Industry guide

Strong motion arrays for civil engineering

Bridges and viaducts provide key infrastructure links in every part of the world, yet they are especially prone to catastrophic damage in the event of a major earthquake.

After pioneering programmes in California, Japan and elsewhere, seismic installations are becoming a standard part of new bridge projects, especially in areas of high local seismicity. Existing structures are also being retrofitted with accelerometers.

Where continuous strong-motion data is available, bridges can be monitored for signs of structural deterioration or unusual levels of vibration. “Early warning systems” can be designed to alert authorities to an earthquake as soon as it occurs.

In addition to their role in hazard mitigation, seismic instruments on bridges provide information on the response of different designs to ground motion, as well as the interactions between soil and structure in the critical areas near the supports.

Long bridges exhibit complex vibration patterns owing to their open structure: the supports are some distance apart, leading to incoherency in input ground motion. Comprehensive ground motion and structure response data is therefore essential for engineers to be able to design bridges for improved seismic resilience.

Similar considerations apply to other types of civil structure, such as tunnels, wharves, and airports.

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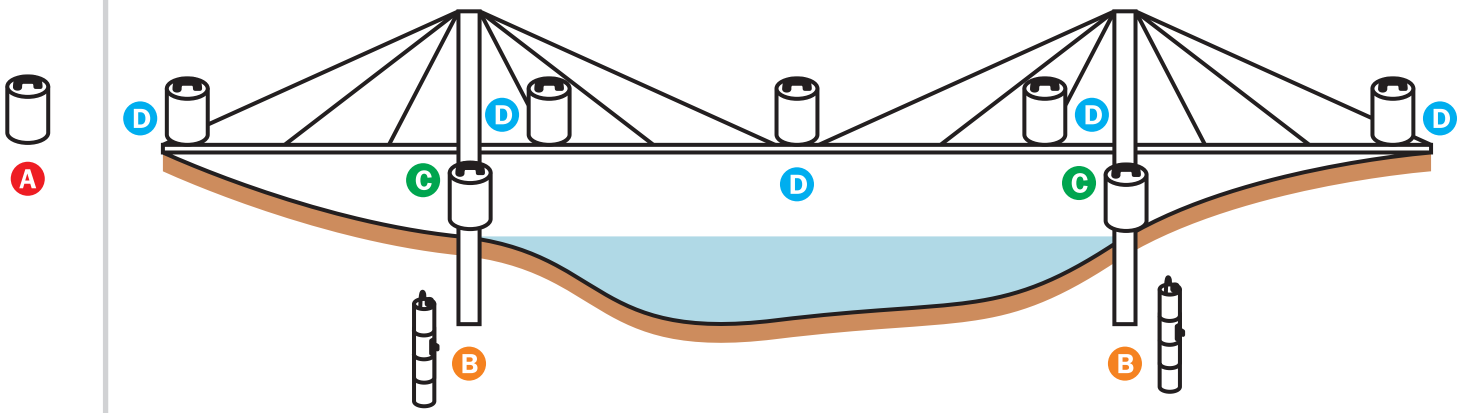
Array design for bridges

The number of sensors used in an installation on a bridge depends on its size and complexity. As of 1999, 58 bridges in California were equipped with instruments, ranging in number from 6 to 42 per bridge. [Huang and Shakal, 2001] More recently, San Francisco's Bay Bridge has been equipped with 88 sensors, comprising 79 on the bridge itself and 9 in a nearby subsurface array. [Ca.D.C, 2004] Whether part of a small or large project, bridge instrumentation needs to measure four key quantities:



The free field. Location A represents an instrument which records local ground motion independently of vibrations within the structure. Suitable free-field sites are often difficult to find in the vicinity of bridges, as they are generally located in developed areas.

Input ground motion. Instruments at locations B measure the motion of bedrock, ideally at the foot of each support. Small arrays of borehole instruments are often used for this [Hutchings et al, 2001] In most cases, however, arrays cannot be installed at the foot of each support.

Motion of the supports. Instruments should be installed at different levels within the bridge supports, *e.g.* at the base and cap of each support pile (locations C.) The Bay Bridge has instruments on five levels in each support. [de Alba, 2001] Where supports are not individually instrumented with boreholes, these instruments provide an approximation to the input ground motion.

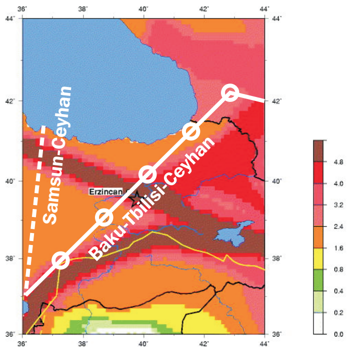
Motion of the deck. Finally, instruments need to be placed at intervals along the deck (locations D) to measure the motion of the bridge in response to the input ground motion.

