6th Canadian Conf. Earthquake Engineering / Toronto / 1991 / 6ème Conf. Canadienne Sismique

Seismograph records processed by Fourier transform

J. Hans Rainer[1]

ABSTRACT

The method presented of processing strong-motion accelerograph film records employs the Fourier transform and boundary conditions of zero mean and initial and final acceleration, velocity and displacement. Ways of achieving instrument correction, integration, baseline correction and filtering are described and the mathematical expressions summarized. Numerical results for the records of the Saguenay earthquake of 1988 are compared with those obtained by the Geological Survey of Canada using the time-domain method. Good agreement is achieved for acceleration and velocity, but substantial differences are encountered for displacements. This is due to differences in boundary conditions used for displacement. It is recommended that the time-domain method adopt the zero mean displacement instead of the current zero initial displacement.

INTRODUCTION

Recordings of motions of the ground and of structures during earthquakes have contributed immeasurably to the technical advancements in seismology and earthquake engineering. From such records, engineers and scientists are able to develop seismic motions for design and analysis. Before such recordings can be used, however, they need to be "processed" so that inaccuracies and distortions that invariably accompany an instrumental recording process are properly accounted for.

Instruments that have been most successful in recording strong seismic motions obtain the acceleration at the instrument location. Early versions, from the 1940's to the 60's, employed a lightbeam that was reflected off a mirror mounted on a damped single-degree-of-freedom oscillator and focused onto photo-sensitive paper. Then up to the 1980's, photographic film replaced the paper. There are now

1 Senior Research Officer, Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario K1A 0R6

thousands of these film accelerographs in use all over the world, including in Eastern and Western Canada (Weichert and Munro, 1987). A description of film instruments, the recording process, and the numerical treatment of the data is given by Hudson (1979). More recently, force-balance or servo accelerometers have been introduced which produce an electrical signal that is proportional to acceleration. This permits the use of magnetic tape or digital storage media and retention of "pre-trigger" information by using a continuously recirculating memory and saving this pre-trigger portion along with the subsequent signal from the seismic motion. Triggering occurs when the instrument is activated as the arriving seismic motion exceeds a pre-set trigger level. The rest of the paper deals specifically with records from film instruments. For other instruments, certain of the steps described need to be appropriately modified.

PROCESSING OF SEISMOGRAPH RECORDS

After the film is retrieved from the instrument, it is photographically developed and then converted to digital format by manual or automated digitizing equipment. This represents the "raw" digital record. Before it can be considered to represent the "true" seismic motion at the recording station, the record needs to be processed with instrument correction, baseline adjustment and filtering. This can be carried out by a step-by-step time-domain process, generally based on the methods developed at the California Institute of Technology in Pasadena, California (Trifunac and Lee, 1973) and further adapted by the U.S. Geological Survey (Converse 1984).

The Fourier transform technique described here provides an alternative means of seismograph processing and can therefore be used as an independent check on the time-domain results. The technique also permits easier introduction of numerical procedures that are inherently frequency dependent, such as filtering and instrument corrections. In the following, the Fourier transform procedure will be summarized and numerical comparisons presented for the results from the Saguenay Earthquake of November 25, 1988. Further details of the mathematical basis for this procedure can be found in Mulder and Rainer (1989).

Instrument Correction

Since the light beam that exposes the film is reflected off the single-degree-of-freedom oscillator in the instrument, the resulting trace is actually proportional to the displacement of the highly damped moving mass. This happens to be fairly close to the instrument base acceleration, but it is still "contaminated" by the dynamic response characteristics of the oscillator. In the frequency domain, this oscillator characteristic is given by the complex transfer function $H(\omega)$ of the transducer,

$$H(\omega) = \frac{\omega^2/\omega_0^2}{1 - \omega^2/\omega_0^2 - 2i\,\beta\,\omega/\omega_0} \qquad (1)$$

where ω_0 = natural frequency of transducer, β = critical damping ratio of transducer, $i = \sqrt{-1}$, and ω = frequency variable.

If $\ddot{X}(\omega)$ is the Fourier transform of the raw time signal $\ddot{x}(t)$, then the instrument-corrected function $\ddot{Y}(\omega)$ in the frequency domain is obtained from

$$\ddot{Y}(\omega) = \ddot{X}(\omega) \,/\, H(\omega) \tag{2}$$

and the division is carried out for every frequency increment. The instrument-corrected time trace of the acceleration, $\ddot{y}(t)$, is then obtained by taking the inverse Fourier transform of $\ddot{Y}(\omega)$.

Integration and Baseline Adjustment:

Integration in the frequency domain is carried out simply by dividing the Fourier transform of the acceleration successively by $i\omega$ and $(i\omega)^2$ for every frequency increment to obtain the Fourier transform of the velocity, $\dot{Y}(\omega)$, and displacement, $Y(\omega)$, respectively. The inverse Fourier transform of $\dot{Y}(\omega)$ and $Y(\omega)$ then yields the time-domain traces for velocity, $\dot{y}(t)$, and for displacement, $y(t)$, respectively.

Unfortunately, this integration produces large discrepancies with what are the known or desired boundary conditions for the records, i.e. nominally zero start and finish of the motion. A realistic boundary condition for an elastic vibratory process is zero mean and zero initial and final values for acceleration, velocity and displacement. This would of course, not be valid if permanent displacements had occurred, but to the author's knowledge such a possibility has so far not been taken into account in actual seismograph processing.

It is now possible to derive correction terms to the acceleration trace so that after integration in the frequency domain, the velocity and the displacement traces satisfy the boundary conditions. This derivation is carried out in steps: step 1, the zero mean acceleration is obtained; step 2, zero mean velocity; and finally step 3, zero mean displacement along with zero start and finish. For purposes of observing the efficacy of the correction procedures and for improved behaviour of the filtering process, "tails" of zeros have been added to the start and finish of the record, from 0 to t_1, and t_2 to T, respectively. Thus $(t_2 - t_1) = \tau$ is the original record length. After processing, these tails are then truncated so that only the original record length is displayed in the resulting plots. In the following summary, the subscripts 1, 2 and 3 refer to the signals after the correction steps 1, 2 or 3.

Step 1. From the acceleration trace $\ddot{y}(t) = a$ compute the first-level corrected acceleration trace $a_1(t)$ by subtracting the mean $\overline{a}'$;

$$a_1 = a - \overline{a}' = a - \frac{1}{\tau}\int_{t_1}^{t_2} a(t)\, dt \tag{3}$$

Step 2. Integrate a_1 to compute velocity v_1 and its mean $\overline{v}'$; derive a correction term to the acceleration a_1 so that both the acceleration and velocity trace have zero mean and start and finish. This results in velocity-corrected acceleration a_2 and velocity v_2:

$$a_2 = a_1 + \frac{6\bar{v}'\,T}{\tau(T-\tau)}\left(\frac{2t-\sigma}{\tau}\right), \quad \text{where } \sigma = t_2 + t_1 \tag{4}$$

Step 3. Integrate velocity v_2 to obtain displacement, u, and its mean $\bar{u}'$; derive correction term to the acceleration trace a_2 so that the new velocity v_3 and displacement u_3 have zero mean and start and finish. This results in the fully corrected acceleration trace a_3:

$$a_3 = a_2 - \frac{30\,\bar{u}'\,T}{\tau^2(T-\tau)}\left\{3\left(\frac{2t-\sigma}{\tau}\right)^2 - 1\right\}. \tag{5}$$

Filtering

Filtering is needed to remove undesirable components of low frequency (high-pass filter) and high frequency (low-pass filter). A high-pass filter is needed to remove those low-frequency components whose presence would overshadow the higher frequency components in the displacement trace. Low-pass filtering is needed to avoid aliasing in the numerical process, and to remove high-frequency components that may not be realistic.

Filtering in the frequency domain is achieved by applying the filter function $F(\omega)$ to the Fourier transform $\ddot{Y}(\omega)$ of the signal $\ddot{y}(t)$:

$$\ddot{Y}_f(\omega) = F(\omega)\cdot\ddot{Y}(\omega) \tag{6}$$

The inverse Fourier transform of $\ddot{Y}_f(\omega)$ then yields the filtered time trace, $y_f(t)$. $F(\omega)$ can be any appropriate filter window; popular ones are the nth order Butterworth filters for low pass and high pass, respectively:

$$F(\omega)_l = 1/(1 + (\omega_0/\omega)^{2n}); \quad F(\omega)_h = 1/(1 + (\omega/\omega_0)^{2n}) \tag{7}$$

Another filter that can be used is the "cosine taper", which reduces the frequency amplitudes to zero via a quarter-cycle cosine curve between two strategically chosen frequencies.

RESULTS FOR SAGUENAY EARTHQUAKE

The Fourier transform method described has been applied to the processing of the ground motions from the Saguenay earthquake of November 25, 1988 as recorded by the Geological Survey of Canada. An example of a record is shown in Fig. 1 for Site 20, Les Éboulements, P.Q., for the transverse instrument direction. For comparison, the corresponding record processed by Weichert and Munro (1989) is shown in Fig. 2. Identical filter values of 0.50 Hz high pass and cosine taper from 50 to 100 Hz were used. The two methods are seen to give results that agree very

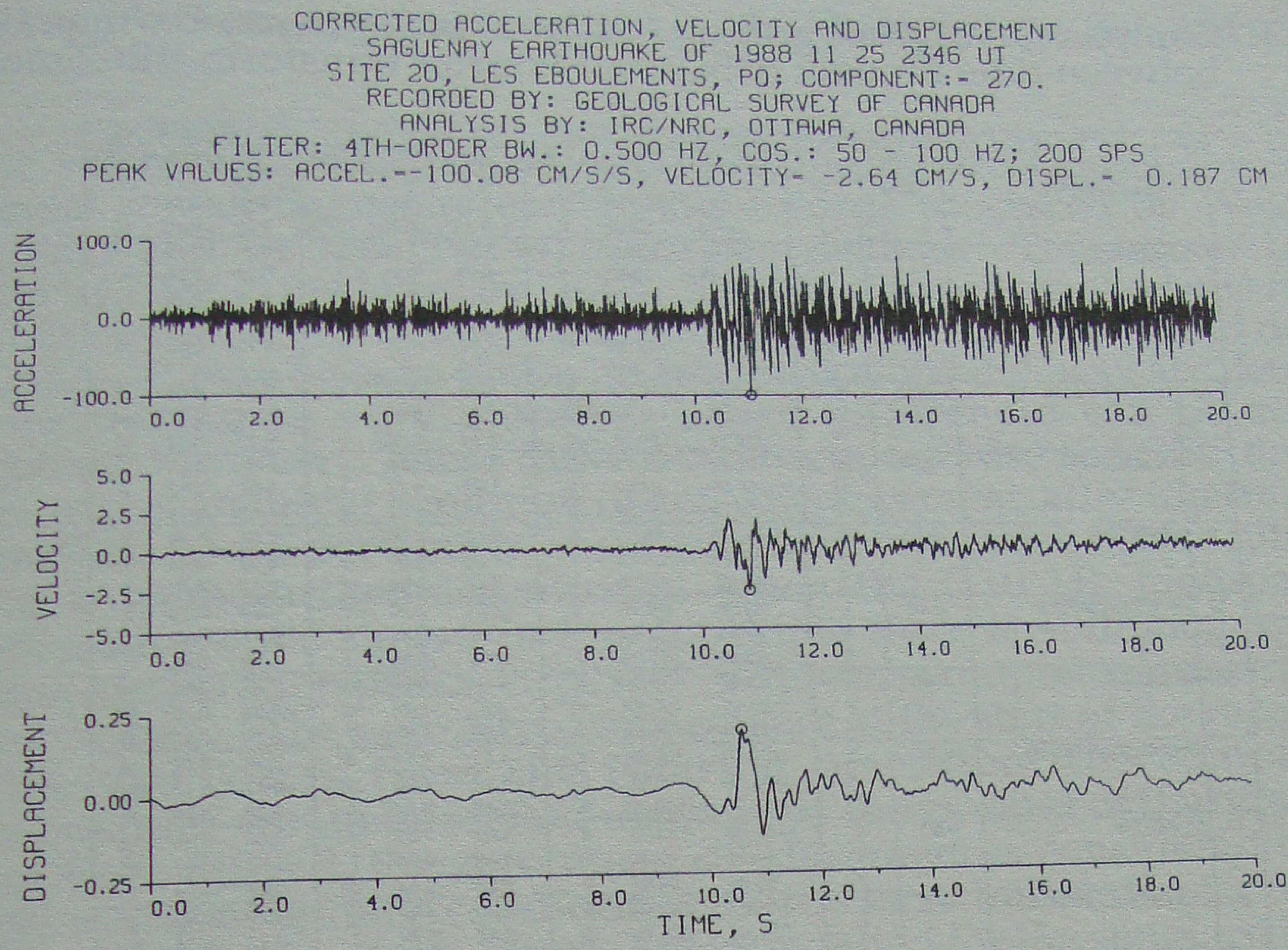

Figure 1. Seismograph record processed by Fourier Transform Method, Filtered at 0.50 Hz

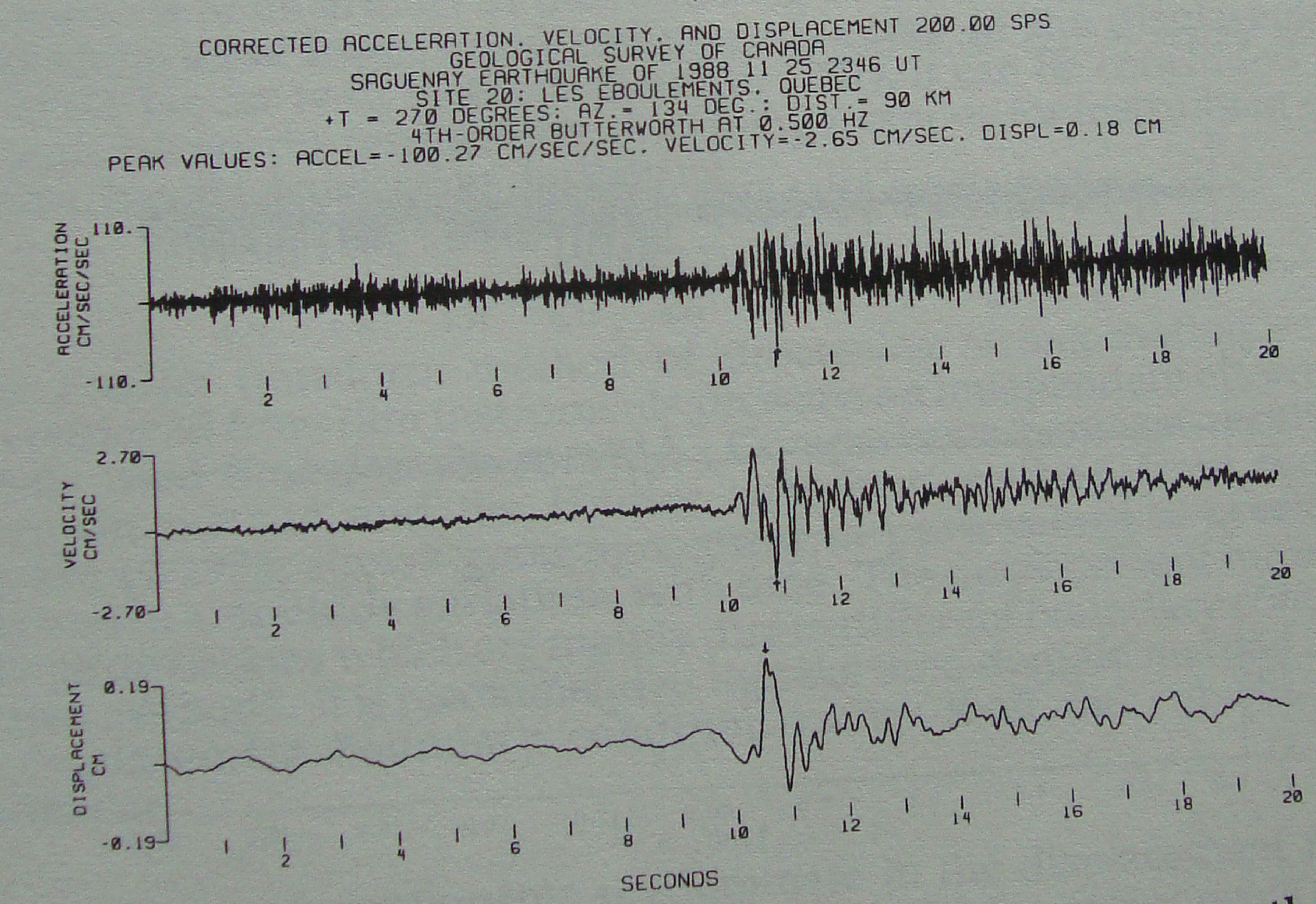

Figure 2. Seismograph record processed by time-integration method (Weichert and Munro, 1989)

Table 1: Comparison of peak ground motions for Saguenay Earthquake 1988 between time domain (GSC) and Fourier transform (IRC) methods

SITE	STATION	FILTER (HZ)	COMP	ACCELERATION, CM/S/S GSC	ACCELERATION IRC	ACCELERATION % DIFF	VELOCITY, CM/S GSC	VELOCITY IRC	VELOCITY % DIFF	DISPLACEMENT, CM GSC	DISPLACEMENT IRC	DISPLACEMENT % DIFF
1	ST-FERREOL	0.50	L	118.79	118.75	0	-2.71	-2.70	0	-0.11	-0.11	0
			V	-61.21	-62.05	1	1.71	1.71	0	0.13	0.14	7
			T	-95.44	-95.08	0	-2.45	-2.42	1	0.09	0.10	10
2	QUEBEC	0.33	L	-49.61	-49.38	0	1.50	1.49	1	0.21	0.18	17
			V	-19.49	-19.38	1	-0.96	-0.95	1	0.14	0.13	8
			T	-49.68	-50.02	1	2.16	2.15	0	-0.16	-0.18	11
5	TADOUSSAC	0.33	L	26.37	25.83	2	0.58	0.58	0	0.10	-0.07	43
			V	52.27	44.43	18	-1.05	-1.05	0	0.15	0.12	25
			T									
7	BAIE-ST-PAUL	0.33	L	122.84	-122.31	0	3.76	3.73	1	0.56	-0.51	10
			V	-121.31	114.20	6	2.43	2.46	1	-0.40	0.27	48
			T	170.62	170.31	0	-5.34	-5.34	0	0.87	0.52	67
8	LA MALBAIE	0.33	L	-121.82	-128.71	5	-4.65	-4.66	0	0.41	0.40	2
			V	66.51	67.17	1	1.72	1.71	1	0.11	0.12	8
			T	58.73	57.37	2	1.33	1.32	1	-0.12	-0.13	8
9	ST-PASCAL	0.40	L	-45.46	-45.59	0	-2.60	2.56	2	-0.34	-0.35	3
			V	35.91	36.13	1	-1.85	-1.85	0	-0.13	-0.14	7
			T	-54.70	-54.19	1	-2.62	-2.60	1	0.19	-0.20	5
10	RIVIERE-OUELLE	0.40	L	-39.59	-40.74	3	2.21	2.20	0	0.28	0.26	8
			V	22.85	22.98	1	-1.30	-1.30	0	-0.12	0.12	0
			T	-55.92	-55.96	0	-3.52	-3.50	1	0.42	0.40	5
14	STE-LUCIE	0.40	L	13.58	13.37	2	-0.64	-0.64	0	-0.04	-0.05	20
			V	-22.91	-23.63	3	-1.23	-1.34	8	-0.23	0.15	53
			T	22.84	20.98	9	1.03	1.11	7	0.19	-0.12	58
16	CHICOUTIMI-NORD	0.67	L	-104.48	107.69	3	1.51	1.57	4	0.08	0.07	14
			V	100.50	103.65	3	-1.85	-1.86	1	-0.51	-0.13	292
			T	128.66	128.39	0	2.52	2.56	2	-0.20	-0.20	0
17	ST-ANDRE	0.80	L	-152.92	-140.11	9	1.83	1.85	1	-0.07	0.08	12
			V	44.36	45.35	2	-0.88	-0.86	2	-0.05	0.03	67
			T	89.36	98.53	9	0.94	0.94	0	-0.04	-0.04	0
20	LES EBOULEMENTS	0.50	L	-123.07	-123.09	0	4.40	4.42	0	-0.32	-0.32	0
			V	-229.89	-260.70	12	-5.01	-5.04	1	-0.43	0.28	54
			T	-100.27	-100.08	0	-2.65	-2.64	0	0.18	0.19	4

NOTES: GSC = Geological Survey of Canada, Energy Mines and Resources Canada
IRC = Institute for Research in Construction, National Research Council of Canada
L = longitudinal, V = vertical, T = transverse - component directions of instrument

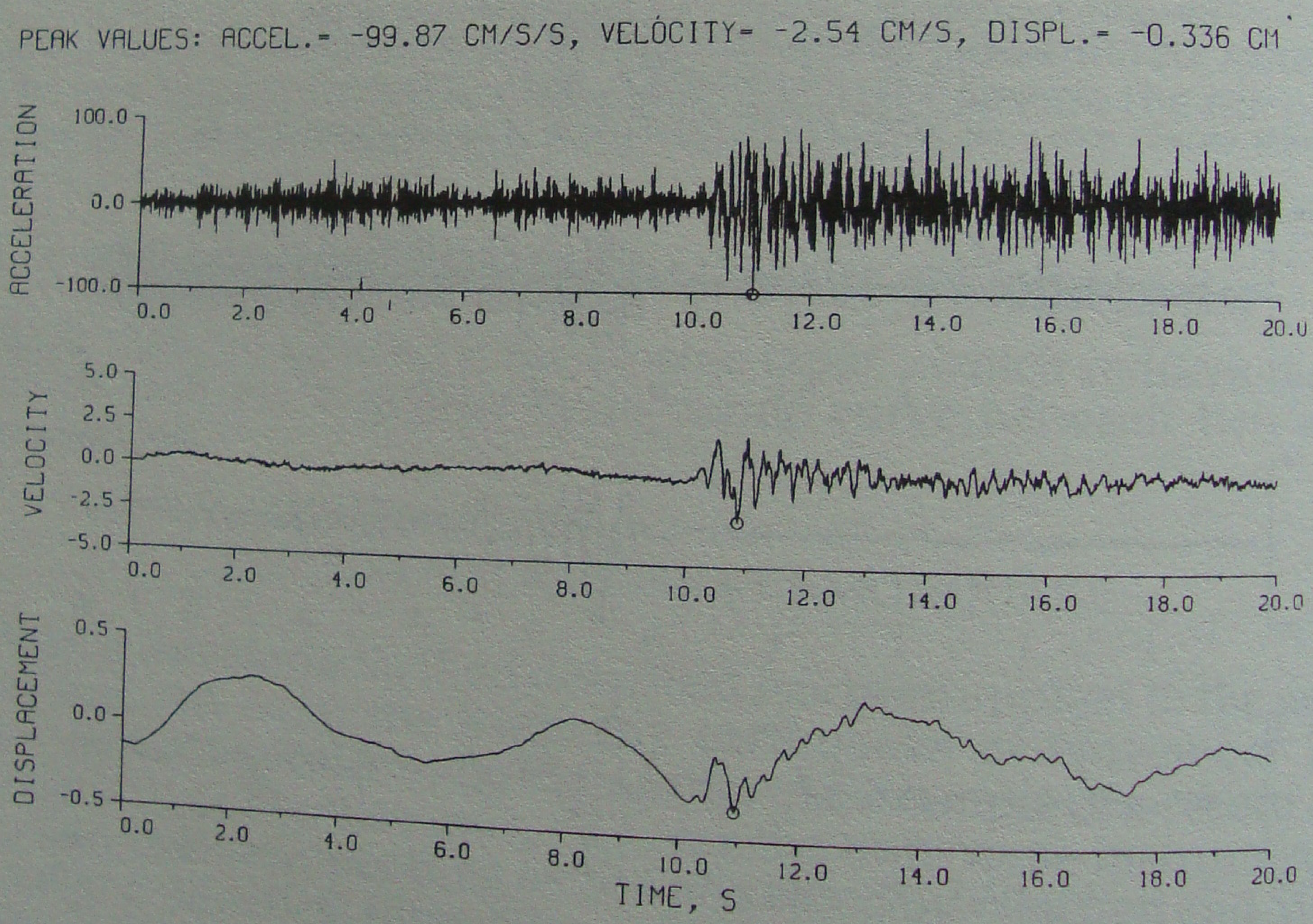

Figure 3. Seismograph record as in Fig. 1 processed by Fourier transform method filtered at 0.1 Hz

closely, as can be seen by comparing the peak values and the detailed amplitude variation with time.

Table 1 presents a comparison of peak values of accelerations, velocity and displacement for all Saguenay earthquake records processed by Weichert and Munro (1989) and by the Fourier transform method. The former results are designated by "GSC", the latter by "IRC". Percent differences of results for the two methods are computed by taking the difference in absolute values and dividing by the IRC value. It may be seen that with few exceptions the peak accelerations and peak velocities agree very closely. Large differences can be seen in the displacements, however. These differences occur because the GSC time-domain method employs an initial condition of zero displacement, after filtering, whereas the IRC method uses a zero mean and a zero start and finish before filtering. This difference is even further accentuated when the 0.10 Hz high-pass filter is employed, with results shown in Fig. 3. While there is still good agreement in velocity and acceleration peaks, large low-frequency components are evident in the displacement trace. The non-zero displacement at the start of the record is clearly discernible and arises from the filtering operation; the comparable GSC displacement trace would be shifted upward by the amount of the offset. After the record has been filtered, the zero mean displacement is considered to be a more reasonable initial boundary condition than the zero initial displacement; thus a change from the latter to the former is recommended for the standard time-domain processing.

Whether the low-frequency components in the displacement trace are real ground motions or an artifact of the recording or processing methods is not clear yet. But since these long-period components occur in the displacement traces filtered at 0.1 Hz for both methods (Munro, 1991), it can be concluded that these components are not the result of the processing methods for instrument correction, integration, baseline correction or filtering.

CONCLUSIONS

The Fourier transform method of processing strong-motion seismograph records retrieved from film instruments presents an independent alternative to the commonly used time-domain method. Comparisons between results from the time-domain method and the Fourier transform method from the Saguenay earthquake of 1988, shows good agreement in peak values of acceleration and velocity and in amplitude variations with time. The displacement traces, however, show large deviations which are mainly due to different boundary conditions used by the two methods. It is recommended that the time-domain method adopt a zero mean displacement boundary condition rather than the current zero initial displacement.

Low-frequency components predominate in the displacement record when high-pass filters of 0.10 Hz are used. The origin of these components is shown not to be due to the integration, instrument correction and filtering procedures.

ACKNOWLEDGEMENT

The assistance by L.J. Mulder and J.V. Marans in processing the Fourier transform results is gratefully acknowledged, as are the fruitful discussions with P.S Munro of the Geological Survey of Canada, Ottawa.

REFERENCES

Converse, A. 1984. AGRAM: a series of computer programs for processing digitized strong-motion accelerograms. Version 2.0. U.S. Geological Survey, Open-File Report 84-525, Denver Colorado, July 1984.

Hudson, D.E., 1979, Reading and Interpretating Strong Motion Accelerograms, Berkeley: Earthquake Engineering Research Institute, 112 p.

Mulder, L.J. and Rainer, J.H. 1989. Processing of Seismograph Records-Procedures and Results. Internal Report No. 587, Institute for Research in Construction, National Research Council of Canada, Ottawa, 74 p.

Munro, P.S. 1991. Private Communication.

Munro, P.S. and Weichert, D. 1989. The Saguenay Earthquake of November 25, 1988 Processed Strong Motion Records. Geological Survey of Canada Open File Report 1996, Ottawa, February 1989.

Trifunac, M.D. and Lee, V. 1973. Routine processing of strong-motion accelerograms. Report EERI-73-03. California Institute of Technology, Pasadena, Calif., 360 p.

Weichert, D.H. and Munro, P.S. 1987. Canadian Strong-Motion Seismograph Networks. Proc. Fifth Canadian Conference on Earthquake Engineering, 6-8 July, Ottawa.