Island region are used for location and magnitude estimates.

Antelope process

The automated earthquake location procedures employed by Antelope use a similar method for individual station detections, whereby LTA/STA behaviour is used to identify detections in multiple frequency bands. Specifically for Antelope there are three frequency bands:

1/ 0.5 – 1.2 Hz
2/ 0.8 – 3.0 Hz
3/ 3.0 Hz Highpass

where the LTA window is set to 4.0 seconds, and STA at 0.5 sec.
The detection threshold requires a minimum signal to noise ratio (SNR) of STA/LTA of 4.5 to produce a detection onset.

In similar fashion as described previously these RDLs are used by the Antelope automated procedure to identify and locate earthquakes in the west coast region of Canada, by identifying detections at nearby stations and building an event and identifying specific seismic phases.

Specific to Antelope, the location procedure is used in discrete regions, where a minimum number of stations are required to accept an automated location. Physically the minimum number of stations required to locate an earthquake in time and space is 3, one station for each orientation in space, 2 horizontal dimensions and depth. The time of the event is parametrically related to an earthquake's location from the chosen Earth velocity model.

The regions and minimum number of stations required for acceptable auto-location by Antelope that are currently active are:

Offshore (generic Pacific Ocean events):	min. 4 stations
Queen Charlotte Islands:	min. 3 stations
Vancouver Island:	min. 3 stations
Western Canada (onshore):	min. 3 stations
Eastern Canada:	min. 6 stations
Teleseismic:	min. 8 stations

The number of stations required for an auto-location has been tailored such that Eastern earthquake auto-locations do not overwhelm PGC seismologists and balance the rate of true auto-locations to false alarms (non-earthquake locations) at local earthquake magnitudes (ML) greater than 2.5-3.0 in and around the populated centers of British Columbia (primarily the Vancouver region). That is events that are likely to be felt by citizens.
Previously another region surrounding the Charlevoix seismic zone of Southern Quebec was employed with a minimum requirement of 6 stations, however this region is no longer in use due to the overwhelming number of events identified and sent to analysts daily at the PGC.

Upon identifying and locating a potential earthquake event, Antelope issues a message to the system (similar to Autoloc) providing the location, time and number of phases used in the automated location procedure. However the specifics of the stations and phases used is not. An example of these messages is provided in Figure 3.

```
This is an automatic earthquake solution from the
Geological Survey of Canada - Pacific Geoscience Centre

Please DO NOT DISSEMINATE this automatic solution.

Lat:    44.4716
Lon:    -129.0101
Depth:  15.0000 km
Time:   2010-05-07 17:46 18.806 UT  (Friday)
        2010-05-07 10:46 18.806 PDT (Friday)

Magnitude: 4.37 ML

39 phases used in solution

This earthquake was:

        529 km   W of Portland
        563 km SSW of Ucluelet
        571 km SSW of Tofino

For more information monitor http://www.earthquakescanada.ca
or call 250-363-6500.  Analysts reviewed solutions will be
posted to the web as soon as they are available.
```

Figure 3: Example of an Antelope finalized earthquake location message.

These auto-locations, similar to Autoloc locations, are automatically revised as new/late station information is provided, with messages typically being revised (as necessary) approximately 2 minutes after the initial solution. Often initial estimates are satisfactory, but have been observed to have been revised from once to up to a maximum 5 iterations.

Comparison to the Reviewed database

The *EarthquakesCanada* NED solutions are used as ground truth in this study as each event in the database has been reviewed by a seismologist prior to its inclusion in the NED and so is viewed as the definitive location for the earthquake.

As this is a performance comparison only of the automated systems, and viewed in light that no specific phase information is provided in the Antelope automated messaging system, the automated locations from both systems will be compared to each other in terms of:

1 – What percentage of the reviewed earthquakes were located automatically at magnitudes (ML) > 2.0? >3.5?

2 – How far from the reviewed location are the automated solutions on average?

3 – What difference is there between the automated location magnitude and that of the reviewed database?

4 – What is the distribution of these automated solutions across the West Coast?

5 – How do the two systems compare with one another?

To compare the automated and reviewed earthquake solutions, the following procedure is used: For each reviewed earthquake larger than magnitude 2.0 the lists of Autoloc and Antelope solutions are searched within space and time to locate any and all automated locations within a specified radial distance and time window. Any automated locations within this search are assumed to be associated with the reviewed earthquake. If multiple automated epicentres lie within the search area, then the automated epicentre closest to the reviewed epicentre is taken as the best candidate (Figure 4).

Once identified, the various differences and statistics between the automated location and NED location are taken.

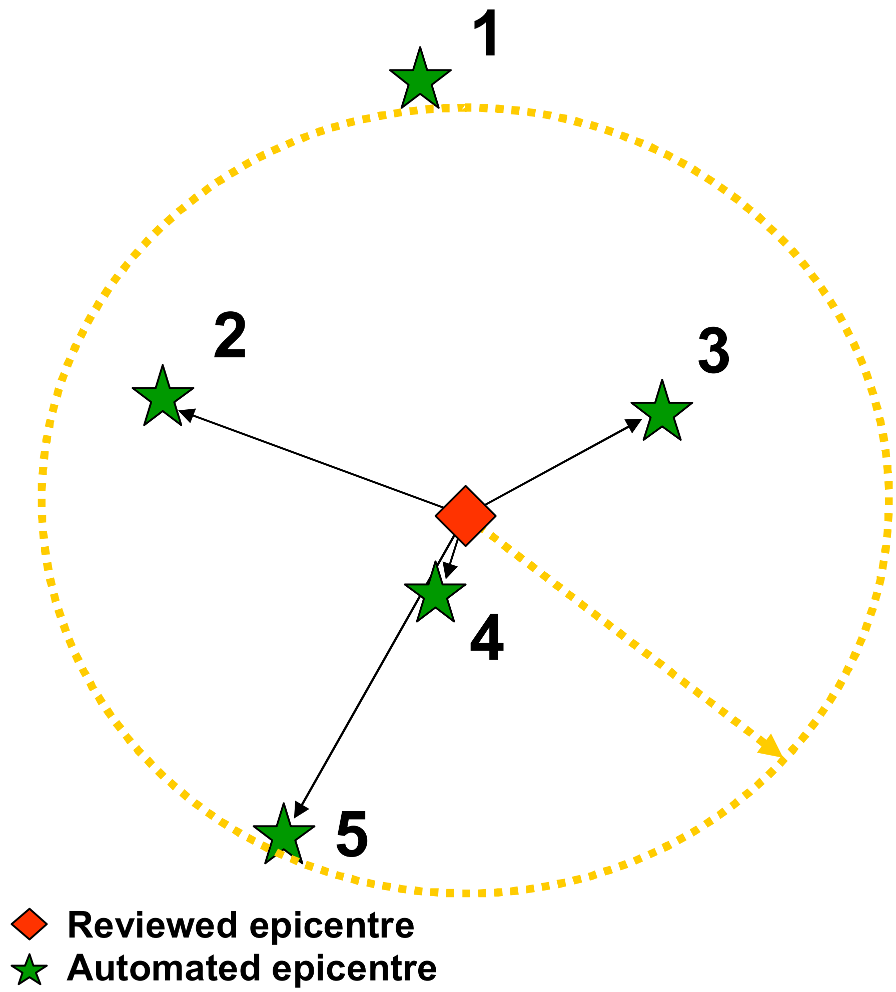
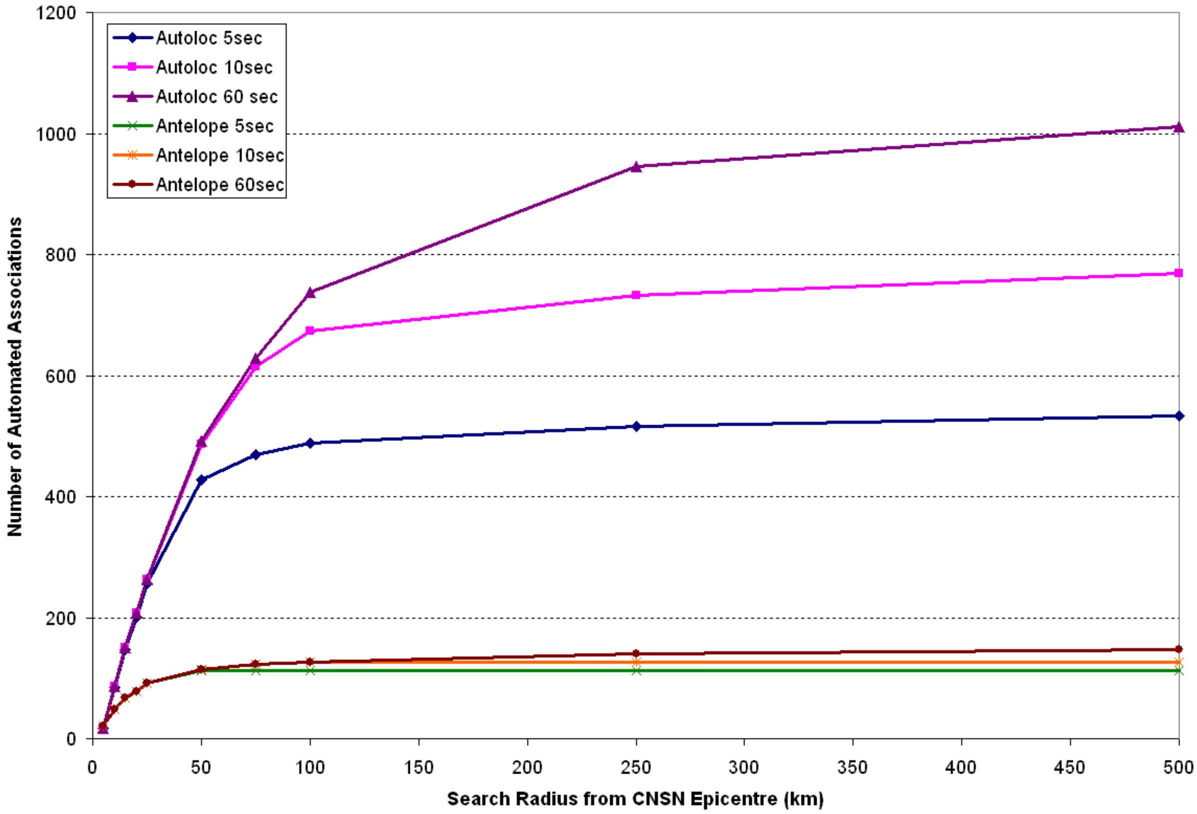


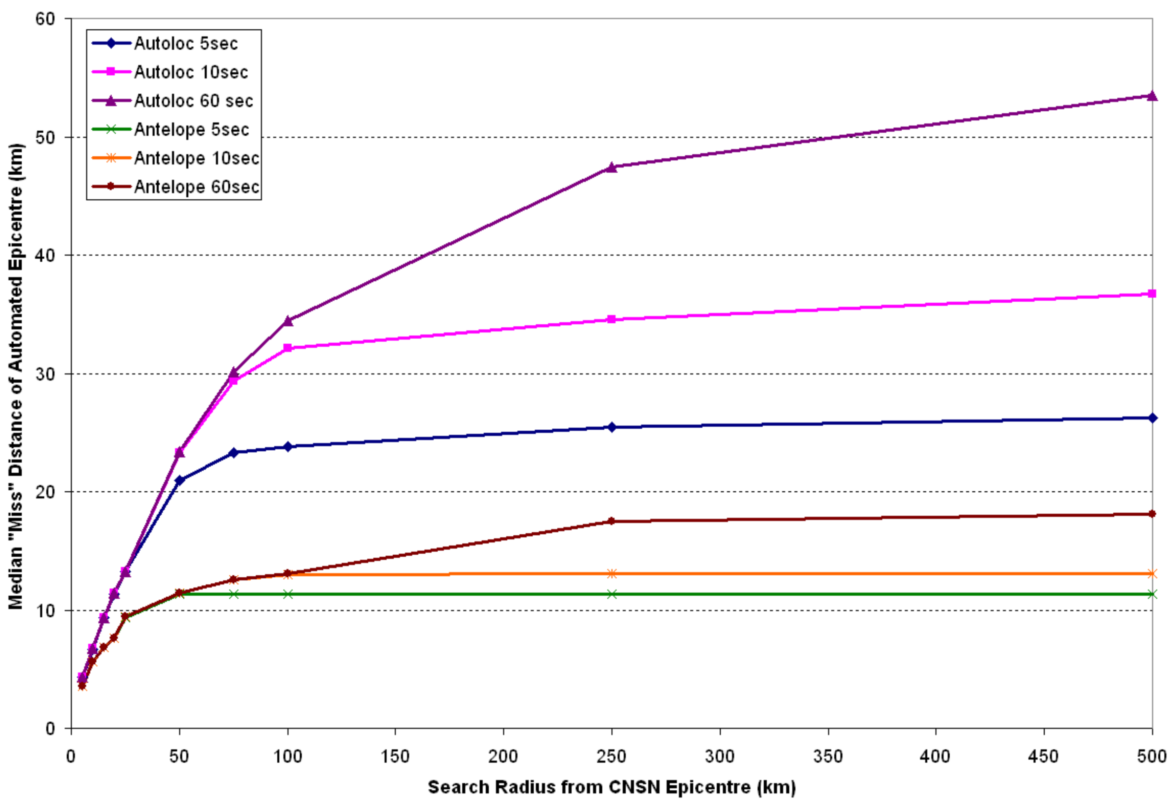
Figure 4: A schematic diagram of the epicentral search for automated solutions for any given reviewed earthquake in the database. A circular region surrounding the event is searched both in space and time (of variable size and duration) wherein any events located in the search region are then associated with the event. If multiple automated solutions exist, then that which is closest to the reviewed epicentre is chosen, in this example automated epicentre #4.

Results:

To determine an optimal size of the search parameters, a variety search radii and time windows were used, ranging from 5 to 500 kilometres with time windows ranging from 5 to 60 seconds. As the larger the search area and time window become, the number of associations made for each epicentre increases accordingly, however, the likelihood of spurious or poor quality automated locations that are not truly associated with the reviewed event also increases. This is shown in Figure 5, where larger beyond ~100 km radius and a 10 second window little change is seen in the number of Antelope associations but large variation in the median “miss” distance is observed, indicating the presence of significant outliers, likely spurious associations adversely affecting the statistics, similarly this occurs with Autoloc at ~75 km. Thus for comparison of the two automated methods, a window of 100 km and 10 seconds for automated/reviewed associations is chosen.



(a)



(b)

Figure 5: Changes in the number of automated epicentre associations (a) and median "miss" distance (b) as the search area radius and time window increase.

Using a search window of 100 km and 10 seconds to associate the numerous automated event locations and those in the NED, the Autoloc algorithm produced the greatest number of event associations per month consistently in comparison to Antelope (Table 1). Yet, in general in terms of quality of the automated location and accuracy of magnitude compared to the NED, Antelope seems to outperform that of Autoloc. Details of the statistics of the associated automated solutions in comparison to the reviewed catalogue are shown in Figures 6-11 for Autoloc and in Figures 12-16 for Antelope.