Array design for pipelines

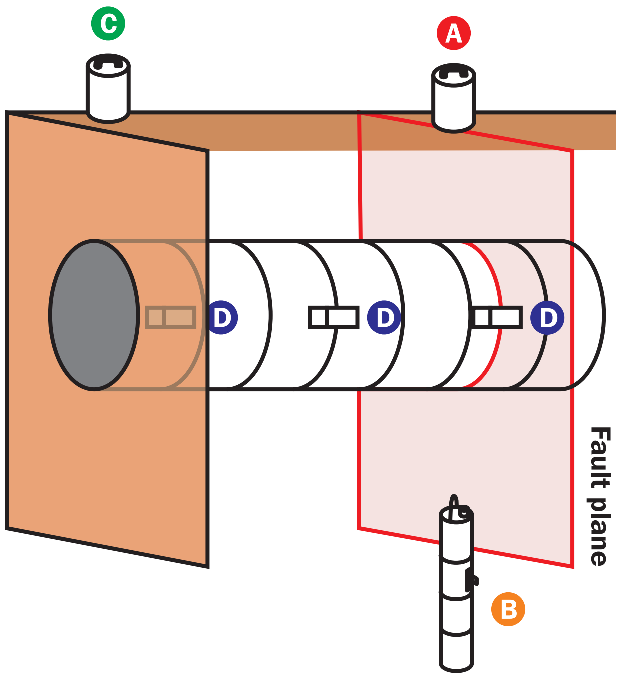
Pipelines present unique challenges. A buried pipeline is subject to the movements of the soil around it for its entire length. Natural slippage along a fault line, even if it does not cause an earthquake, places strain on any structure which crosses it. Sections of pipeline may also be subjected to stress due to lateral spreading, liquefaction or landslides. Seismic instruments can help operators detect stresses in a pipeline before a failure occurs.

The importance of seismic monitoring is increased where a pipeline crosses a geologically-active area. For example, both the Baku-Tbilisi-Ceyhan and the proposed Samsun-Ceyhan oil pipelines run through areas of high seismicity in eastern Turkey. Seismic instruments along such a pipeline have several important roles:

- to measure local seismicity, locate earthquakes when they occur and determine their magnitudes;
- at fault zones, to measure slippage and other ground motion that could affect the pipeline; and
- on the pipeline itself, to measure its response to seismic events and geological activity.



TURKEY
2003 01 27 UTC
Peak Ground Acceleration (m/s²) with 10% Probability of Exceedance in 50 Years
USGS National Earthquake Information Center



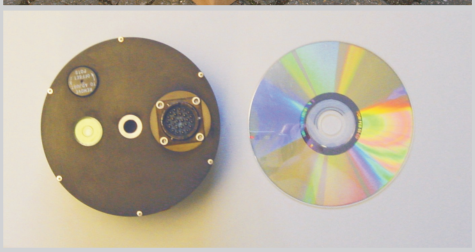
A typical design includes both surface (A) and borehole (B) strong-motion sensors at stations in fault zones along the route of the pipeline.

Weak-motion broadband stations (C) are included in areas away from the fault zones (where they would quickly saturate) to detect and locate seismic events.

Finally, uniaxial or triaxial sensors (D) may be mounted on the pipe itself to monitor its response to ground motion.

Elevated pipelines can be instrumented using a similar design.

Güralp Systems' strong motion range



Güralp Systems produce strong-motion broadband sensors suitable for a range of installation types.

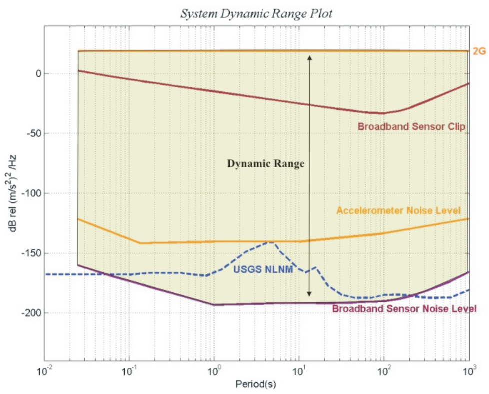
Our latest surface strong motion instrument, the **CMG 5T Compact**, is a full three-component sensor housed in a case about the size of a standard CD.

The well-regarded original design **CMG-5T** is also available. This instrument can also be fitted with an internal CMG-DM24 digitizer module to form the **CMG-5TD**.

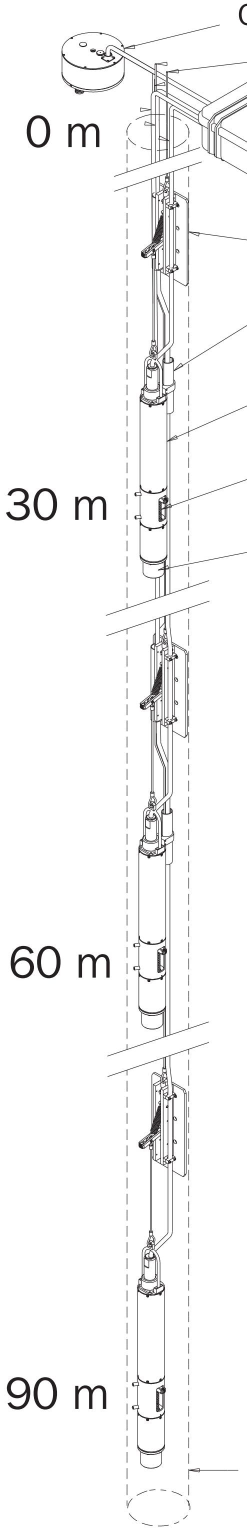
The 5TD offers support for high sample rates and low latency data transmission, as well as direct data download over FireWire. At-a-glance status information is available on its optional LCD display as well as being transmitted with the data streams in GCF format. Full configuration and firmware updates can be carried out remotely over the standard serial interface.

