The Canterbury Accelerograph Network (CanNet) and some Results from the September 2010, M7.1 Darfield Earthquake

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**ABSTRACT:** The majority of the close-in accelerograms from the Mw 7.1 September 4th, 2010 Darfield Earthquake were recorded by the local Canterbury Network (CanNet), which was being installed in the central South Island of New Zealand in anticipation of both a great earthquake on the Alpine Fault and moderate events on the Marlborough fault system. At the time of the earthquake, 36 of the planned 60 free field instruments were in place on the Canterbury Plains, in and surrounding the epicentral region, and across the nearby City of Christchurch. This paper presents a brief history of the network, and examines some results. The underlying policy of having a dense network of lower-resolution instruments rather than fewer high dynamic-range ones is clearly vindicated.

1 **INTRODUCTION**

The Mw 7.1 September 4th, Darfield, New Zealand Earthquake was recorded on many tens of strong-motion accelerographs, including 30 within 40 km of the fault system. Of these 30 instruments, 22 belonged to the Canterbury Network (CanNet), which had its origins in the University of Canterbury in 1996 and was taken into the EQC-funded national strong-motion network, GeoNet, in 2003. The high density of close-in recordings is enabling a detailed reconstruction of the source mechanism of the earthquake, has shown the presence of basin-edge effects from the Port Hills south of the nearby city of Christchurch and has confirmed the importance of site effects within Christchurch. Further, individual records have proved valuable in the calibration of numerical models of major items of infrastructure, giving confidence in their results and has minimised the need for physical investigation.

The Canterbury Network was set up to record the propagation of shaking across the Canterbury Plains and within the City of Christchurch in the expectation of major earthquakes within the next few decades on the Alpine and Hope Faults. The main aim of the CanNet project was to supplement the sparse network of 18-bit strong-motion accelerographs in the region, belonging to the national network, with as large a number as possible of low-cost, less-sensitive instruments. In brief, the aim was to get many more points on the map. The discovery of the Springbank Fault 20km from Christchurch in the late 1990s increased the perceived seismic hazard in Christchurch, and added impetus to the project. However, rather than the Alpine Fault, it was a hitherto unknown fault system, buried beneath the Plains sediments near the centre of CanNet, that ruptured on September 4th, 2010.

The aim of this paper is to give a brief description of the aims and history of CanNet and to present some results from the records.
2 THE CANTERBURY NETWORK

CanNet had its origins in the study of the Alpine Fault in the mid-1990s by Yetton (2000), who found that a major rupture of about M8 was likely in the next few decades over a length of about 400km of the Fault in the central South Island. Further, the systematic study of regional tectonics by Pettinga’s group at the University of Canterbury along with GNS geologists brought to light a rich set of faults along the range front of the Southern Alps and beneath the Canterbury Plains (Stirling et al., 2008), adding to the case for a dense regional accelerograph network.

Before the work of Yetton (2000), it had been thought that the average recurrence interval for large events on the Alpine Fault was about 500 years. Yetton found convincing evidence for a recurrence interval of about 260 years, with characteristic earthquakes of around M8 and with the last event dated by dendrochronology precisely at 1717. These results, together with evidence of a seismic gap several decades long in the central South Island, suggest that a great earthquake is likely on the Fault within the next few decades, providing an excellent and rare opportunity to record in detail strong shaking from such an event, in both the near and the far field. The region was already served by a backbone of instruments, generally 18-bit accelerographs, in the national network operated as part of GeoNet within GNS Science. However, this network was not dense enough to gather a robust set of data from an Alpine Fault event or to cover the quite variable geologic conditions beneath the city of Christchurch.

The Engineering Seismology Group at the University of Canterbury sought to add about 80 instruments, the “Canterbury Network”, in three sub groups, as follows:

1. A dense array near the Alpine Fault, designed to follow the progress of rupture on that or nearby faults. This would comprise about 20 instruments.
2. A group of about 20 instruments at selected sites in the city of Christchurch, to record site effects on the highly variable fluvial and estuarine soils beneath the city.
3. About 30–40 instruments spread over the Canterbury Plains and the coastal plains of the Buller and West Coast regions, to record regional attenuation of strong ground motion.

