Seismic Instrumentation

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1. Introduction

The past few years have seen considerable change in seismic instrumentation. The impact of small computers has changed the way in which earthquakes are recorded, and the way data are analysed. A seismograph no longer has the traditional drum recorder as shown in geography books or as seen in a museum. Drum recorders still exist but an increasing proportion of seismic data is recorded and stored digitally, and viewed on computer screens.This paper will place emphasis on recording local earthquakes and engineering seismology applications, rather than seismological recording on a world scale.

2. Use of Seismic Instruments

Seismic instruments are used to measure vibrations within the earth, on the surface of the earth, or on structures such as dams or buildings. The vibration measurements, or seismograms, are then used for the following:

Earthquake Source Parameters

- The origin time of the earthquake, and the rupture duration.
- The earthquake location, including epicentre and depth.
- The size of the earthquake, expressed as a magnitude, moment, or rupture area.
- The earthquake rupture process, the focal mechanism or moment tensor

Seismic Wave Travel Path Information

- Seismic velocity model giving the variation of seismic velocities within the earth. In the past these models have consisted of horizontal or near horizontal layers, but tomographic analysis methods are now leading to three dimensional models.
- An attenuation model, giving the reduction of seismic wave amplitudes with distance from a earthquake due to absorption of energy within the rock and to scattering.

Site Effects

- Site amplification is a complex frequency dependent process, but is often of critical importance for earthquake hazard. Amplifications of two to four times are common, and values up to 50 times or more have been reported in unusual circumstances.
- Soft sediments at the surface affect earthquake ground motion in a number of ways. Their low impedance results in an increase in wave amplitudes. Resonance at particular frequencies depending on their depth and elastic properties leads to frequency dependent amplification, especially for horizontal shear waves. The interface between the sediments and underlying bedrock will cause a reflection of a proportion of the seismic energy approaching the sediments from underneath back into the earth. The sediments themselves are more likely to absorb seismic energy than the hard bedrock, especially at higher frequencies, and may lead to a reduction in motion at the surface.
- Surface earthquake ground motion is also affected by the topography and by deeper geological structures in the area.

Effects on Structures

- The dynamic properties of a structure may be determined from measurements of its response to ambient vibration (for example wind), to artificial vibrations from blasts or mechanical shakers, or to small or distant earthquakes.
- Measured earthquake ground motion may be used to compute response spectra for structures.
- Earthquake motion measured on a structure, if compared with nearby ground motion, is a direct measure of the structure response.

Earthquake Alarms

- Seismographs may be connected to alarm and pager systems to provide an alert within minutes of the occurrence of a significant earthquake. If a preliminary earthquake location and magnitude can be rapidly determined,appropriate information will allow most effective use of emergency services resources. In the period after a moderate or large earthquake it is quite feasible that most reports will be coming from places that have not been seriously affected, while communications with most seriously affected places may be cut.
- Provided that planning has been undertaken beforehand, a preliminary earthquake location and magnitude will allow computation of a prioritised series of engineering inspections for critical structures.

3. Components of Seismic Instruments

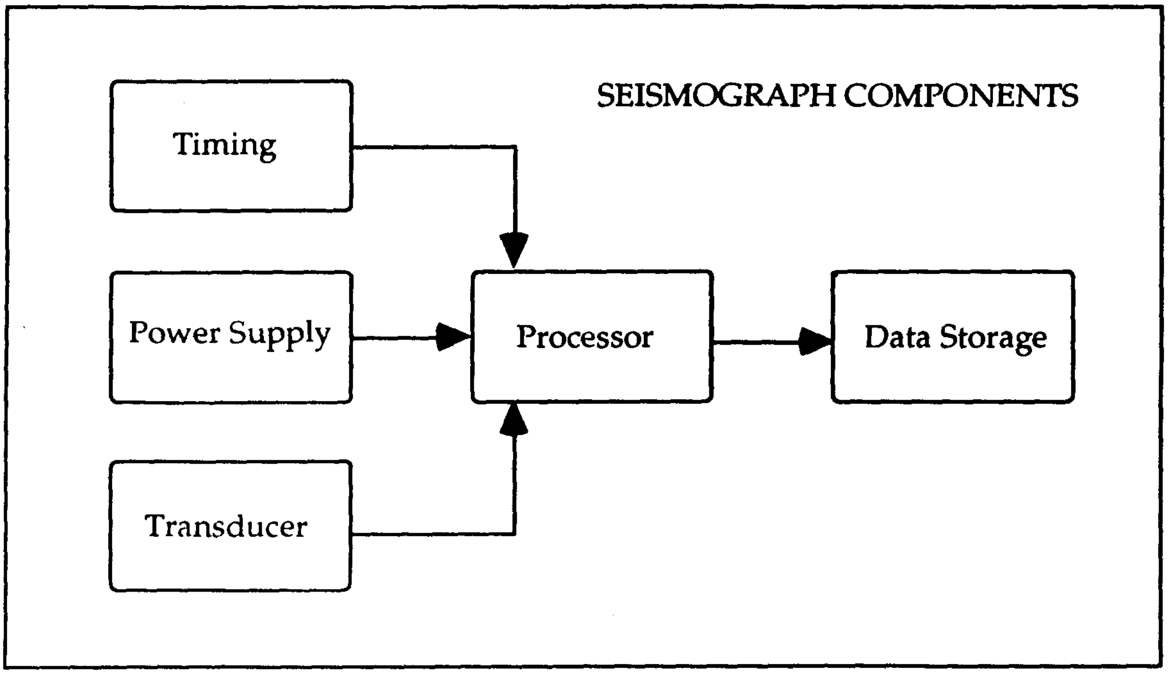


Figure 1. The major components of most seismographs

Transducers

Transducers convert ground motion into a signal that can be recorded, usually an electrical voltage or current. Transducers can measure displacement, velocity, acceleration, pressure or strain. A seismic recorder that measures displacement or velocity has traditionally been called a seismograph, while one measuring acceleration has been called an accelerograph. There are two types of transducer currently widely used for recording local earthquakes, seismometers and accelerometers.

Seismometers Seismometers have a suspended mass, a magnet and a coil. As the seismometer case moves the mass tends to remain stationary, and relative motion between the magnet and coil produces a voltage that can be related to its velocity. The suspended mass acts as a damped harmonic oscillator. Damping may be controlled in many ways, ranging from vanes in a fluid to dissipation of the electrical output in a resistor.

A seismometer has three primary parameters. The output is usually measured in volts/mm/s. The damping is normally measured as a ratio of critical damping, and is normally set to a value of about 0.7 critical. The natural frequency of the seismometer is measured in hertz and for local earthquakes normally has a value less than 2 Hz, with 1 Hz often being used. The lower the natural frequency, the larger and heavier the seismometer tends to be. Small high frequency seismometers (8 to 15 Hz or more) used for geophysical exploration are often called geophones.

Each seismometer can measure motion in one direction, either vertical or horizontal. They are often packaged as a triaxial seismometer to record east-west, north-south and vertical motion. It is often difficult to obtain similar parameters for the horizontal and vertical seismometers. A single channel seismograph used to detect and record earthquakes usually uses a vertical seismometer, because vertical ground motion is usually less affected by noise and provides larger first motion (P waves).

Another parameter used to define a seismometer is the amount of free movement. For many seismometers this is limited to about 1 to 3 millimetres, so for strong motion the seismometer will be driven to full scale. Seismometers are very sensitive and use no power, but do not record strong motion. It is not easy to compute the exact input motion from the output voltage, especially at frequencies lower than a couple of times the natural frequency of the seismometer.

Accelerometers Most modern accelerometers are feed-back devices. They consist of a mass on a pendulum and a motion detection system, which may be optical, capacitive, or piezo-electric. They also have an electromagnet system to control the position of the pendulum. If the accelerometer case moves, a displacement of the pendulum is detected and a feed-back current is applied to the electromagnet until it returns the mass to its original position. The feed-back current required to keep the pendulum stationary is proportional to the acceleration of the device

The detection and feed-back system must operate very quickly to keep up with high frequency motion. Because the pendulum does not move significantly, it is possible to design the accelerometer to give its peak output signal at levels of strong earthquake motion, usually 1g or 2g. Most modern feed-back accelerometers are quite sensitive, being able to detect accelerations down to between 1 and 10 micro-g. This is still about 1000 times less sensitive than that which can be detected by an equivalent seismometer. Feed-back accelerometers require power to operate the pendulum motion detection and control system, some types requiring a significant amount of power. Each accelerometer can measure motion in one direction, either vertical or horizontal. They are normally packaged as a triaxial accelerometer to record east-west, north-south and vertical motion.

A single channel accelerograph used to detect and record motion on a structure usually uses a horizontal accelerometer, because horizontal motion is usually more hazardous for engineering structures than vertical. Accelerometers have similar parameters to seismometers, but normally their natural frequency is well above the frequency of vibrations to be measured, 50 to 100 Hz or more. The output is usually set so that full-scale corresponds to 1g or 2g. The noise level of the accelerometer is then measured in micro-g.

Other Transducers Other motion transducers exist, but many are too insensitive in the frequency range used for local earthquakes. New transducers using fibre optics and other techniques are under development but at present are too sensitive to temperature variations for practical use.

Broadband feed-back seismometers can be used to measure very low frequency motion, with periods up to over an hour or more. They usually require a very stable temperature and power supply, and may require installation in an expensive borehole or an evacuated container. They are particularly useful for global seismology, but are not yet practical for local earthquake measurements.

Timing System

Earthquakes are located by precisely measuring the arrival times of seismic waves from the earthquake at a number of seismographs. Differences in arrival times are used in the earthquake location. The precision required depends on the travel time from the earthquake to the seismographs. On a world scale, where it takes a little over 20 minutes for waves to travel from the opposite side of the earth, a timing precision of 1 second is required. For local earthquakes a precision of 0.1 seconds is required, and for epicentral studies where the seismographs are within a few kilometres of the earthquake a precision of 0.01 seconds may be required. This means that each seismograph clock must be this accurate over a long period, perhaps months, or that its time must be correctable to this accuracy.

A seismograph timing system includes both the clock and means used to set and adjust the clock. Seismograph clocks usually use clocks with a temperature compensated crystal oscillator. These can usually be set to an accuracy corresponding to a drift of a few milliseconds per day. Temperature compensation is imperfect and this drift will vary over day and night, and over winter and summer.

Accurate time can be obtained from several sources. The most common source used at present is a short-wave radio time signal such as the Australian VNG radio time signal. This provides a beep each second, a longer beep each minute, and other encoded information. The main error is due to the radio transmission path, but the start of each beep detected is usually no later than a couple of milliseconds after the precise time.

Other sources of precise time include the telephone system time beeps and the hour time beeps on commercial or national radio. These may vary by a significant amount if radio programs are sourced from different states or satellite relays are used. The Omega low frequency navigation system may be used to obtain precise signals each ten seconds. There seems little doubt that in the future, a satellite based timing system will become standard.

The NAVSTAR Global Positioning System (GPS) established by the US military may be used to determine time to a small fraction of a microsecond. As a bonus it will provide the location of the seismograph to an accuracy of a few tens of metres. The NAVSTAR system has an artificially imposed "Selective Availability" that limits the accuracy of locations. The Russian GLONASS system will be similar, but is expected not to include the equivalent of selective availability. Timing precision is adequate even with selective availability. Portable hand held GPS receivers are readily available, but not all provide an appropriate output time signal. Currently available GPS electronic systems use more power than most seismograph installations can afford, so they must be switched on and off for time checks. The GPS signal is line of sight, so the aerial must be mounted in an unobstructed area.

Power supply

Most seismographs operate on a single 12 volt power supply, usually a 12 volt battery. Mains power is not normally used to power a seismograph directly because it is likely to fail in a large earthquake, but it may be used to continuously charge the battery.

Mains power is often not available at remote seismograph sites, so solar panels are used for charging.

It is desirable to minimise the power consumption of a seismograph for several reasons. Low power consumption means smaller and less expensive solar panels, a longer period of operation from batteries after the charger has failed, and a lower level of electrical noise in the recorder. A typical seismograph recorder will use about 1 watt. Additional power may be used if feed-back transducers, a GPS timing system, telephone modems or cellular telephones are included. Some of these may be switched on and off as required.

Processor

Analogue to digital conversion The processing part of most seismographs starts with electronic amplifiers, usually with high pass and anti-alias filters. The output of this is recorded directly by analogue recorders, or converted to numeric values for digital recorders.

The analogue to digital converter plays a key role in digital recording. The sample rate must be higher than the highest seismic frequency that must be recorded. If seismic signals to 25 Hz are to be recorded, then a sample rate of at least 100 samples per second is desirable. If the seismic signal frequency approaches or exceeds one half of the sample rate (the Nyquist frequency), then a fictitious low frequency output called aliasing is produced. The analogue anti-alias filter is usually set to about 25% of the sample rate to prevent this. If detailed waveform analysis, or differentiation or integration is to be performed, it is desirable to have more samples per cycle at the maximum seismic frequency.

The resolution and dynamic range of the digital recorder depends very much on the nature of the analogue to digital converter. Most converters are linear, with a fixed number of data bits. With more bits the precision of the numeric values is greater, but the conversion will be slower, use more power, and the converter will be more expensive. The most common values are:

Number of bits	Full scale counts
8	128
10	512
12	2048
16	32 768
18	131 072
20	524 288
24	8 388 608

Alternative methods of conversion may be used. Rather than a linear conversion, the numeric value may give a logarithm of the input signal. This may be used to give a wide dynamic range, but with decreasing resolution with amplitude. A similar result can be achieved by producing a floating point value with mantissa and exponent. Both of these methods use less computer storage than is required for linear values. They can be used when dynamic range is important but resolution is less important. They are most useful when the seismograph is used to locate earthquakes, and may not be appropriate when wave form analysis is to be undertaken.

On multiple channel recorders, older types of digital recorder would use the same analogue to digital converter to sample each channel in turn. This would give a small time offset between each channel, sometimes constant and sometimes variable in length, but often a significant proportion of the sample interval. This did not matter if the seismograms were only being used for earthquake locations, but if they were used for polarisation studies, such for P wave directions or S wave splitting to determine anisotropy directions, such time skews were most important. Most modern digital seismographs give synchronous sampling on all channels.

Signal processing

Data from the analogue to digital converter usually must be processed before it is stored. This includes gathering multiple channel data for a sample, filtering the data if software decimation is to be used (if only one in n data samples is to be kept), and the event detector for triggered recording. Although a triggered recorder can be set to record when the signal exceeds a constant pre-set value, this type of trigger is not normally useful because many types of seismic noise include short spikes.

A trigger which takes the input signal and averages it over two different time periods, then takes the ratio of the short term average over the long term average, is less likely to trigger on noise. More complex event detectors have been developed, and may be optimised for particular applications. Repetitive signal processing may be facilitated by using a Digital Signal Processor (DSP) which is a computer optimised for repetitive computations.

User interface

Another major function of the seismograph processor is the user interface. This allows the user to change the settings of the recorder so that they will be appropriate for the particular purpose, to monitor the operation of the recorder, and to extract data from the recorder. Before computers, these functions were provided by switches and dials.

The recorder interface can vary from exchange of codes and information (for seismograph to computer interaction), to formatted and graphical screen outputs with optional help information (for seismograph to human interaction) The seismograph processor may be responsible for alarm functions to alert staff or equipment that a significant earthquake is taking place, and that something may have to be done about it.

Handling abnormal situations

A major function of the processing system in a modern seismograph is to handle abnormal situations. The recorder should be designed to handle situations such as a power failure or lightning strike. If power fails, data should not be lost, the seismograph clock should not stop, and the seismograph settings (sample rates, number of channels, filter, trigger parameters, etc) should not be lost. When power is restored, the recorder should continue monitoring. The seismograph should have independent "watch dog" systems that will detect anomalous operation, then give an alarm or restart the seismograph.

Data storage

Analogue Analogue recorders produce a direct wiggly trace on a drum recorder, using either pen and ink, smoked paper with diamond stylus, or photographic paper or film. Photographic recording is becoming too expensive and time consuming for most applications.

Triggered Digital A triggered digital seismogram of an earthquake will typically require a few thousand bytes per channel. About 50 to 100 triaxial seismograms can be stored in a megabyte. In areas of low to moderate seismic activity, one megabyte is sufficient storage capacity for a typical triggered digital recorder. The original triggered digital seismographs recorded data on magnetic tape, usually cassettes, with a capacity of about one megabyte. Current recorders mainly use battery backed CMOS memory, which has very low power consumption, with similar or slightly greater capacity. Future triggered digital recorders will take advantage of developments in memory technology, with lower cost and greater capacity. Removable PCMCIA memory cards with capacities from 2 to 20 megabytes will simplify field servicing of recorders, with the old card being replaced by a new one without the need to copy data. The old card will then be plugged directly into the replay computer system for analysis of data.

Continuous digital A continuous digital seismograph requires a great deal of storage. A single channel recorder with 100 samples per second, two bytes per sample, will require over 17 megabytes per day. Until recently, continuous digital recording could only be performed at sample rates too low for local earthquake studies. Digital recording is developing rapidly, with many new methods of storage becoming available. The original digital tape recorders could store from about one megabyte on a small cassette, up to a few tens or hundreds of megabytes on computer tapes. Recent developments in computer disc and tape technology mean that greater storage capacity can be provided at reasonable cost. Hundreds of megabytes can be provided on exchangeable magneto-optical discs, and several gigabytes on removable tapes such as DAT (Digital Audio Tape) cartridges. Disc and tape mechanisms are more susceptible to mechanical damage than solid state data storage, and are more likely to be affected by very hot or very cold conditions.

4. Specification of seismic instruments

The two primary aspects of a seismograph that must be considered are the frequency range, which is determined by the type of earthquakes to be recorded, and the sensitivity and dynamic range which are determined by the seismograph system and fix the smallest ground motion that will be detected and the ground motion that will give full scale.

Both frequency and amplitude of seismic waves range over many orders of magnitude. The natural frequency of the earth as a whole is about 0.0003 Hz (a period of about an hour), and rockbursts in mines can give waves with frequencies up to 10,000 Hz. Measurable ground displacement varies in amplitude from a few metres down to about one million millionth of this. Frequency Response The earthquake motion of significance for earthquake hazard studies is usually in the range from 0.2 Hz to 25 Hz. For distant earthquakes, most of the signal above a few hertz is attenuated, while earthquakes within a few kilometres can give significant vibrations at frequencies of 100 Hz or more. This high frequency motion does not normally affect structures. If accelerometers are used rather than seismometers, higher frequencies are accentuated and may require higher sample rates. The frequency response and sample rates used depend on the type of earthquake being recorded, and are usually in the following ranges:

	lower frequency	*higher frequency*	*typical sample rate*
Free oscillation of the earth	0.0003	0.01	1 or less
Earthquakes beyond 1000 km	0.03	5	20 (10 to 40)
Local earthquakes	0.2	25	100 (50 to 200)
Strong motion accelerographs	0.2	50	200 (100 to 250)
Rockbursts in mines	1	500 - 10 000	400 to 20 000

Dynamic Range

By definition, the amplitude of ground motion at any distance from a magnitude 8 earthquake is 100 million times greater than that from a magnitude 0 earthquake, complicated a little by the difference in frequency content. Small earthquakes do not cause any damage, but with appropriate seismograph coverage they can be located precisely and may be used to delineate active faults. They also give useful information about the relative number of small and large earthquakes in an area. It is often found that within certain magnitude ranges there are about ten times as many earthquakes larger than magnitude M-1 than there are greater than magnitude M. The ratio varies from place to place, and may be about six in areas of high stress (not necessarily areas of high earthquake activity, but rather in areas where the stress within the earth is compressive producing reverse or thrust faults).

Recording small earthquakes provides useful data more quickly than recording only larger earthquakes. Traditional analogue accelerographs measured strong motion only, and would not resolve motion much less than that which can be felt. Traditional analogue seismographs were very sensitive, and reached full scale for motion perhaps 100 or 1000 times less than that which can be felt. Digital recording may have a much greater dynamic range, with the ratio of 1:1,000,000 or more. The same recorder will provide data for small or distant earthquakes, and still record much stronger motion without going to full scale. This may give an overlap between the motion recorded by digital strong motion accelerographs and sensitive digital seismographs.

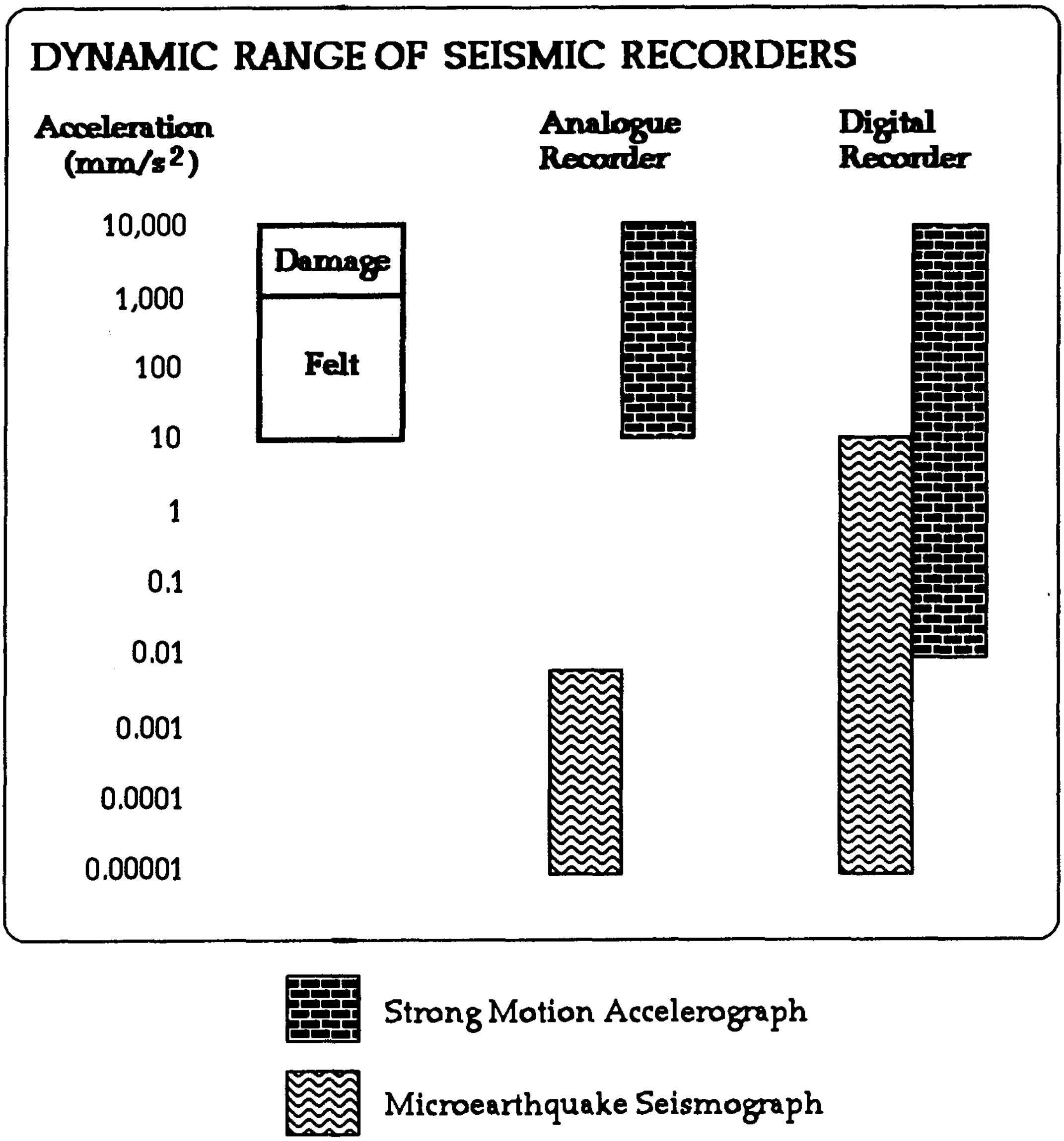


Figure 2. The analogue recorder may be a high quality pen and ink, hot pen or film recorder. The digital recorder assumes analogue to digital conversion with a dynamic range of 120 dB. The dynamic range of actual recorders varies from two orders of magnitude lower to an order of magnitude higher than this.

5. Design of a seismic instrument installation

Seismometers or Accelerometers Seismic instruments may use either accelerometers or seismometers. Accelerometers will not go full scale for a major earthquake and may be used to detect non-linear behaviour at stronger ground motion, but are less sensitive than seismometers so will not record small or distant earthquakes. Seismometers will record many more events than accelerometers, so will allow computation of a site transfer function more quickly, with better uncertainty estimates, and with a better indication of the effect of earthquake direction. An ideal configuration includes both accelerometers and seismometers.

Single or Multiple Channel Earthquake ground motion is three dimensional. There are a number of differences between horizontal and vertical ground motion. Soft sediments at the surface amplify the horizontal motion, and can be particularly noisy in the horizontal directions. The first wave to arrive from an earthquake (the compressive P wave) approaches the surface at a sediment site near to vertically, so is best recorded on the vertical component. For locating earthquakes, a single channel vertical seismometer gives good P wave arrival times, but poor S wave arrivals. Installation of a recorder on a structure to measure its response will normally be to study amplified horizontal motion that causes damage. A single component strong motion recorder would use a horizontal component in the critical direction.

For most digital seismic recorders there is only about a 15% increase in cost for the additional transducers and amplifiers for three components over the cost for a single component, so most use three channels. To determine the response of a sediment site, the ideal configuration would be to have six channels at the proposed site and on bedrock nearby, each with a triaxial strong motion accelerometer and a triaxial seismometer in parallel. The cost of a six-channel system is about 25% higher than a three-channel system, and 40% higher than for a single channel system. This is mainly the cost of the additional detector, amplifiers and data storage. The operating costs are comparable. The six channel system would give better site transfer function data, and it would be much more useful as part of the regional seismograph and accelerograph network for development of bedrock ground motion recurrence estimates. In the future, additional channels may be used to measure rotational motion.

Continuous or triggered, analogue or digital

The traditional drum seismograph produced a continuous helical analogue trace on a rotating drum. The pen moved across the drum at a constant rate, and the seismogram had to be changed at regular intervals, usually each day. The traditional accelerograph used an analogue trace on a film recorder that was triggered into motion by the earthquake. This meant that accelerograms could not include the start of the earthquake motion, or pre-event background noise.

Apart from the greatly increased dynamic range, digital recorders have a number of other advantages over analogue recorders. Data may easily be subjected to numerical processing, such as filtering or computation of response spectra. Digital data can be plotted at the most appropriate scales, in time and amplitude. Multiple channels can be recorded synchronously on a digital recorder, so a three dimensional representation of ground motion can be produced, while multiple analogue records give an uncertain skew between channels. A triggered digital record such as that plotted in figure 3, can be printed to give the optimum view of the particular earthquake. However, a continuous analogue drum record shows all seismic activity over the period at a glance.

Continuous digital data on a computer disc or tape requires replay, and still does not give the seismologist a good feel for the nature of seismic activity over the long-term. A good compromise is to use mainly triggered digital recording, with a small number of continuous analogue recorders.

Distributed or Central Recording

Seismic data is accumulated at a range of sites, and must end up in the observatory. Cost and reliability factors determine when data is removed from remote sites. A telemetry system with no data storage at field sites and telemetry to a single central recorder may be convenient, but it has a number of disadvantages. The cost of telemetry may be high, especially if moderate or high sample rates and multiple channels are used. Most of the data would not be used. If the telemetry or the central recording system fails, then all data may be lost. This could happen in a major earthquake. On the other hand, a totally distributed seismic instrumentation system has disadvantages. Following a major earthquake, it may take considerable time to get the data, then determine the earthquake location and magnitude.

The optimum solution may be a combination of the two. Each field seismograph may run multiple channel triggered recording at a high sample rate with data being stored on site. This is accessed at regular intervals (perhaps every two weeks or month), and immediately after any major earthquake, preferably by telephone. The vertical channel from a number of the field seismographs is telemetered continuously by radio or telephone line to the laboratory. At least three channels from different sites would be required, and perhaps up to 10 or 15 for a larger network. The sample rate used can be lower than that being recorded in the field.

The signals can be recorded continuously on analogue recorders (which are much easier to operate if all are located at the observatory), and at the same time on a central computer triggered digital system that will provide alarms and possibly a preliminary earthquake location and magnitude computation. Continuous digital recording may also be carried out to get additional data for small or distant earthquakes.

	distributed	*combined*	*central*
Earthquake alarm	Poor	Immediate	Immediate
Multiple channel	yes, triggered in field recorders	yes, triggered in field recorders	expensive
High sample rate	possible, triggered in field recorders	possible, triggered in field recorders	expensive
Chance of loss of all data	very low	very low	normally low, high after a large earthquake
Replay and analysis time	time consuming	a little less than for distributed recording	easy, with appropriate software
Continuous analogue	difficult, needs onsite staff	easy, observatory staff	easy, observatory staff
Continuous digital	expensive, tape or disc at each site	easy, for telemetered channels only	easy

Borehole or Surface Transducers

The easiest way to determine a site transfer function is to record a number of earthquakes at the site, and simultaneously at a nearby bedrock site. Spectral ratios then give an estimate of the site transfer function.

The bedrock detector may be within a borehole or on a nearby rock outcrop provided it is not too far away. Depending on the size, distance and direction of earthquakes of concern, the bedrock outcrop should not be more than a few kilometres from the site. Although a borehole installation may give more realistic results, it has two disadvantages. A triaxial borehole installation is very expensive, possibly costing more than the combined sum of all other components required. The free-surface amplification must be considered separately with a borehole installation, so the site transfer function is more difficult to determine from spectral ratios.

A practical problem at a soft sediment site is that noise levels are very much higher than on bedrock. Unconsolidated sands and silt can often be regarded as just a little firmer than a bowl of jelly, or a pond of water. The site will be strongly affected by regional factors such as wind, ocean waves, and city traffic, and by local factors such as nearby machinery or passing vehicles. A triggered seismic recorder at a soft sediment site will either trigger often on noise, or be set much less sensitive than one on bedrock. Ideally, the site and bedrock recorders should trigger simultaneously.

The site recorder could be triggered by the bedrock recorder using radio or a permanent cable connection. This could also be used to synchronise the recorders, and to provide a watchdog warning system should either fail. Multiple Purpose Recorders It is highly desirable for any seismic instrument to perform multiple tasks. Although the main problem is often the determination of a site transfer function, earthquake records will also be useful for developing the seismo-tectonic model and the regional attenuation function.

6. Operation of the instruments

There have been significant improvements in seismograph coverage and cost efficiency over the past few years. There are several reasons for this. Modern digital seismograph recorders provide more and better data, and do not require daily seismogram paper changes. Most new instruments are operated by telephone with calls at intervals between one and four weeks, and require less field work and travel than was needed in the past.

Staff

The operation of a digital seismograph network and routine analysis of the data is a specialised task requiring staff with a range of skills. A network requires electronics staff for maintenance, field staff for operation of recorders, and seismologists for analysis of data, no matter how many instruments are operated. Skills in computing and telecommunications are also required. It would be unusual to find the range of skills required in fewer than three or four people.

Most successful seismic installations are operated by a local seismological authority. In most states of Australia there is a single authority, either the state geological survey or mines department, or a university. The Australian Seismological Centre at the Australian Geological Surveys Organisation (AGSO, ex-BMR) co-ordinates national requirements, and provides international links.

Operating cost

The cost of operation of a seismic recorder depends on the type of recorder (digital or analogue, continuous or triggered, onsite or telemetered data, etc), on the sensitivity of the instrument (an accelerograph deliberately set insensitive requires minimal support), and on the number of recorders operated by the authority. This ranges from under A$2000 per year (1992 values) for a low sensitivity triggered digital accelerograph to over $14,000 per year for a telemetered continuous recorder with a triaxial triggered digital recorder in parallel.

There is a significant economy of scale when operating a seismograph network, and the minimum number of instruments for cost-effective operation would be something like 20 instruments. Routine Procedures Most seismological observatories process and exchange data on a calendar month basis. In the past, data from many seismographs located in remote areas were received irregularly, so most of the analysis was performed on data a few months old. Recent improvements to communications mean that most analysis is now done within a month, and data from relatively few seismographs are added for the "final" analysis a few months later.

8. Trends

A number of trends are becoming apparent in the operation of seismic instruments.

More Sites with Simpler Site Works

- Study of earthquake sources, seismic wave travel paths, and site studies all need recordings from as many places in the seismic motion field as possible, rather than very high quality data from a single expensive installation. A number of very high quality sites with broadband instrumentation are required within Australia for study of world earthquakes, but it would be too expensive to install this type of equipment for all local earthquake studies.
- Use of more and simpler sites brings a degree of redundancy to the network, and the temporary loss of one site through equipment failure is not critical.

Increased Automation, Reducing Field Work

- This has several benefits, primarily a reduction in the operating cost of a seismograph network, but often an increase in data quality, and more rapid access to data and results.
- Automation inherently involves triggered digital recording to identify earthquakes.
- Automation will normally involve telemetry of data to the observatory, either continuous or dialup. Use of cellular telephones has improved access to remote recorders, and this will be extended with the introduction of satellite based mobile telephones.
- At least one continuous analogue drum recorder will be required at each observatory to simplify replay and analysis of digital data, and to provide seismologists with a complete visual record of seismic activity.

Seismometers and accelerometers

- High resolution digital recording means that it is becoming possible to integrate and differentiate seismograms, accurately converting between displacement, velocity and acceleration. Acceleration data can be computed from digital seismograms.
- Accelerometers record the high accelerations from high frequency motion of nearby small earthquakes very well. With accurate timing, accelerograms can be used for source, path and site studies. This means that accelerometers are very useful for epicentral studies. They do not record distant earthquakes well, because high frequencies are attenuated with distance more than low frequencies.
- Seismometers are very sensitive, especially at the lower frequencies from 0.2 to 25 hertz of concern in engineering. They can be used to give useful engineering information about dynamic properties of structures, especially their natural frequencies. Results may be obtained much quicker than if less sensitive accelerometers are used, using data from small or distant earthquakes. Unfortunately, seismometers will go to full scale for strong motion.

Multiple channel synchronous recording

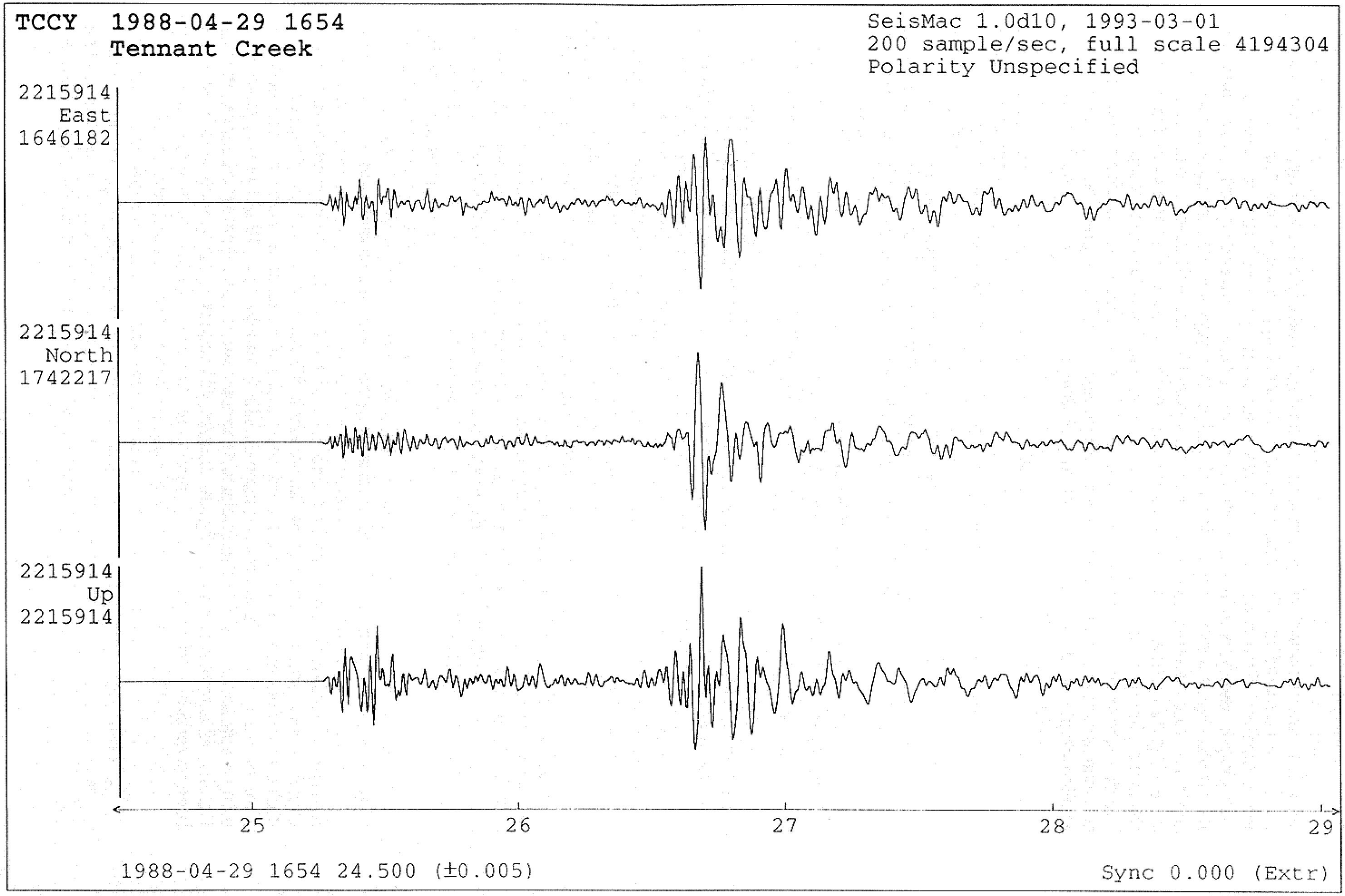
- Routine analysis of seismograms will no longer include just measurement of arrival times for earthquake locations and peak amplitudes for magnitudes. Spectra will be used to compute earthquake moments. Synchronous recording will be required for azimuth and polarisation studies
- Triaxial recording allows S wave processing for shear wave splitting and anisotropy.
- Bedrock installations using six channel recorders with a triaxial seismometer and a triaxial accelerometer will record the total range of earthquake ground motion between noise and very strong motion. Compared with a three channel digital recorder, the capital cost is about 25% greater, and the operating cost is negligibly greater.
- For measurements on structures, recorders with six or more channels allow comparison between maximum structural motion (usually at the top), foundation motion (combining input ground motion and motion fed-back from the structure), and/or the free-field motion on nearby bedrock, using just one recorder. In addition to the cost saving, the recorded motion will be synchronous.

9. Conclusion

Seismic instrumentation will continue to use analogue and digital recording, continuous and triggered recording, distributed and central recording, seismometers and accelerometers. There are now more options, and more opportunities for providing multiple purpose systems that provide for secure redundant recording. The provision of alarms immediately following major earthquakes, then preliminary earthquake locations and magnitudes within a few minutes are now possible, and will become an increasingly significant function of seismological observatories. The use of multiple channel digital recorders mean that seismic instrumentation is becoming more integrated, with particular recorders being used for different functions. The distinction between sensitive seismographs used by seismologists and strong motion accelerographs used by engineers is rapidly vanishing.

Figure 3 (next page). Tennant Creek aftershock accelerogram

A series of earthquakes of magnitude MS 6.3, 6.6 and 6.9 occurred near Tennant Creek in the Northern Territory on 22 January 1988. A network of Kelunji triggered digital recorders was installed to record aftershocks. This accelerogram was recorded 9 kilometres from an aftershock of magnitude ML 4.9 on 29 April 1988. It was recorded using a Sprengnether HSA-3 triaxial accelerometer, and a KA1 Analogue board in the Kelunji. The peak motion is 0.53g, the strongest earthquake ground motion to have been recorded in Australia.


TCCY 1988-04-29 1654
Tennant Creek
SeisMac 1.0d10, 1993-03-01
200 sample/sec, full scale 4194304
Polarity Unspecified
2215914
East
1646182
2215914
North
1742217
2215914
Up
2215914
25
26
27
28
29
1988-04-29 1654 24.500 (±0.005)
Sync 0.000 (Extr)