Identical components to the 5T are also used in the CMG-5TB borehole accelerometer. Strong motion borehole instruments can provide important information on the sub-surface soil movements which cause a high proportion of the damage sustained by structures during an earthquake.

A CMG-5TB module can also be fitted as part of a combined weak- and strong-motion borehole instrument, providing unsurpassed resolution and dynamic range for both local events and teleseisms. Weak-motion data is useful because it allows engineers to perform dynamic analysis under normal conditions, highlighting areas of concern before an event occurs. [Hutchings et al., 2001.]



Strong motion boreholes



As for all our standard instruments, the CMG-5T is available in both surface and borehole forms.

The borehole CMG-5TB is well suited to exploring behaviour around the soil-foundation interface and provide important data about the environment of bridge supports.

Borehole instruments in soil layers provide the best way to detect deformation and slippage, whilst instruments installed into bedrock give high-quality data on input ground motion.

Larger bridges may be equipped with extensive borehole arrays, including instruments at several different depths [Hutchings et al., 2001]

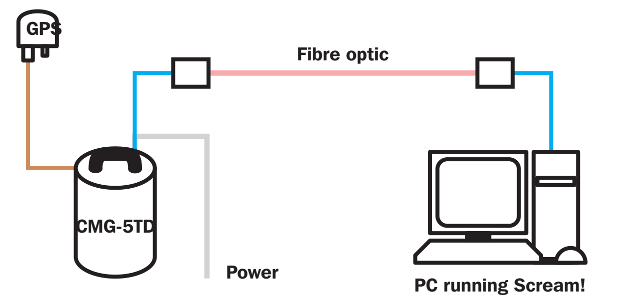
Pass-through systems are available which allow instruments to be located at different depths within the same borehole, greatly reducing construction costs. Up to 4 surface and borehole instruments can be connected to a single 12-channel DM24 digitizer.

The CMG-5TB can be colocated with a CMG-6TB medium-motion instrument, providing scope for more detailed study of ambient vibrations and the structure's response under normal loading. The CMG-6TB is capable of operating at up to 8 ° of tilt. Alternatively, a full combined weak- and strong-motion borehole sensor can be installed.

The exact orientation of the sensor can be determined using an optional built-in electronic compass.

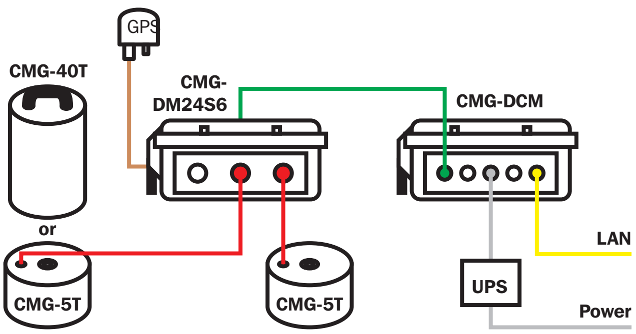
Telemetry and networking options

Güralp Systems' hardware forms a modular system using standard protocols, giving engineers the flexibility to design the network to their needs.
A single array can combine a wide range of technologies.



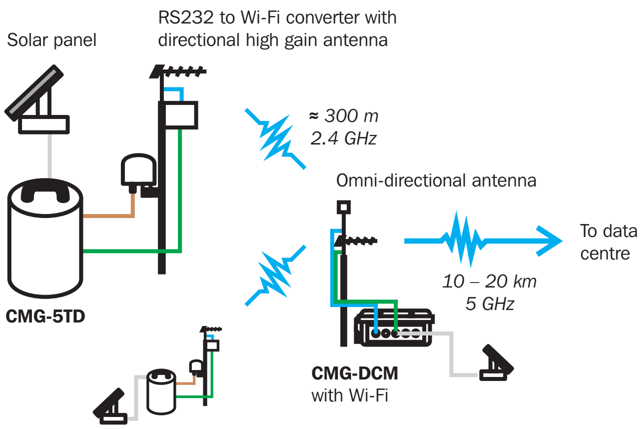
Example 1: A CMG-5TD installation. The digitizer outputs data streams over an RS232 or optional RS422 link using Güralp Systems' compact GCF format and block recovery protocol. Media converters or modems can be used to carry serial data over fibre-optic cables or telephone lines.

Streams are received by an acquisition PC running Scream! software, where they can be archived or retransmitted as desired.



Example 2: An installation using a six-channel digitizer connected to two analogue instruments. Velocity (CMG-40T or 6T) and acceleration (CMG-5T) instruments can be used interchangeably.

Data streams output from the digitizer are transmitted onto the network by a CMG-DCM data communications module.



Example 3: An array of autonomous CMG-5TD sensors powered by solar panels. Data streams are transmitted over 802.11b ("Wi-Fi") to a compact concentrator station at a convenient location on the structure.

A CMG-DCM combines the streams and store them on an internal hard disk. Using DSS, the DCM provides the data centre with instant updates on acceleration levels and spectral intensity. Operators at the data centre can connect to the DCM over the Web to access real-time or triggered data, configure and update the array.