At the time of instigation of the project, the range of available instruments was limited. The established manufacturers were focusing on high dynamic range instruments with consequent high selling prices. However, as Trifunac and Todorovska (2001) point out, typical earthquake engineering applications require high spatial resolution, not high amplitude resolution. To address the problem of cost, both in initial outlay and in ongoing maintenance, the Engineering Seismology Group worked with the Electrical and Electronic Engineering Department at the University of Canterbury to design a simple, low-cost, low-maintenance 13-bit accelerograph. This instrument, the CUSP-3A, has been described by Avery et al. (2004), and Avery (2005). In brief, it was designed around the Internet for ease of instrument monitoring, maintenance and data transfer. To reduce cost and the risk of obsolescence, it employed standard industrial components where possible, such as MEMs accelerometers and an industrial single-board computer, as well as standard software modules such as the Apache web server.

2.1 The Dense Array

In parallel with development of the instrument, work within the Group also progressed on the design of various components of the dense fault-rupture array (François, 2003, 2004). These included:

1. The improved coding of the MUSIC algorithm of Goldstein and Archuleta (1991) for use both in designing the array itself and in inverting data obtained from it.
2. The selection of potential sites.
3. Finding the optimal array configuration at the selected sites.

François (2004) found that the optimal array would: a) be situated between 40 and 70km east of the eastward dipping Alpine Fault, b) be on a plane rock site, ideally with a level layout or dipping up to about 45 to the east, and c) best be circular in layout, for omnidirectional efficiency; but that a tee-shaped array would be sufficient and would likely be better accommodated in the mountainous terrain found east of the Fault.
Ideally, two arrays would be employed, one to the south and the other to the north. However, under the constraints of restricted University funding and the difficult terrain of the Southern Alps, we opted for a single array. The site proposed by François (2004) was near the settlement of Cass, about 20km east of the village of Arthurs Pass, and a tee-shaped array was designed. However, this site is now felt to be too inaccessible and difficult to supply with power to be viable, and installation has been deferred while other sites are investigated. The present intention is to seek sites for two smaller arrays, one in the Coleridge - Cass area and the other further south.

2.2 Transfer to GeoNet

By 2003, the CUSP-3A had been developed and proven in shaking-table and field tests, and funds were sought to install the instruments. One of the funding agencies approached was the New Zealand Earthquake Commission (EQC), which at the time was supporting a major upgrade of the national geophysical networks, GeoNet, within GNS Science. Their response was to suggest that CanNet be taken into GeoNet, with GeoNet buying and installing the instruments and operating the network, but leaving scientific direction, principally site selection, to the University. This suggestion was readily accepted. However, the EQC was unwilling to buy instruments from a university laboratory and insisted that a private company be set up to manufacture them, and that the CUSP (Canterbury University Seismograph Project) instruments be used only if they won a competitive assessment. Accordingly, Canterbury Seismic Instruments Limited was formed in August 2003, and manufacture and installation of the first batch of CUSP-3A accelerographs undertaken in 2004. Over the following two years, the original 13-bit CUSP-3A was developed to the 14-bit 3B, and the 18-bit CUSP-3C. Most of the instruments deployed in September 4th, 2010 were 3A and 3Bs, with a few 3Cs.

Outside the dense array, sites were selected to give a fairly even coverage of the 80km-wide Canterbury Plains between Christchurch and the foothills, with a target instrument spacing of around 30 km, and an even geographical and geological coverage of the city of Christchurch itself. At the time of the September 4th, 2010 earthquake, most of the Plains and North Canterbury sites were operational along with about half the 20 sites proposed for the city.

2.3 Communications and operation

GeoNet adopted a wireless continuously-connected virtual private network (VPN) over the cellular CDMA network for CanNet communications. The cellular system has proven to be robust, even in the aftermath of the September 4 Darfield event. The only issue that caused early trouble was an undocumented disconnect at the cellular provider’s end if insufficient activity was detected. This was overcome by sending periodic ping messages from each instrument.

At the Lower Hutt headquarters of GeoNet, the instrument connection status is continuously monitored and daily reports of instrument health (principally temperature, battery voltage and sensor noise) are received and automatically scanned for anomalies. The instruments operate in triggered mode (although a recent update has also allowed continuous transmission using SEEDlink), and any records made are automatically sent by ftp to a server in Lower Hutt and mirrored to a site in the Bay of Plenty. Raw records are posted daily on the GeoNet ftp site and processed data and plots of interesting events added soon after, in the Caltech/USGS Vol II-IV format.