Detection

At all magnitudes Autoloc is able to identify consistently more events than Antelope across the Western Canada study region, while for Antelope most detected events tend to lie closest to the region between Vancouver and the Queen Charlotte Islands (Figure 16). In part this is due to the tailoring of the Antelope algorithm for optimal performance within this region (T. Mulder, Private Communication, 2009), however even in instances within this region a significant number of >3.5 magnitude earthquakes went unlocated by Antelope. In particular during the November period, where 20 of 23 earthquakes were unlocated (Table 1), 14 of which where within the optimized region being significant aftershocks of the Queen Charlotte Islands Mw 6.5 earthquake. In comparison, Autoloc achieved a nearly 96% success rate during this period, with the only unlocated event being a 5.3 magnitude aftershock event occurring ~7 minutes after the main quake.

Month	**# of Eqkes >2.0**	**# of Eqkes >3.5**	**# >2.0 Located Autoloc**	**# >2.0 Located Antelope**	**# >3.5 Located Autoloc**	**# >3.5 Located Antelope**
May 2009	96	3	29	7	2	0
June 2009	114	2	51	19	1	1
July 2009	92	4	35	16	2	2
August 2009	119	5	46	18	4	1
September 2009	109	5	44	10	3	0
October 2009	138	7	63	14	7	1
November 2009	259	23	81	6	22	3
December 2009	239	3	68	8	3	1
January 2010	175	5	65	8	4	1
February 2010	135	4	58	11	4	1
March 2010	155	7	62	4	7	1
April 2010	169	2	63	3	2	0
May 2010	33	1	8	2	0	1
Total	***1833***	***71***	***673 (36.7%)***	***126 (6.9%)***	***61 (85.9%)***	***13 (18.3%)***

Table 1: Distribution of earthquakes in time during the duration of the study and the number of auto-located events greater than magnitude 2.0 and 3.5 identified by Autoloc and Antelope. Autoloc's ability at identifying events significantly outperforms Antelope during this period both at small (2.0) and larger (>3.5) magnitudes, in particular during the aftershock sequence of the Queen Charlotte Islands Mw 6.5 earthquake on November 17, 2009.

Location

Despite its apparent current inability to locate earthquake events consistently in comparison to Autoloc, Antelope's strength appears to be in the quality of its event solutions and by extension its ability to identify specific phases and choose arrival times. In terms of distance and origin time from the seismologist reviewed location, the Autoloc algorithm produces locations that have a mean "miss" distance of 37 +/- 24 km, and an origin time offset of +2.0 +/- 4.0 seconds (Figures 6, 8, 9). The Antelope algorithm in comparison produces a mean "miss" distance of 20 +/- 19 km and -0.04 +/- 0.25 seconds in origin time, a nearly 50% improvement in distance and significantly better in time (Figures 12, 14, 15). On average this is achieved with 7 to 9 seismic phases (Figure 17). It is difficult to directly compare this on average to Autoloc, as Autoloc uses a quality factor rather than phases to measure its location effectiveness, with a mean quality factor of 11.3 +/- 4.8. This will be looked at more directly on a case by case basis in the next section.

As the magnitude of the earthquake increases, it is seen that the Autoloc location algorithm improves marginally, but yet still does not reach level with Antelope (Figure 18a).

Magnitude

Of all the comparative quantities, magnitude is most difficult to directly compare due to the general lack of specific control of the reviewing seismologist to control or change the amplitudes and periods chosen on the waveform to be used for magnitude calculation in Antelope. In Antelope the seismologist has independent control over the time picks for the arrival of a phase and the specific phase to which this pick belongs, however, the amplitudes and periods used for magnitude measurement are automatically picked by the system and not by the seismologist. This automated measurement likely uses the same algorithm employed by the automated Antelope system. When an automated solution arrives, the seismologist may add or remove phase picks or new stations, but not independently pick amplitude measurements. Thus the computed magnitude of an automated Antelope location is only greatly affected when arrivals are significantly mis-identified and the location is significantly incorrect, otherwise only minor magnitude differences are likely to result from the minor changes in epicentral location and depth and is seen in the comparison of magnitudes between Antelope and the NED reviewed solution (Figure 13) with a mean magnitude difference of -0.04 +/- 0.25. This result does not change appreciably with magnitude, save for events with magnitudes between 4.0 and less than 5.0, where the small number of associated events with a number of quite poorly located events skew the mean significantly (Figure 18b).

In comparison, Autoloc solutions and magnitudes are completely independent of the PGC Antelope systems and so may be compared more confidently to those of the reviewed database. In the case of Autoloc associated location magnitudes, an over mean of -0.30 +/- 0.42 magnitudes is observed for all events (Figure 7), yet this is dominated by the numerous small < 3.0 magnitude events, where presumably SNR of arrivals may be quite low. As magnitude of the earthquake increases, this difference in magnitude improves significantly becoming comparable to that seen for the Antelope algorithm (Figure 18b).

Autoloc Associated Automated Locations (Figures 6-11)

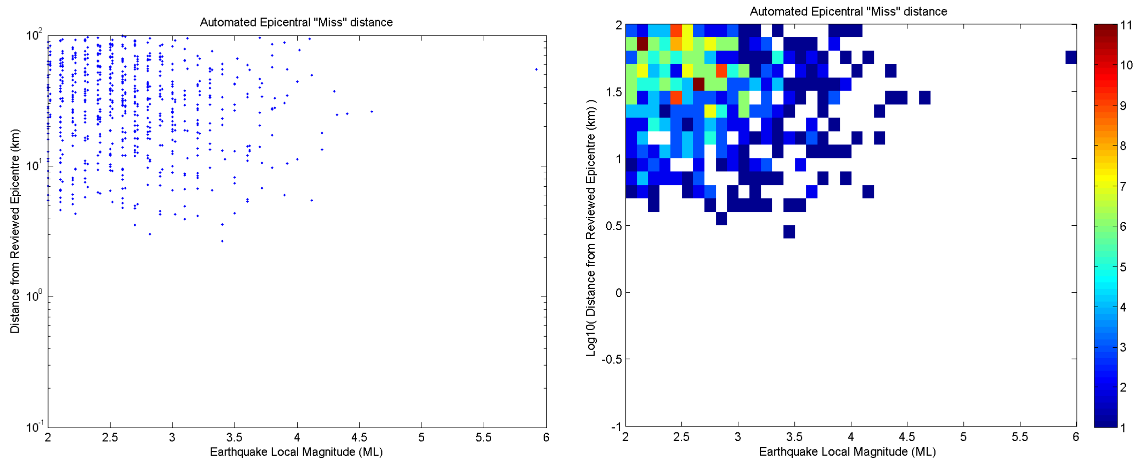


Figure 6: Distribution of Autoloc miss distances as a function of local magnitude ML from their associated reviewed locations in the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 10% of log(distance) and 0.1 magnitude difference. Overall mean: 37 +/- 24 km.

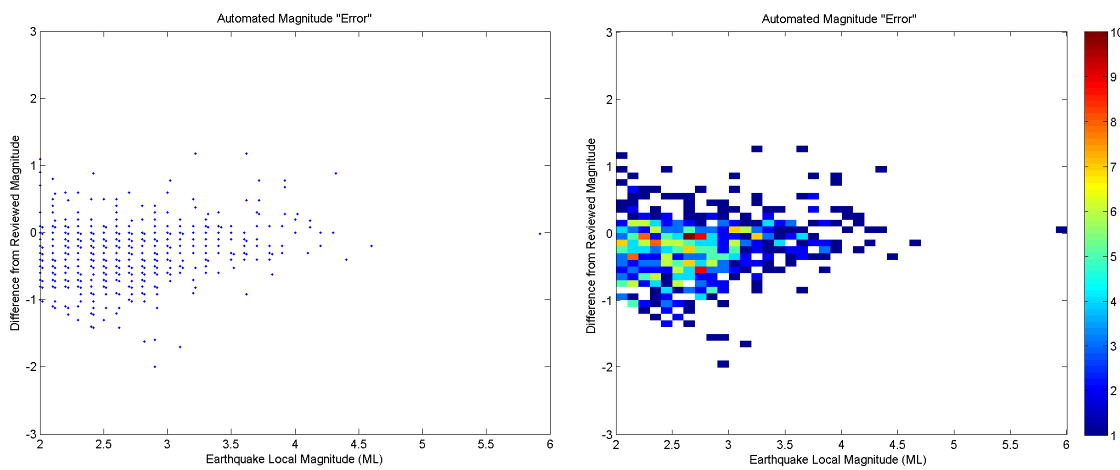


Figure 7: Distribution of associated Autoloc earthquake magnitude differences as a function of local magnitude ML from the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 0.1 magnitude and magnitude difference. Overall mean: -0.30 +/- 0.42 magnitudes.

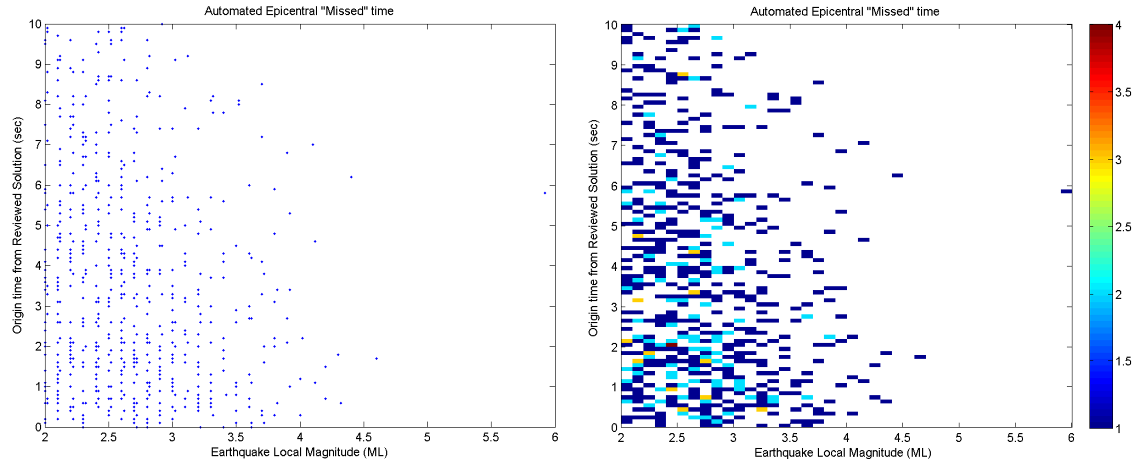


Figure 8: Distribution of Autoloc earthquake absolute timing differences as a function of local magnitude ML from the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 0.1 second and magnitude difference.

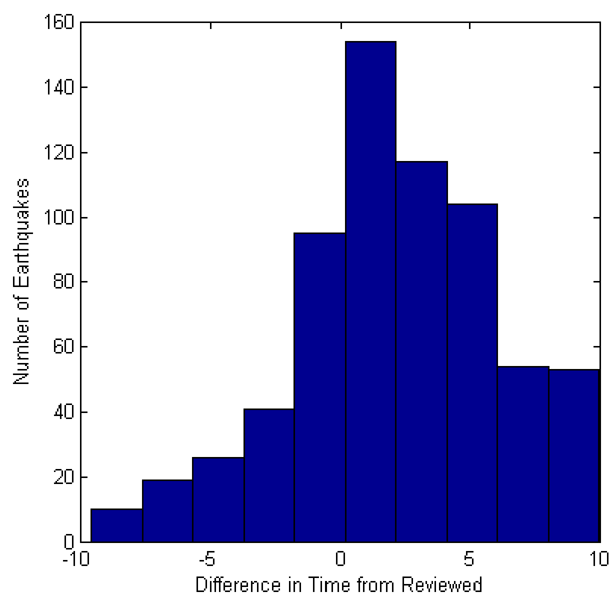


Figure 9: Distribution of origin time differences between associated Autoloc locations and the NED reviewed earthquake. Note that the distribution is skewed to later origin times due to the larger "miss" distances of Autoloc locations. Overall mean: 2.0 +/- 4.0 seconds.

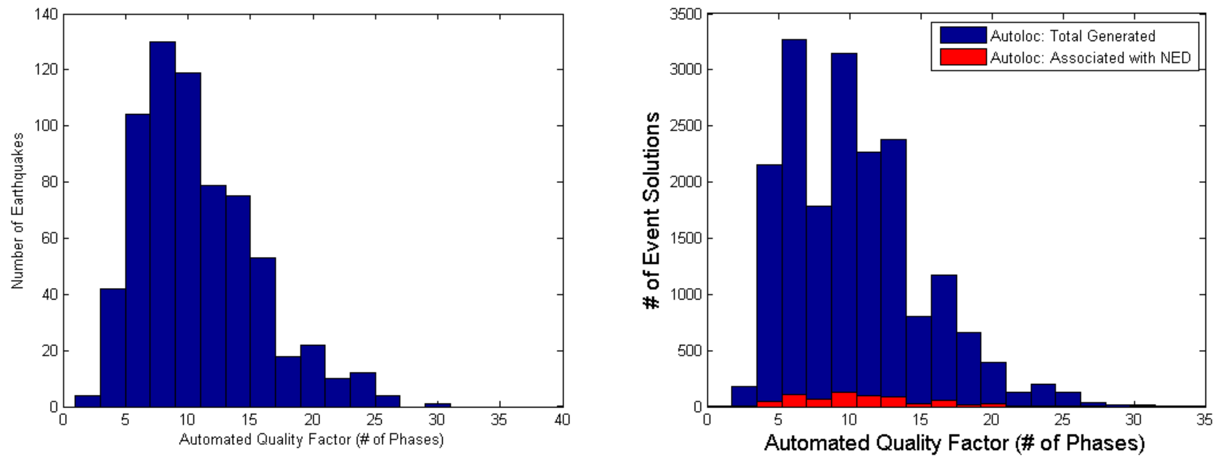


Figure 10: Distribution Autoloc location algorithm quality factors for those associated with NED earthquakes (left). Mean: 11.3 +/- 4.8. Median: 10. Compared to the total number of event solutions generated by the Autoloc algorithm (right), the associated events represent only a minor subset, suggesting a high rate of false positives.

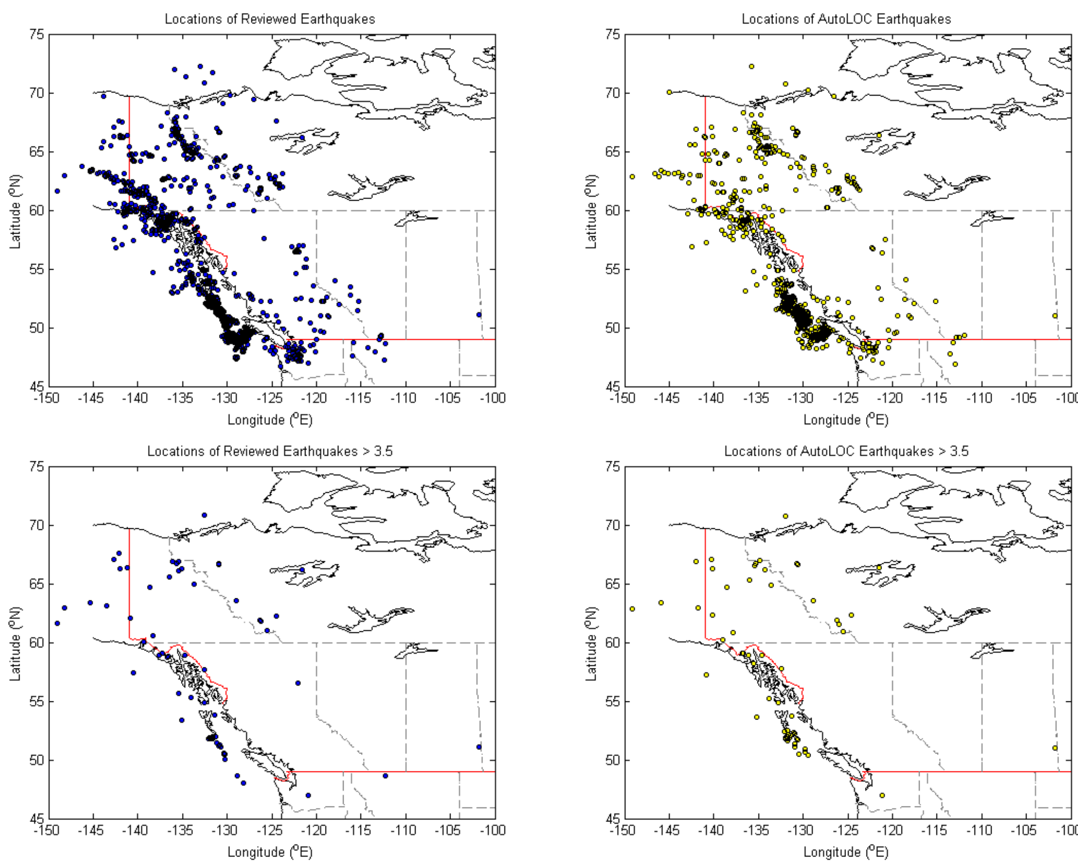


Figure 11: Locations of reviewed (left) and their associated Autoloc locations (right) for earthquakes with magnitudes >2.0 (top) and >3.5 (bottom).

Antelope Associated Automated Locations (Figures 12-18)

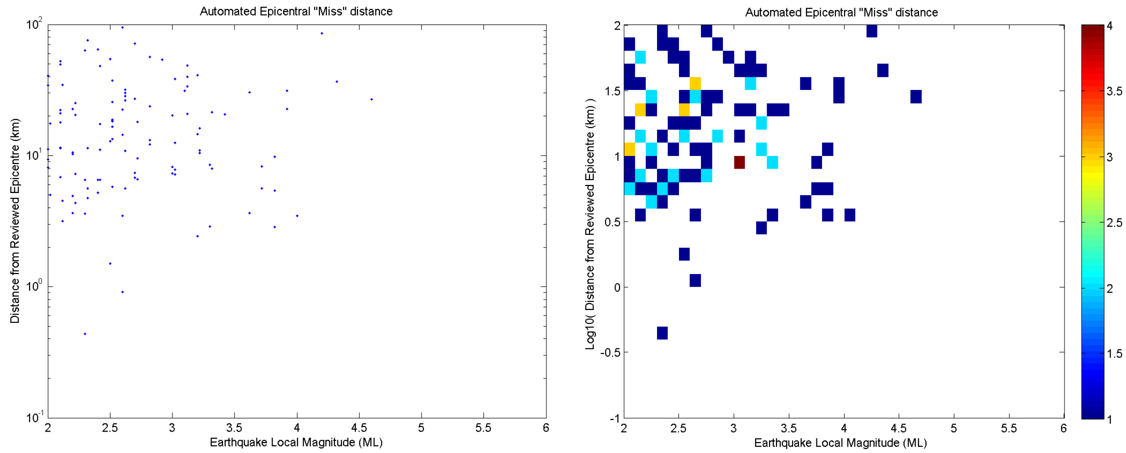


Figure 12: Distribution of Antelope miss distances as a function of local magnitude ML from their associated reviewed locations in the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 10% of log(distance) and 0.1 magnitude difference. Overall mean: 20.0 +/- 18.9 km.

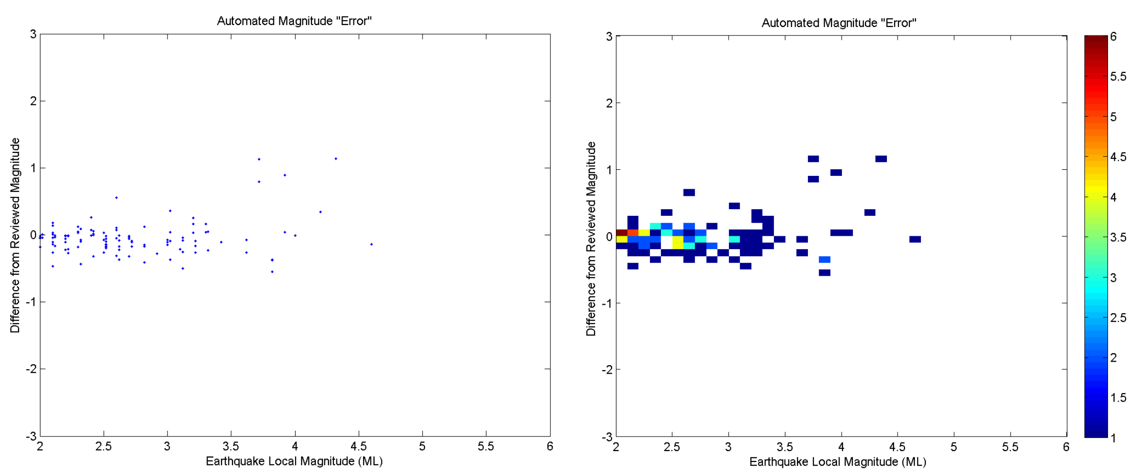


Figure 13: Distribution of associated Antelope earthquake magnitude differences as a function of local magnitude ML from the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 0.1 magnitude and magnitude difference. Overall mean: -0.04 +/- 0.25 magnitude.

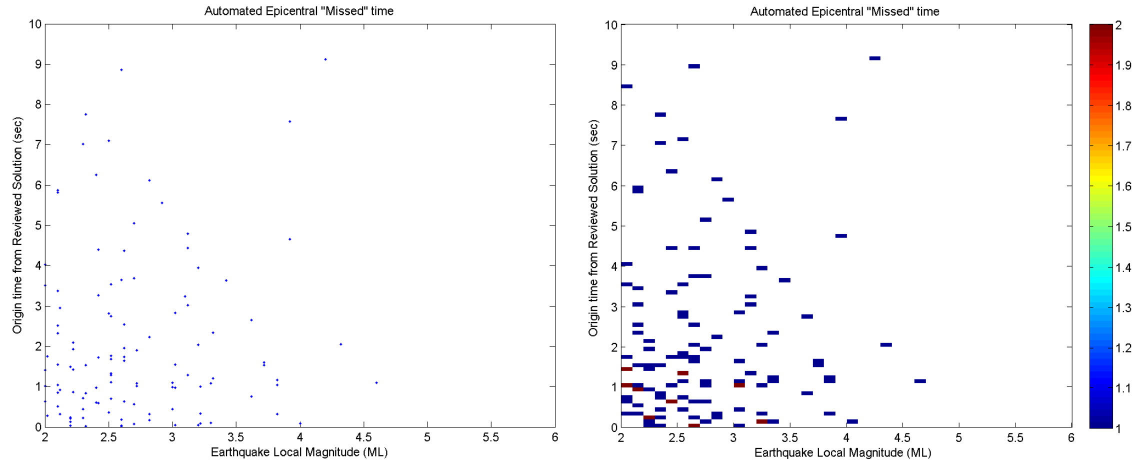


Figure 14: Distribution of Antelope earthquake absolute timing differences as a function of local magnitude ML from the NED catalogue. (left) Scatter plot of individual values. (right) Density plot of (left) binned in increments of 0.1 second and magnitude difference.

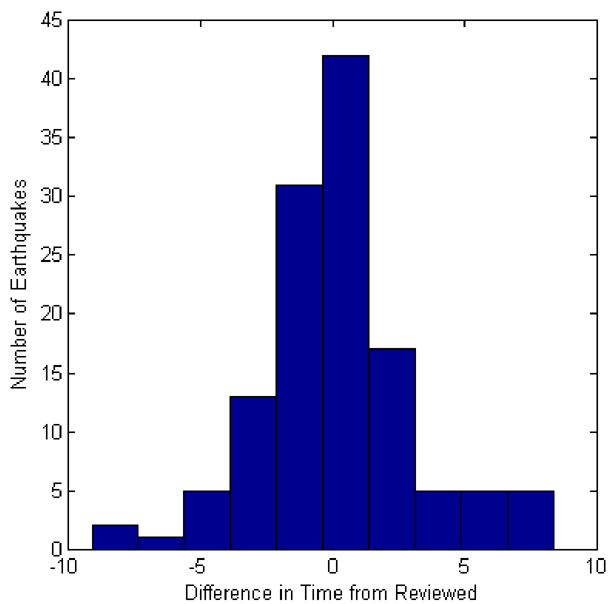


Figure 15: Distribution of origin time differences between associated Antelope locations and the NED reviewed earthquake. Note that the distribution is more Gaussian in structure than that Autoloc (Figure 10). Overall mean: -0.04 +/- 0.25 seconds.

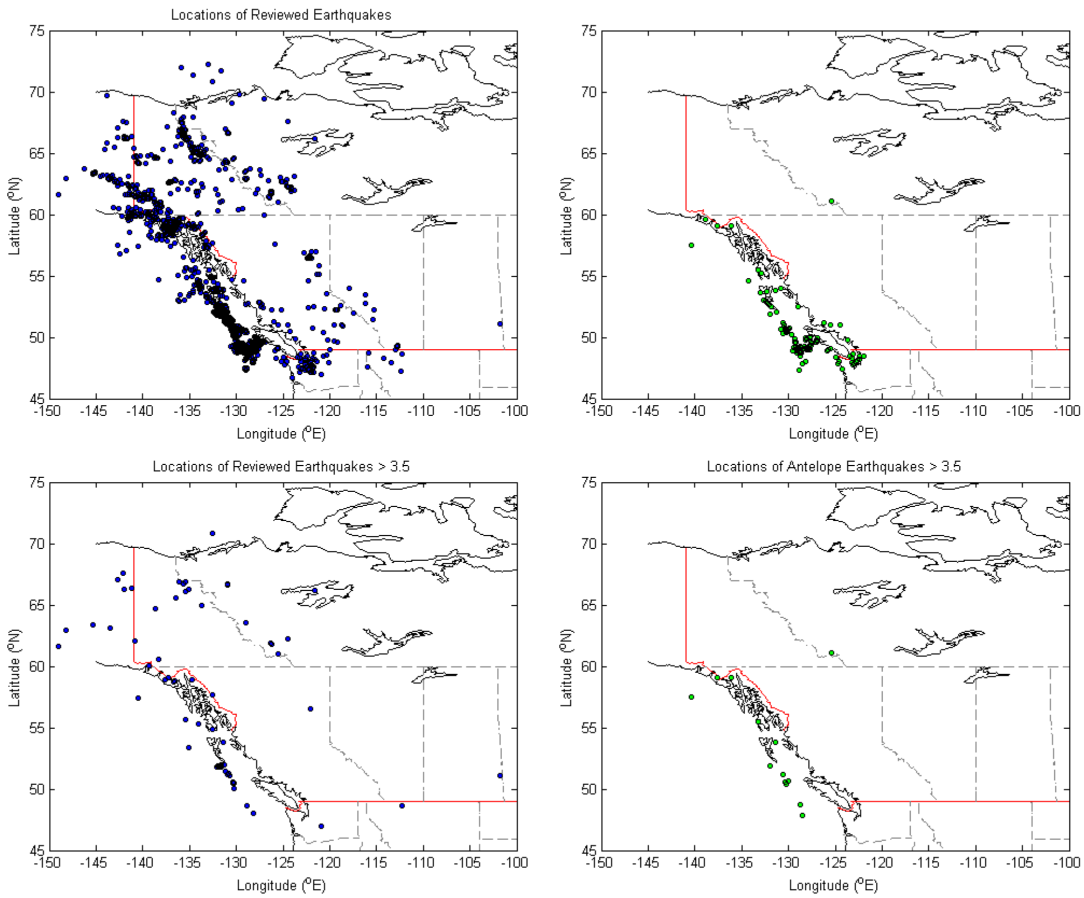


Figure 16: Locations of reviewed (left) and their associated Antelope locations (right) for earthquakes with magnitudes >2.0 (top) and >3.5 (bottom).

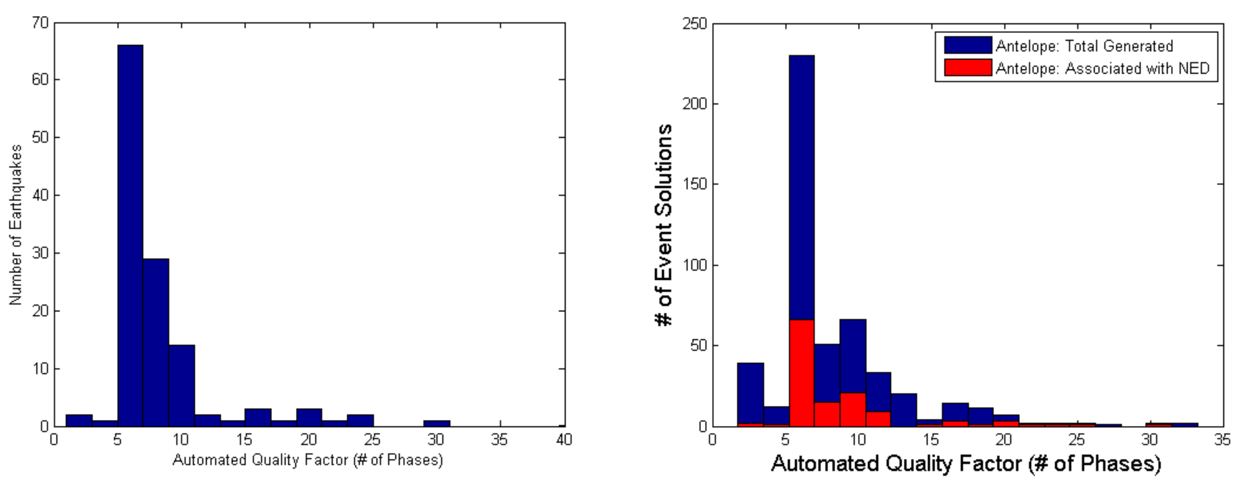
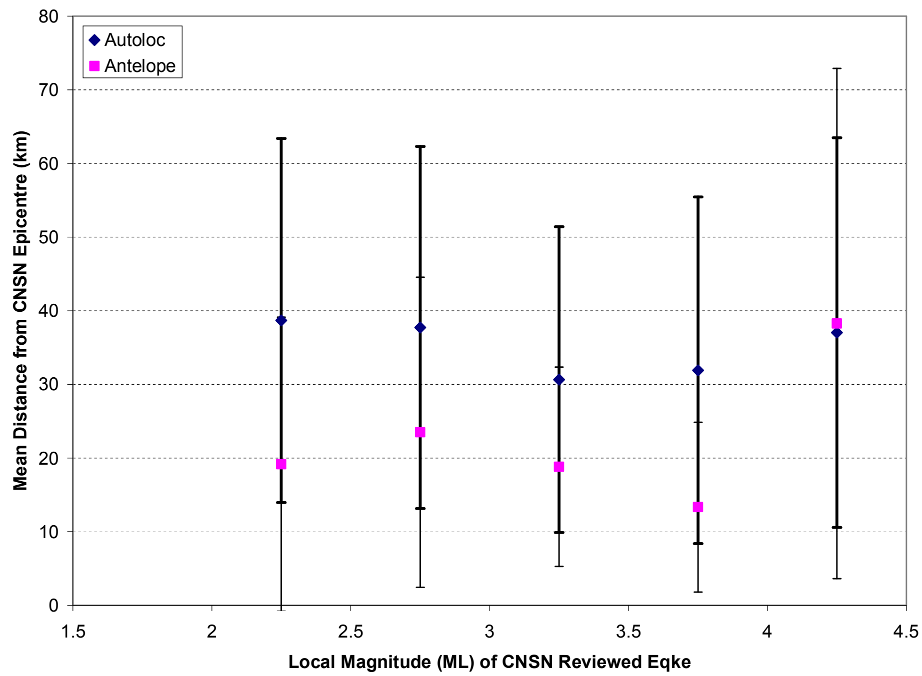
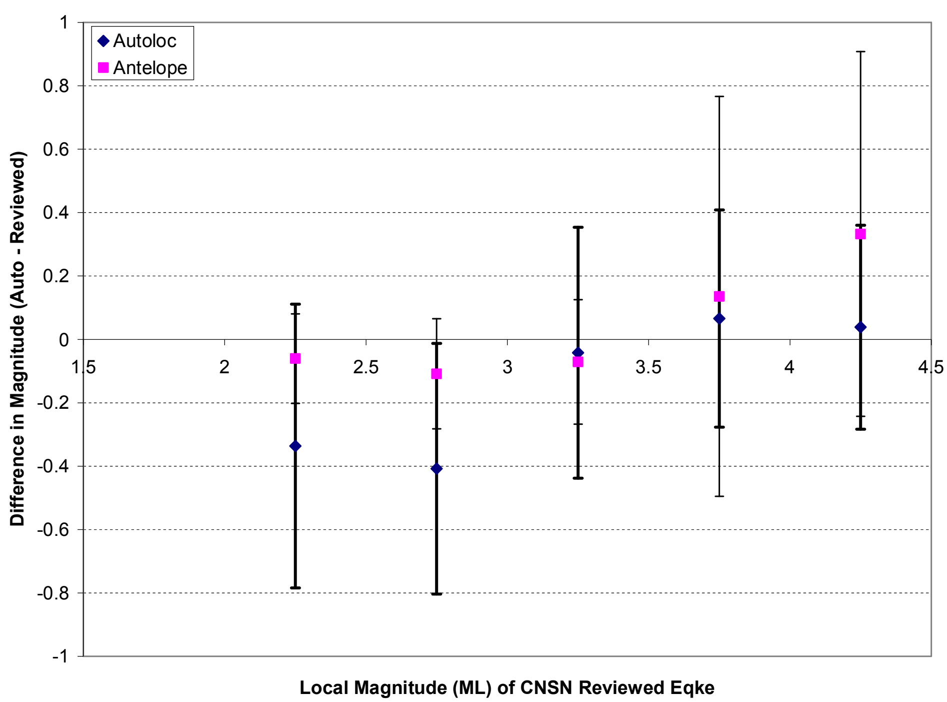


Figure 17: Distribution of the number of phases required for solution for an associated NED earthquake by the Antelope location algorithm (left). Mean: 9 +/- 4. Median: 7. Compared to total number of automatically generated solutions (right), Antelope has a relatively lower number of false positives compared to Autoloc (Fig. 11).



(a)



(b)

Figure 18: Changes in (a) the distance from the reviewed epicentre and (b) difference in magnitude of the automated associated events from reviewed earthquakes as a function of earthquake magnitude.

Common Events

In the total of 673 Autoloc and 126 Antelope associated earthquake locations, 95 were found to be common to both datasets, of which 11 have magnitudes >3.5 (Figure 19). These 11 events are summarized in Table 2 with their various statistics and the number of phases used in their solution. For those events (31 in total) located by Antelope and not by Autoloc; all are located within the region between the Queen Charlotte and Vancouver Islands where Antelope has been optimized. Only two of these have magnitudes >3.5, and both are located off the coast of Vancouver Island:

2010/01/12 21:51:45 UT	48.67°N, 128.89°W	ML: 3.82
2010/05/06 23:12:29 UT	48.04°N, 128.19°W	ML: 3.92

For the majority of the cases for events >3.5 between the Autoloc and Antelope algorithms results mimic the previous findings of the dataset as a whole, where Antelope solutions tend to be closer to the reviewed solution with somewhat smaller differences in magnitude than those of Autoloc. Interestingly this is reported as being achieved in general using a limited number of seismic phases in comparison to either the Autoloc procedure or the reviewed database, on average 8 phases versus 22 and 27 respectively (Table 2). This degree of success with fewer arrivals with the Antelope algorithm for picking arrival times and associating phases may provide an area of investigation, to enhance that which is currently used by the Autoloc algorithm, in effect combining the best abilities of both systems.

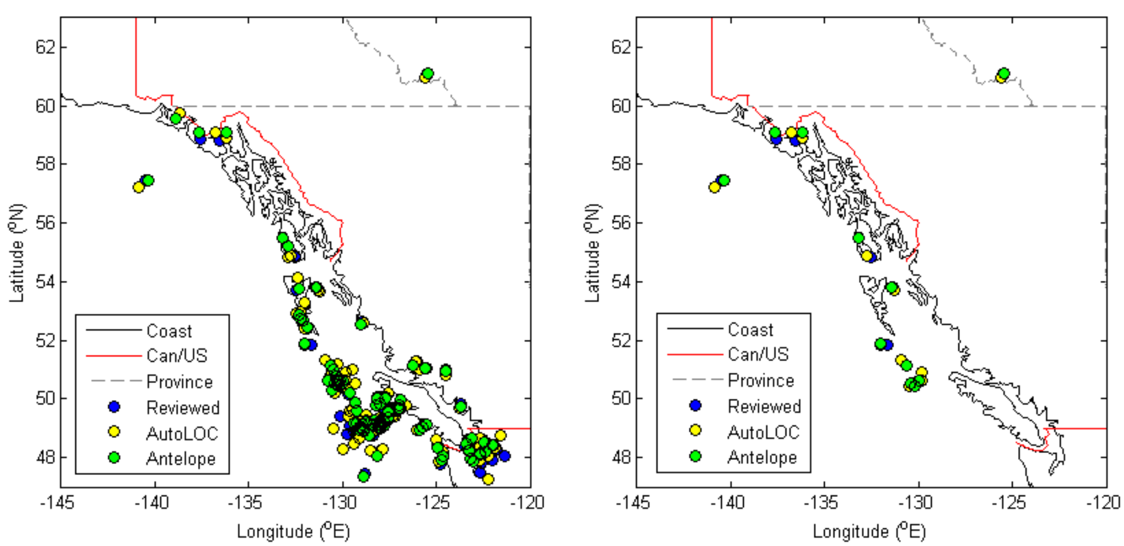


Figure 19: Map of common associated events between Autoloc and Antelope. (left) Earthquakes with magnitudes >2.0, total: 95. (right) Earthquakes with magnitudes >3.5, total: 11.

Type	Time yyyy/mm/dd.hh:mm:ss +/- dTime (sec)	Latitude (°N)	Longitude (°W)	Depth (km)	Magnitude (dmag)	# Phases Used	"Miss" Distance (km)
Review	2009/06/07.23:24:36	58.81	136.56	15	4.32	24	0
Autoloc	+0.6	58.8879	136.1605	10	+0.88	20	24.6
Antelope	+2.05	59.0720	136.1674	0.0	+1.14	8	36.8
Review	2009/07/03.03:06:41	53.80	131.40	7.4	4.00	12	0
Autoloc	+1.2	53.7151	131.3051	10	0.00	35	11.3
Antelope	-0.09	53.8290	131.4201	18	-0.01	8	3.5
Review	2009/07/31.17:46:50	61.05	125.50	1.0	3.72	39	0
Autoloc	-1.6	60.9593	125.5603	10	+0.28	49	10.6
Antelope	+1.54	61.0861	125.4268	20	+1.13	7	5.6
Review	2009/08/06.22:39:37	50.52	130.37	10	3.62	37	0
Autoloc	-0.1	50.4556	130.5234	10	-0.32	20	13.0
Antelope	-0.76	50.5516	130.3830	10	-0.07	12	3.6
Review	2009/10/12.11:10:03	50.47	130.20	10	3.82	27	0
Autoloc	+3.4	50.6331	129.8084	10	-0.62	32	33.1
Antelope	-1.16	50.4221	130.1865	10	-0.37	10	5.4
Review	2009/11/06.10:19:52	57.45	140.51	10	3.72	16	0
Autoloc	-3.8	57.2062	140.8547	10	+0.48	27	34.1
Antelope	+1.60	57.4619	140.3739	15	+0.79	9	8.2
Review	2009/11/08.20:54:44	54.84	132.55	20	4.20	18	0
Autoloc	-1.5	54.8625	132.7542	10	0.00	43	13.3
Antelope	-9.12	55.5111	133.2174	20	+0.34	6	85.8
Review	2009/11/17.16:26:21	51.82	131.64	20	4.60	13	0
Autoloc	+1.7	51.8606	132.0152	10	-0.20	24	26.2
Antelope	+1.10	51.8845	132.0184	12	-0.14	6	27.0
Review	2009/12/23.08:08:31	50.55	130.37	10	3.62	27	0
Autoloc	+4.2	50.8986	129.8232	10	-0.92	20	54.6
Antelope	+2.66	50.6402	129.9653	10	-0.26	11	30.3
Review	2010/02/15.17:29:12	58.87	137.60	1.0	3.92	13	0
Autoloc	+5.3	59.0933	136.7453	10	+0.68	17	54.9
Antelope	+7.58	59.0737	137.6338	35	+0.89	7	22.7
Review	2010/03/04.22:29:14	51.13	130.66	10	3.82	14	0
Autoloc	+0.6	51.3227	130.9168	10	-0.32	18	27.9
Antelope	-1.05	51.1501	130.6245	10	-0.38	7	2.9

Table 2: Common associated earthquake epicentres detected by both the Autoloc and Antelope automated algorithms as compared to that of the reviewed database. Time and magnitude differences are shown as residuals where: residual = automated – reviewed.

Summary & Future Work

Two different automated earthquake location algorithms are currently in use by the *EarthquakesCanada*; Autoloc and Antelope. Although Autoloc is currently the only one in use for day-to-day country-wide application for preliminary earthquake location for reviewing seismologists and first alert messaging for critical infrastructure messaging (i.e. AENEAS), it is of interest to compare the Autoloc procedure to other methods to both assess its effectiveness and determine if improvements or refinements may be made. Fortuitously, over the last several years the Antelope system has been used at the PGC and has run its own automated earthquake location algorithm independently from Autoloc, and provides such a comparison.

Comparing the two algorithms over the period of a year (May 2009 – May 2010), in the study area where both algorithms are active (Pacific and Western Canada, approximately west of 100°W longitude), the following conclusions can be drawn:

1/ In terms of detection and identification of earthquakes in the National Earthquake Database, Autoloc currently significantly outperforms the Antelope procedure across all observed magnitudes. While there is large incompleteness (65%) at low to moderate earthquakes at magnitudes of 2.0 – 3.5, Autoloc's performance at larger magnitudes >3.5, more likely to be felt and damaging, is significantly better, locating 61 of 71 events over the one year period (86%). Antelope in comparison falls significantly short of this mark, locating only 6% of low magnitude earthquakes and 18% of those with magnitudes >3.5. In part this is due to the optimization of the Antelope algorithm to the populated region surrounding the Vancouver and Queen Charlotte Islands, yet even within this region a large number of >3.5 events went unlocated as evidenced by the 14 large aftershocks during November 2009 around the Queen Charlotte Islands. This optimization of Antelope, however, appears to result in relatively low false positive rate when compared to Autoloc, which generates hundreds of possible solutions per associated event by virtue of its methodology. A more in-depth study to determine the characteristics of these false positive rates is warranted for future work.

2/ In terms of location accuracy of the automated solution to that of the reviewed database, Antelope on average performs better than Autoloc with an average epicentral separation from the seismologist reviewed solution or "miss" distance and narrower distribution of 20 +/- 19 km as opposed to Autoloc at 37 +/- 24 km. This larger inaccuracy in position for Autoloc translates into a skewed distribution in origin time towards later time with a mean of 2.0 +/- 4.0 seconds as compared to the more normally distributed Antelope at -0.04 +/- 0.25 seconds. More interesting is that this greater location accuracy is apparently achieved using significantly fewer seismic phases, suggesting that Antelope's ability to pick and identify seismic phases is an improvement over Autoloc's current procedure.

3/ Direct comparison of magnitude estimation by Autoloc and Antelope over the course of the study period is complicated by the current limitations of the Antelope software. Currently, direct user control over period and amplitude measurements is not possible in Antelope. Although the user may add or remove stations and seismic phases, the associated amplitude and period measurements used to determine earthquake magnitude are picked automatically by Antelope. As this same algorithm to determine amplitude and period measurements is used for automated solutions, and as the quality of these solutions tends to be high, very little difference is seen in magnitude differences between the reviewed and automated solutions for Antelope (-0.04 +/- 0.25). Thus a truly independent assessment for Antelope cannot be made at this time. Autoloc, however, is seen to perform surprisingly well for those automated events associated with reviewed earthquakes, but tends to somewhat underestimate events on the whole with a overall mean for events >2.0 of -0.30 +/- 0.42 magnitudes. This mean value improves, however, as the magnitude of the event increases with a slight reduction in its scatter to 0.07 +/- 0.34 between magnitudes of 3.5 – 4.0 and 0.04 +/- 0.32 for magnitudes of 4.0 – 4.5.

Overall as an automated earthquake location system, Autoloc appears to have performed quite well, particularly as magnitude increased during the study period. Antelope, however, has shown that improvements can still be made. While Antelope as it is currently configured may not be the most effective at event detection, its ability to identify/associate phases and pick arrival times is consistently better than Autoloc suggests improvements to Autoloc by incorporating similar time pick methods and investigating alternatives. Similarly improvements to Antelope's automated detection may be desirable as the current schema seems to underachieve, particularly at larger magnitudes even within its optimized region.

Finally, in terms of automated alert systems such as AENEAS, it may be desirable to add or at least consult with Antelope automated locations for hazardous West Coast earthquake events, as this may provide an alternative means of confirming the presence of and the location and magnitude of a hazardous earthquake. Extension of the Antelope procedure may also be desirable in particularly active sub-regions of Canada and/or where hazardous earthquakes have been observed in the past; such as the Charlevoix region in Quebec.