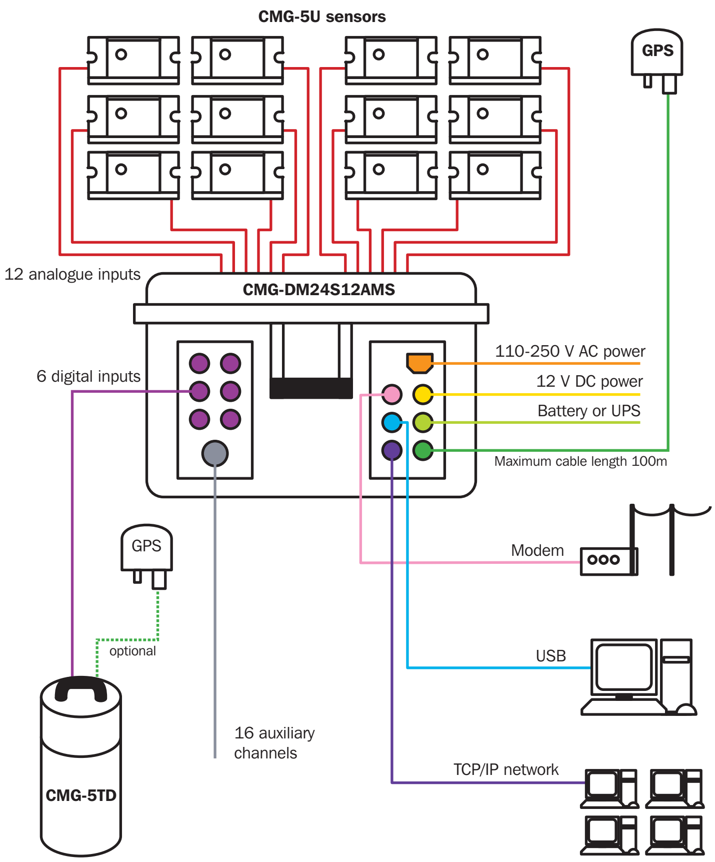
CMG-DM24S12AMS monitoring system

The CMG-DM24S12AMS is a self-contained acquisition and monitoring system, designed for use with 12 CMG-5U uniaxial accelerometers distributed around a structure.

Portable and self-contained, it is ideal for exploratory studies and seismic hazard assessments.

In combination with an external digital instrument (e.g. a CMG-5TD) for measuring free-field ground motion, the uniaxial sensors provide high-quality data suitable for modal analysis and modelling.

- 12-channel digitising capacity
- 6 external digital inputs
- GPS distribution
- 8 auxiliary 16-bit channels
- On-board laptop PC with Scream! acquisition software
- Modem, LAN, and USB support
- Battery, mains AC or external DC power



The CMG-DM24S12 is a similar unit, but lacking the on-board PC. Data from the DM24S12 can be relayed over a serial link to a DCM or PC for archival or retransmission.

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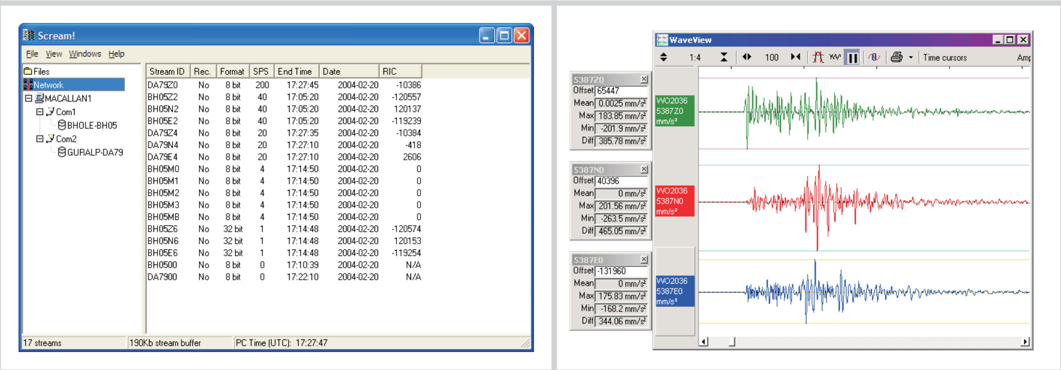
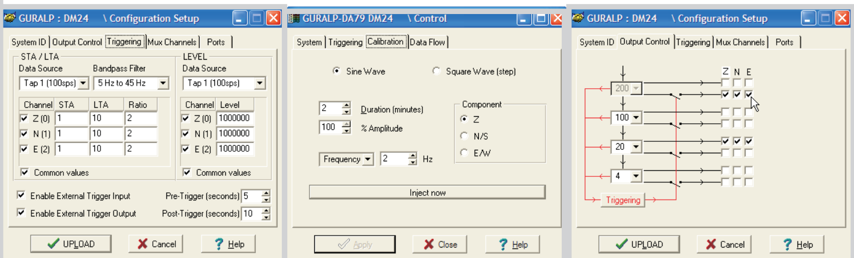
Scream!

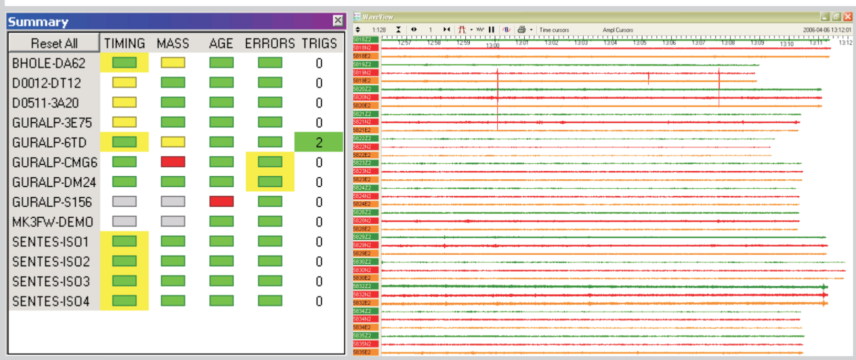
A PC running Güralp Systems' **Scream! software** can collect data from any number of sources and archive it to a local hard disk, or retransmit to a data centre further afield. Using Scream!, operators can view data streams in physical units, and apply filters to pick out events.



Scream! can **replay archived data** and **convert data** into a number of common formats, including MiniSEED and UFF. Güralp digitizers can also be fully **configured and controlled** using a graphical interface.



As well as displaying real-time data from any number of instruments side by side, Scream! provides features for **monitoring seismic networks.** Timing, mass position and data integrity information for the entire network is summarized in a convenient window.



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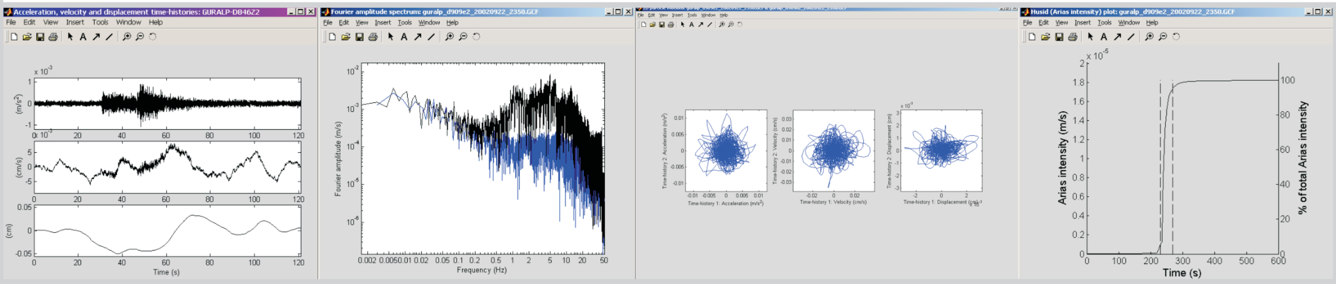
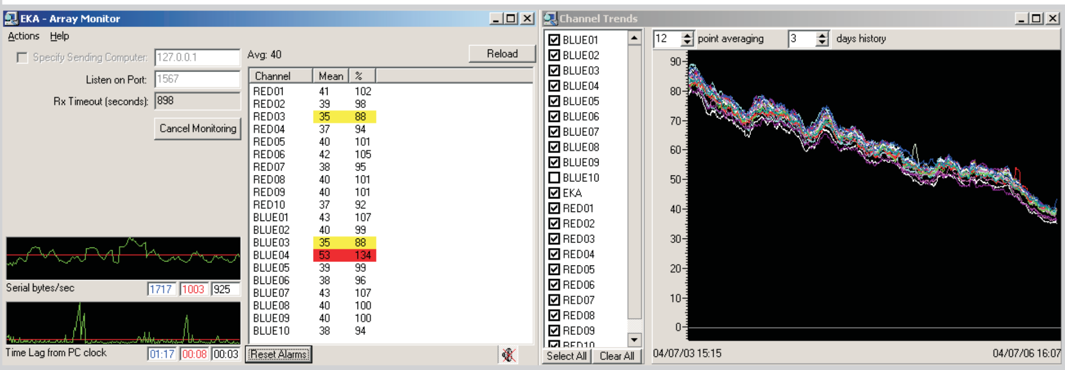
Monitoring and analysis software

Standard **extensions to Scream!** allow operators to generate instant PSD plots, and interpret calibration experiments.

Güralp Systems' strong-motion analysis tool, **ART**, extends Scream! still further. ART offers a wide range of commonly-used analysis techniques, including uncorrected and corrected response spectra, particle motion analysis, spectral intensity and Arias intensity plots.



Completing the suite of analysis and monitoring software, **ArrayMon** focuses on the **seismic network** as a whole. Developed for use at existing arrays operated by Güralp Systems, ArrayMon provides operators with constantly updated information on **state of health, instrument outputs and channel trends.** It can also alert operators to potential problems by SMS.



Güralp Systems' data formats are well supported by third party software. Import filters are provided in the standard distributions of **Earthworm** and **Antelope**; tools are freely available for importing data into **SeisLog** databases; and Scream! fully supports the file formats used by **ARTeMIS, PITSA, sac, PC-SUDS** and other packages.