3 THE SEPTEMBER 4TH, 2010 EARTHQUAKE

In this section, we describe briefly some results that have come from the CanNet data. The aim is not to present detailed descriptions of the underlying studies. Instead, it is to illustrate the value of having dense sets of recordings from instruments of adequate resolution (Class A and Class B, in the USGS classification), rather than a smaller number from costly, high dynamic range instruments. We focus on two results: the source studies of Holden et al. (2011) and Fry et al. (2011), which show the complex nature of the September 4th source, with at least three distinct faults, and on the application of the wavelet transform technique, pioneered by Chanerley and Alexander (2010), to obtain credible integrated displacements from even 13-bit accelerograph data. For other early engineering results, the reader is referred to Cousins and McVerry (2010) and Cubrinovski et al. (2010).
3.1 Rupture studies

Thirty-six stations located within 50km of the rupture recorded the event (eight stations recorded peak accelerations larger than 0.5g). Nine stations out of the 36 belong to the national strong motion network, the rest are from CanNet. The stations are close enough to the earthquake source to record sufficiently high frequencies to allow detailed analyses of the spatial and temporal evolution of the rupture. Using data from this network we have been able to apply an inversion technique not only to resolve one fault plane rupture, but at least 3 (Holden et al. 2011). We used the 3-component acceleration data, integrated into velocities and band-pass filtered up to 0.2 Hz. Our 3-source model fits the data very well, especially for the 3 closest stations to the epicentre, GDLC, DFHS and HORC. However the waveform fit decreases for sites further west and needs further investigation.

Using this unusually dense data set we are also exploring two source-tracking techniques to highlight the temporal evolution of the rupture: a source scanning algorithm (SSA) (Fry et al., 2011) and dense-array analysis (MUSIC). For the SSA, we create a 3D model of the Canterbury plains by dividing the region into 0.5km cubic blocks. For each 0.1s time window, we generate a 'brightness' function for each block showing the relative likelihood of the block as a source of energy contained in the seismograms. Significantly, a large amount of energy is radiated from Banks Peninsula, a volcanic edifice to east of the rupture, and to the south of the city of Christchurch.

For the MUSIC (Multiple Signal Characterization) analysis, we analysed data from a dense sub-array of 16 stations, located within a 15 km radius area and with spacing ranging from a few hundred meters to a few kilometres. We generate the slowness spectra for the signal as a parameter of azimuth and time. Preliminary results indicate a sharp change in ray parameters at about 10s into the waveforms, where the energy source shifts to the south of the hypocentre. This is in agreement with results from strong motion data inversions, that the rupture initiated north of the main Greendale fault and propagated about 10 second later along the Greendale fault. This (unplanned) dense array is not ideally located, being along the main fault rupture rather than perpendicular to it. However, it does show some promising results and supports the development of dense arrays for large fault rupture studies, using low cost accelerographs.

3.2 Ground Displacements by wavelet transformation.

Obtaining accurate displacement data from the double integration of accelerograms has been a problem from the beginning of strong motion recording. In the days of analogue accelerographs, where pre-event acceleration zeros were unknown and the film or paper wandered slightly during recording, introducing spurious low frequency components, accelerograms were band-pass filtered and their baselines corrected according to one of a number of arbitrary schemes. While this gave an acceptable representation of motions from a few tenths of one Hertz up to an upper cut off frequency determined by the density of digitisation and instrument characteristics, the low-frequency information and static displacements were lost. However, with taller and longer structures and the introduction of base isolation, our interest in the long period components of ground motion increases, as does our quest to obtain accurate structural displacements for the estimation of inter-storey displacement and hence structural damage. The advent of digital recording allows the retention of a pre-event signal, to give an estimate of current accelerometer baseline values. However, it is still difficult to obtain accurate displacement records by double integration, due to the effect of small errors in acceleration from sources such as instrument noise and tilting of the ground, which integrate to large errors in velocity and displacement as the record progresses. So the practice of band-pass filtering and somewhat arbitrary baseline correction has continued, albeit with a fairly high degree of sophistication. But as long as the very low frequency components of motion are filtered out, there is little hope of recovering static displacement. Clearly, a fresh approach was required.

Such an approach has been advanced by Chanerley and Alexander (2010), who employ a wavelet transform technique to first separate the low-frequency, so-called “fling”, components of acceleration from the high-frequency “dynamic” components. The separated signals are de-noised and recombined to obtain corrected acceleration, velocity and displacement time-histories. Briefly, the process is this:
After de-convoluting the instrument response (Chanerley, Alexander 2008, 2007), the wavelet transform is applied. Wavelet filters separate the accelerogram into two sequences of sub-bands from which we recover the low-frequency, fling, and higher frequency acceleration time histories separately. The general properties and application of wavelet filters are discussed by Daubechies (1992), and their application to seismic accelerograms by Chanerley and Alexander (2010). After the separation, a de-noising scheme, based on the approach of Coifman and Donoho (1995), is applied to the sub-bands. Finally, the extracted low frequency fling acceleration time history is zeroed at the time-point at which the velocity crosses the zero axis at the end of the fling motion, and the combined accelerogram re-integrated to yield velocity and displacement.