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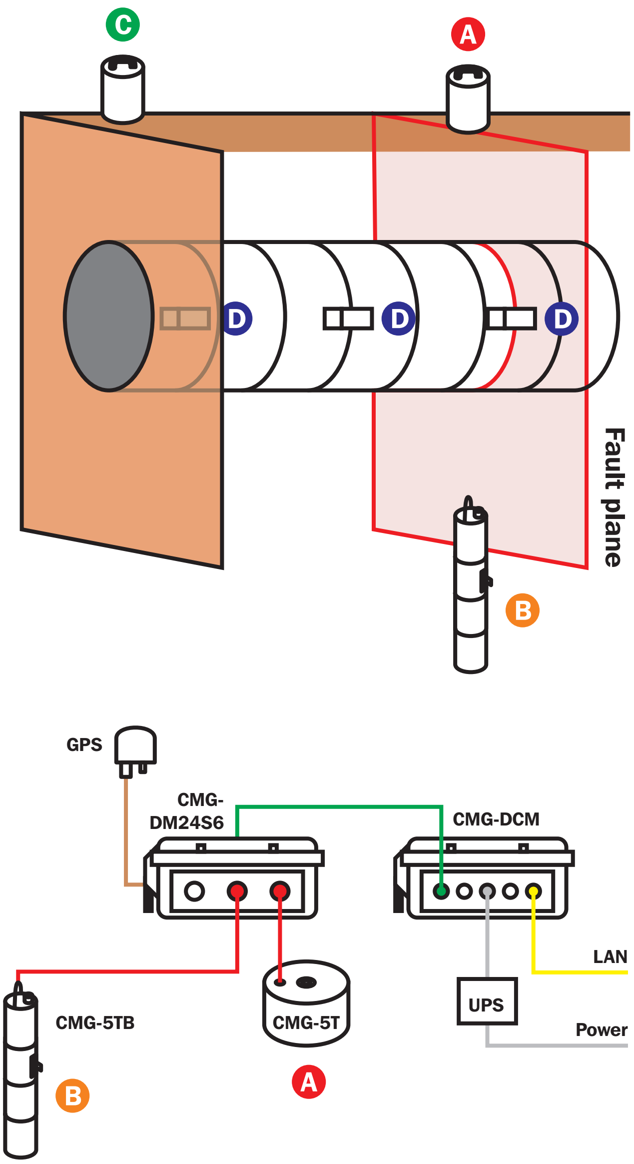
Networked installations: pipelines

The network design shown on page 3 can be entirely realized using Güralp Systems hardware.



At A and B, on the fault plane, a combined installation includes a CMG-5TB borehole accelerometer at depth, and a CMG-5T instrument in an enclosure on the surface.

Both instruments output signals to a CMG-DM24 digitizer, which produces data in GCF format.

If local storage is required, a low-power CMG-DCM data module can be connected to the digitizer. This unit can

- input GCF data over a serial connection;
- store it on an internal hard disk, or an external USB device, in several formats;
- interface directly to a local network using its full Linux operating system; and
- run data servers for connection to one or several data collection facilities situated either along the pipeline (*e.g.* at pumping stations) or elsewhere on the network or Internet.

Alternatively, a Güralp Serial Server can transmit GCF data over the local network to a PC running Scream!. Both the DCM and Serial Server support concurrent serial and network communication, allowing engineers to monitor signals and configure instruments on the spot.

Installations C can be designed in a similar way, using a DM24 or a self-contained digital weak motion instrument such as the CMG-3TD.

The installations D along the pipeline may be combined into sets of 6-12 to be digitized by an additional DM24 at a convenient surface station. The DCM can accept input from 2 connected digitizers simultaneously.

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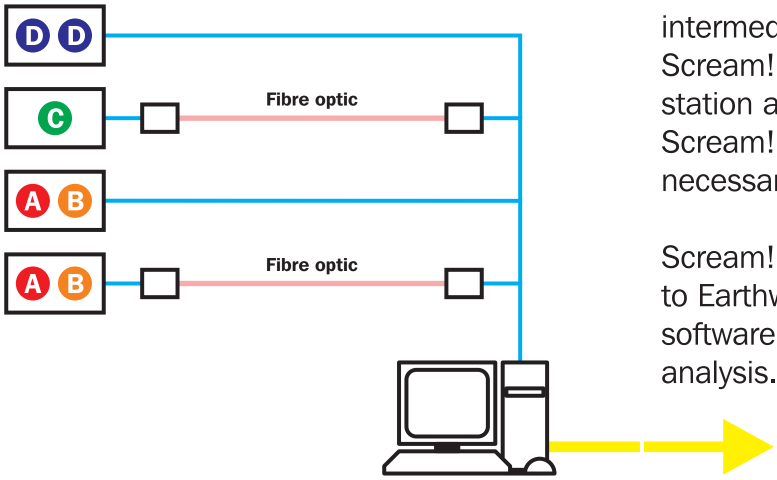
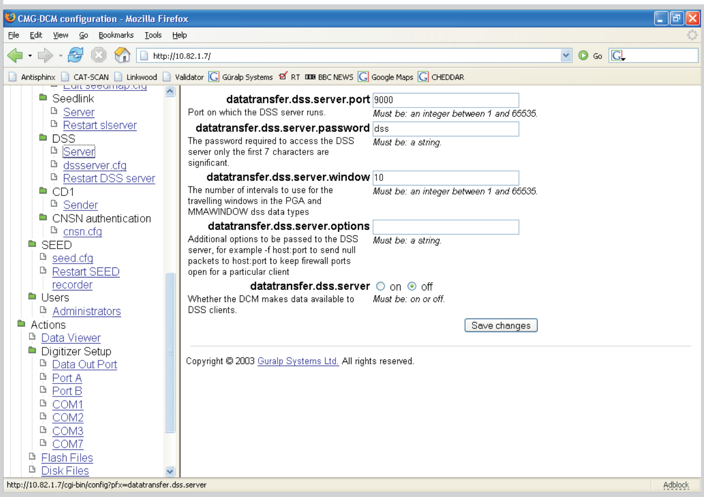
Networked installations: pipelines

Using PPP, fully supported by the CMG-DCM, installations connected by modem or optical fibre links can be attached seamlessly to the local network.



At the central control centre, or at an intermediate location, a PC running Scream! software collects data from every station and records it, or relays it to Scream! clients on the network as necessary.

Scream! can also transfer real-time data to Earthworm and other third-party software packages for event location and analysis.

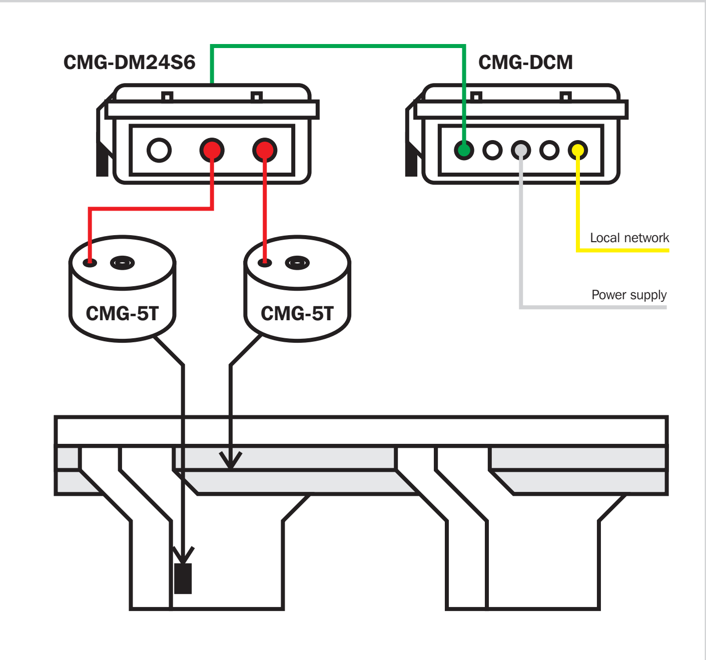


Güralp Systems' DCM data modules also support DSS (Data Subscription Service), a low-latency protocol providing instant access to quantities such as peak and RMS average acceleration levels, spectral intensity, and total horizontal acceleration.

These quantities can be reported for every station along the route, allowing you to build comprehensive safety monitoring systems.

When the statistics indicate that an event has occurred, or there is a problem with the structure, DSS allows station operators to request the raw seismic data and determine the best course of action.

Case study: Monitoring railway viaducts



This new project, comprising 80 Güralp strong-motion accelerometers, gathers real-time data from structures along a newly-built high-speed railway line, and transmits it to operators using a combination of Scream! and DSS protocols.

With this information, the operators of the railway can

- monitor the safety of structures along the line;
- assess how the structure responds to seismic events and to vibration arising from normal activity on the line; and
- contribute to the knowledge of seismicity in the region.

40 stations have been installed at regular intervals over 250 km of the railway line. Each station contains two CMG-5T triaxial accelerometers, connected to the network using DM24 digitizers and DCM data modules.

For example, seismic stations along a viaduct on the route have one CMG-5T unit installed in a recess in a supporting column, and a second within the hollow concrete superstructure. Each instrument is secured to the structure with a single fixing bol.

The instruments are connected to a single 6-channel DM24 mk3 digitizer in a nearby building, which is linked to the local TCP/IP network with a DCM. The DCM runs a Scream! server so that real-time data can be viewed from anywhere on the network.

Only one of the two digitizer input ports on each DCM is used, giving the array scope for future expansion as necessary.

Case study: Monitoring railway viaducts

Güralp Systems' DCM data modules include a module which can communicate with installations using DSS.

DSS (Data Subscription Service) is a packet format, widely used in strong-motion projects, which enables data and statistics to be requested from a seismic installation.

A DSS server is designed to handle many concurrent requests from clients with varying levels of privilege, and may prioritize requests according to their origin and urgency.

The DCM can act as either a DSS server or a client. A simple, stand-alone DSS server is also available which receives requests on a network port and replies to them.

In this network, each DCM runs a DSS server providing data on

- peak acceleration levels
- RMS (root mean square) average acceleration levels
- spectral intensity
- magnitude of horizontal acceleration (combined N/S and E/W components)

These statistics are relayed to a data centre once every second, where they may be used to trigger automatic warning systems.

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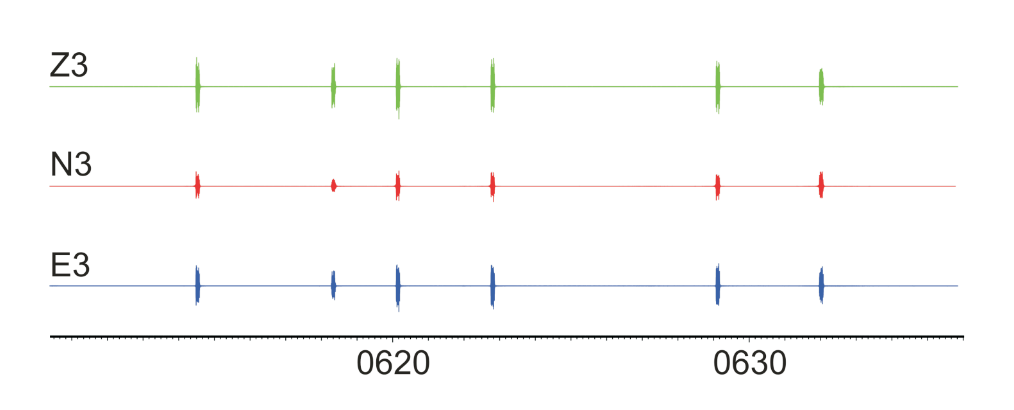
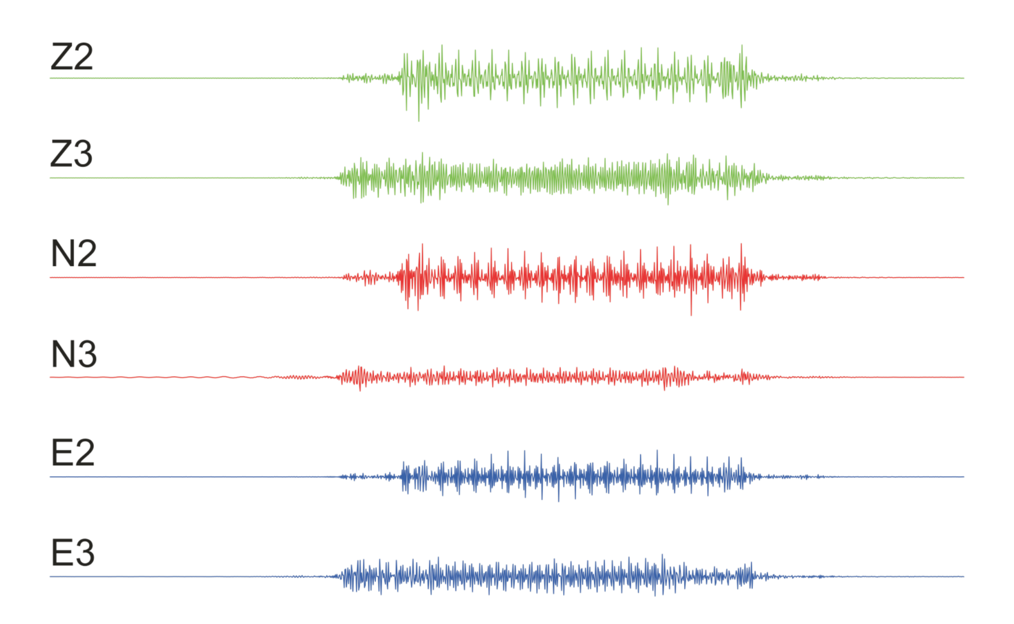
Case study: Monitoring railway viaducts



Preliminary results from the station show it working well, recording vibrations on the line resulting from passing trains.



A detailed view of the traces, below, clearly shows how the structure experiences greatest vertical accelerations when the front and rear of the train pass over the viaduct.

In between, the sensor in the superstructure (Z2,N2,E2) shows regular peaks in acceleration. There are 21 peaks in all. This is consistent with the passage of a 20-carriage train, where the sets of wheels at the end of each carriage are giving rise to the peaks.

The sensor in the column beneath (Z3, N3, E3) shows this detail to a much lesser extent, implying that the concrete has flexed and evened out the accelerations in the structure.

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References

L. Hutchings, P. Kasameyer, L. Long, T. V. McEvilly, R. Clymer, R. Uhrhammer, L. Baise, *"Deep borehole instrumentation along San Francisco Bay bridges",* Lawrence Livermore National Laboratory, 2001.

J.Huang, A. F. Shakal, *"Structure instrumentation in the California Strong Motion Instrumentation Program"*. In M. Erdik, M. Çelebi, V. Mihailov, N. Apaydın., eds. "Strong motion instrumentation for civil engineering structures", NATO ARW on Instrumentation for Civil Engineering Structures (1999, Istanbul), Kluwer Academic, Dordrecht / London, 2001., 17.

M. Çelebi, C. B. Crouse, *"Recommendations for Soil-Structure Interaction (SSI) Instrumentation",* COSMOS (Consortium of Organizations for Strong-Motion Observation Systems) Workshop on Structural Instrumentation, Emeryville, CA., 2001.

P. de Alba, *"Site selection and instrumentation of geotechnical arrays: gaps in our knowledge",* COSMOS International Workshop for Site Selection, Installation, and Operation of Geotechnical Strong-Motion Arrays: Workshop 2, Guidelines for Installation, Operation, and Data Archiving and Dissemination, 2006.

A. F. Shakal, P. Hipley, V. Graizer, *"CSMIP instrumented geotechnical arrays",* COSMOS International Workshop for Site Selection, Installation, and Operation of Geotechnical Strong-Motion Arrays: Workshop 1, Inventory of Current and Planned Arrays, 2004.

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