The wavelet transform approach has been tested on records from two earthquakes for which there were good measurements of co-seismic displacement, and the agreement was close in both cases. The first was the 1999 Chi-Chi, Taiwan TCU052 and TCU068 records for which approximately 10m of vector displacement was reported for the latter, compared with 9.66m by the wavelet decomposition method (Chanerley and Alexander, 2010) and for TCU052 (N,E V) (Chanerley et al, 2009) was (635cm, -355cm, 337cm) compared with GPS readings of (845.1cm, -342.3cm, 397cm). The other records were from the M6.3 Olfus (2008), Iceland Earthquake, with a total of 33 components integrated, from 11 CUSP-3Clp instruments. In that case, a 19cm ± 0.09 displacement (NW) was observed using co-seismic offset measurements at a continuous GPS station, compared with a mean total permanent displacement of 20.7 ± 2.40cm (NW) from the CUSP accelerogram records, which used the wavelet approach (Halldorsson et al, 2010). The five Darfield accelerograms processed using this technique are listed in Table 1. At the time of writing, no survey results were available right at instrument sites, but for the near-fault Greendale site, a set of displacement observations was available about 2 km of the recording site. The Greendale record is discussed in some detail, below.

<table>
<thead>
<tr>
<th>Site</th>
<th>Component</th>
<th>Displacement, cm</th>
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</thead>
<tbody>
<tr>
<td>Greendale, CDLC</td>
<td>N55W</td>
<td>-177.8</td>
</tr>
<tr>
<td></td>
<td>S35W</td>
<td>-45.84</td>
</tr>
<tr>
<td></td>
<td>UP</td>
<td>-66.5</td>
</tr>
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<td></td>
<td>UP</td>
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<td></td>
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<td></td>
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<tr>
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</tr>
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<td></td>
<td>UP</td>
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</tbody>
</table>

3.2.1 The Greendale Record, GDLC
The Greendale accelerogram was recorded on a 14-bit CUSP-3B instrument about 1.2 km north of the Greendale Fault, close to the point where it swings to the north in a releasing bend near its western end. We illustrate the wavelet transform process with the N55W component. Figure 1 shows the extracted low-frequency fling components, the higher frequency components and the resulting sums.
Figure 1. Greendale, GDLC, (N55W component) results for 1\textsuperscript{st} and 2\textsuperscript{nd} Integration of superimposed ‘fling’ component (red), higher frequency component (black) and resultant sum of low-frequency fling and higher frequency component (blue). Permanent displacement shows \(-177.8\text{cm}\).

Figures 2 shows the power plots and demonstrates that at frequencies as low as 0.01Hz, the low-frequency fling power is significant. The higher frequency and noise powers on the other hand, are relatively small in comparison.

Figure 2. Greendale GDLC (N55W) power plots for low frequency fling (LFS), higher frequencies (HFS), and noise. Note that at frequencies less than about 0.07Hz, the LFS (fling) component dominates.

Figure 3 shows the final results for the S35W and vertical components, and Figure 4, displacement in three dimensions. Measurements of permanent displacement 2.2 km to the north of the Greendale station are available from Beavan et al (2010), who used before and after GPS observations at the site BPMJ, finding \((dE, dN, dUP) = (1560, -1081, -552)\), compared with \((1719, -664, -665)\) from the corrected accelerogram. The magnitude of the vector displacements are very close indeed, with 1900 mm at S65E from the GPS readings at BPMJ and 1840 mm at S69E by the wavelet method applied to the Greendale record. Given the separation of the two sites and the complexity of the displacement field at the bend in the fault, this agreement is encouraging.

4 \textbf{CONCLUSIONS}

Data from the comparatively low-resolution instruments of CanNet have proved quite adequate in source rupture studies and yield credible double-integrated displacements when processed by the
wavelet transform procedure. The Darfield records indeed appear to support strongly the argument for more instruments on the ground, at the expense of high dynamic range.

Figure 3. Results for the N35W (-45.84cm) and vertical components (-66.5cm) of the Greendale record.

Figure 4. (a) Resultant ground displacement traces for GDLC. Note that axes show orientation opposite to sensor direction, since all displacements are negative. (b) Table of displacements and resultants.

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REFERENCES:


