2007-2009 USGS Cooperative Agreement
Final Technical Report

Project Title: "Operation and Maintenance of the UCLA Factor Array"
Principal Investigator: Monica Kohler

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1. UCLA Factor Building Seismic Array

The UCLA Factor building is a 17-story, steel, moment-frame structure with an embedded 72-channel accelerometer array. The array serves as a prototype for real-time state-of-health monitoring and full-scale, soil-structure interaction experiments. The Factor building seismic array provides the opportunity to examine the vibrational behavior of a typical mid-level moment-frame building that is common in urban settings. The purpose of the array is to produce waveform data that can be used in analysis and predictive modeling of structures for damage assessment and building code modification. The users of these data are civil engineers and seismologists.

The Factor Array has been operated and maintained primarily by UCLA since late 2002 when it was initially incorporated into the Center for Embedded Networked Sensing as a dense array application. Since the beginning of support by the USGS in 2005, the long-term plan was to turn it into an ANSS structural array to feature spatially dense, high-quality data for engineering research purposes. During the first half of this grant period, Kohler and Project Engineer Stubailo performed tasks related to upgrading and troubleshooting the system, managing quality control, data archiving, real-time waveform display, and web site content development. The focus of the tasks covered in this grant period was to operate and maintain the array, and to document hardware upgrades that took place in early 2006. In addition, Kohler continued to guide the work of an undergraduate-level programmer in the development of an array-dedicated website (factor.gps.caltech.edu) that has a large volume of graphical and text content. Throughout the year we worked with IRIS DMC personnel to ensure that waveform data and metadata were archived on-site and made available for immediate distribution.

The second half of the grant period was a transition year for the Factor Array. Array operations and maintenance were converted from joint UCLA-USGS to USGS alone. Part of this final report describes how the transition took place, and how activities associated with hardware and software maintenance were distributed among USGS, UCLA, and external engineers.

Discussions among Monica Kohler, Mehmet Celebi, Roger Borcherdt, and Doug Given regarding the logistics of array operations and maintenance transition took place September-December, 2007. Most of what followed in the transition stemmed directly from those conversations. The transition year saw Kohler and Stubailo working with USGS engineers to turn it into an entirely USGS-run array as smoothly as possible. The transitional activities were designed to take advantage of USGS technical staff expertise in hardware and software. The resulting system can hopefully be a model for long-term operations and maintenance of other ANSS structural arrays.

Hardware

The building array (Fig. 1) comprises 72 channels (four horizontal channels per floor except for the basement and subbasement which have two vertical and two horizontal channels each) recording waveforms. The horizontal sensors are oriented north-south and east-west along the mid-sections of most floors. GPS receivers for timing are located on the roof. The power sources for the data loggers and sensors (Kinemetrics Episensors) are located in the machine room in the attic. Six channels from nearby downhole and surface borehole seismometers, and four free-field stations contributed data for ground and soil-structure interactions (Fig. 2). A dedicated fiber optic internet connection was installed within the Factor building to enable continuous data streams from Factor into other laboratories.

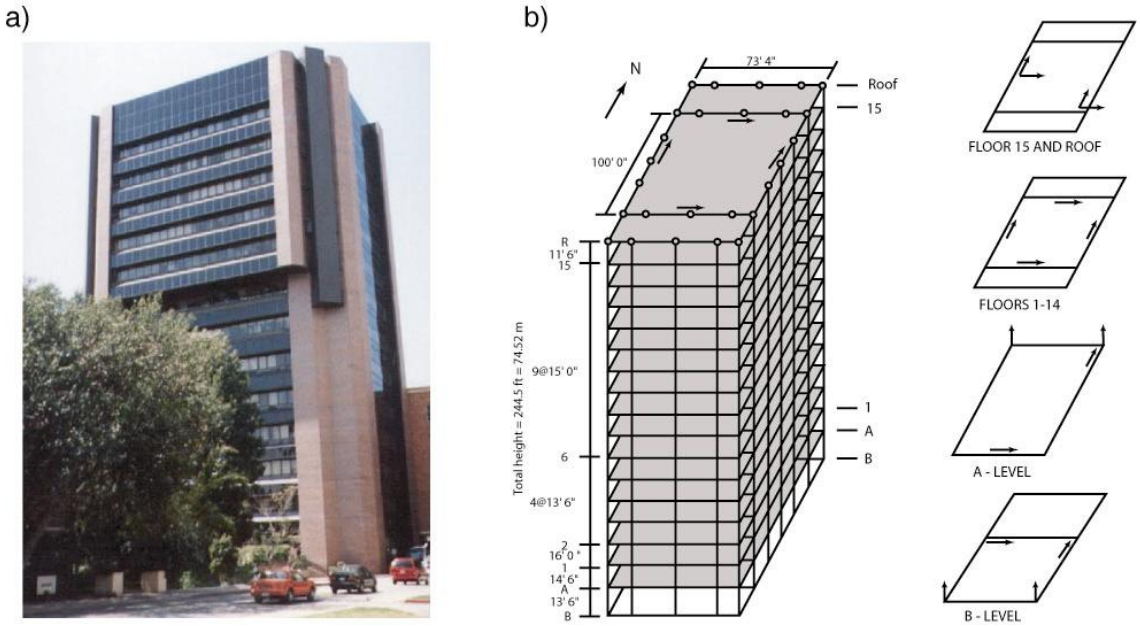

Figure 1. (a) Photo of Factor building taken from the northeast side of the building and (b) diagram of Factor building sensor locations. Arrows show polarities of sensors on each floor.

Figure 2. Campus master map showing the Factor building (pink circle), nearby borehole seismometers (green square), and free-field sites (red stars). The dimensions of the map are approximately 1 km by 1 km.

During and after the 2007-2009 award period, NSMP staff continued to maintain the sensor hardware. NSMP staff in Pasadena and Menlo Park received training to operate the Quanterra 4120 data loggers and took over full operation and maintenance of this hardware. During 2008, NSMP staff worked with Stubailo to become familiar with the Factor setup and operation. This required

that they become familiar with the data logger configuration files which were necessary for booting and changing operation parameters. After this grant period, the data loggers were replaced with two 36-channel Kinemetrics Dolomites, also recording continuous data at 100 sps and triggered data at 500 sps.

Towards the end of the grant period, one free-field site in the UCLA Botanical Gardens ("Tiverton") was removed altogether and the other ("Greenhouse") was retained but still needs new hardware for wireless telemetry at the time of this report. The telemetry plan for the Greenhouse site was to convert it to broadband radios as is typically done within CISN. The building basement free-field sites (Geology and Life Sciences) were not touched, but are not currently contributing data to the network. The borehole site was also not touched, except to perform maintenance on the Q4120 datalogger. There remains an issue with access to the site from external locations due to increased internet security on campus. After early 2008, these data were being streamed to the USGS.

All stations are part of the ANSS structural monitoring program. Station location and hardware information can still be obtained from factor.gps.caltech.edu/Instrumentation, and from the dataless miniSEED files. The sensors were and continue to be maintained by NSMP technicians Arnie Acosta with assistance from Jim Smith. The data loggers, data management and archival system, web site, real-time waveform display, metadata maintenance, and event-based data file distribution were initially operated by Kohler and Stubailo. The web site is still monitored and infrequently modified by Kohler.

Software/Data Server

Discussions in late 2007 among Kohler, Celebi, Borcherdt, and Given focused on implementing a new data server system that would take advantage of CISN/Earthworm software officially adopted by the USGS to manage data from other networks, including the SCSN. ISTI software engineer Paul Friberg converted the Factor data server to Earthworm, and assisted Pasadena NSMP staff on how to use the modified version and its associated Winston Wave Server tools. Transition tasks included converting from Antelope to an Earthworm mode of data acquisition. Friberg was hired to customize Earthworm so that it could operate with the Factor Array. Earthworm 1) acquires data from the data loggers, 2) forwards waveform data to third parties such as USGS and the IRIS DMC, 3) provides NSMP or Caltech with the ability to automatically grab data from the waveserver tool once a significant event has occurred, convert it from miniSEED to V0, and send it to the National Center for Engineering Strong Motion Data (NCESMD), and 4) provides tools to monitor and ensure the state of health of the system. Earthworm can be further modified to send alert emails for peak accelerations exceeding a predetermined threshold value. Kohler and Stubailo worked with the USGS to install a USGS-purchased, array-dedicated server in the Factor attic space for running Earthworm and for data management.

The advantage of converting the data management software to Earthworm was that it could be easily modified to automatically grab data from the wave server when there is a significant event, convert the miniSEED to the engineers' preferred ASCII-based format V0, and send it directly to the NCESMD. With Earthworm in place, the array's state of health and performance can now be monitored using the USGS-supported SWARM software tool. The Earthworm system set up at Factor could potentially serve as the model for data servers at other ANSS building arrays. To meet the ANSS performance standards, structural arrays would be treated as mini Tier 2 regional networks with a six-month buffer of building data maintained by the system in the building to protect against short-term disruptions.

The Winston Wave Server running on the UCLA computer was set up to allow four connections. One was for the IRIS DMC and the other three were made open for external users to view the data. Viewing the waveforms can be configured by installing SWARM software on a user's computer and adding a Winston Wave Server with the dedicated IP and port numbers. Once users have the Factor array listed in their list of wave servers, they can then get a list of channels, and view the waveforms for any specific channel by clicking on that channel. The Winston wave server was also set up for data extraction by accessing Earthworm and using the *waveman2disk* module to extract snippets in various formats such as SAC.

Data Products and Archival

The primary product produced by the Factor Array is the continuous and event-based waveform data for structural engineering research purposes. During the grant period, we continued archiving the continuous 100 sps waveform data at the IRIS DMC. The new Earthworm software now also provides for automatic push of the continuous 100 sps waveform data to the IRIS DMC. The Earthworm modifications also now provide for the automatic creation of 500 sps event-based files for archival at the NCESMD. Note that unless a large local earthquake occurs, this new procedure for creating triggered files will not produce more than one or two datasets per year depending on how the "significant earthquake" parameters are defined.

We continued to add content to a dedicated web site (factor.gps.caltech.edu) already well-stocked with information related to the waveform data that includes the detailed metadata information, detailed site conditions, a manual on obtaining the data from the IRIS DMC, a list of known problems and system modifications, and a growing archive of photos related to the building and the seismic hardware. Once Antelope was removed, the real-time viewer was also removed. In addition to routine operation and maintenance tasks, we updated the station characteristics so that the dataless SEED volumes were accurate. Ongoing maintenance of the web site included updating all information related to transition-related changes in hardware, data server software, and triggered data availability at the NCESMD.

The secondary array products, also available via the web site, are processed data products useful for research and educational purposes. Kohler worked with an undergraduate assistant to continue creating 5-minute SAC-format files of all earthquakes that were recorded with good signal-to-noise ratios on the 100 sps data streams. These files were saved on the dedicated Factor Array web site factor.gps.caltech.edu/data_sets/5_minute_files where they continue to be available for immediate download by any interested party. There are data from approximately 40 events/year since 2004 on that link. An associated table of source parameters for convenient reference by anyone wishing to access the 5-minute data files is also available. Since 2003 the array has recorded several dozen local and regional earthquakes per year with good signal-to-noise ratios. We kept our event-based file cutting process in place during 2007, to ensure high data quality of the triggered waveforms through comparison of the two procedures.

The most significant local earthquakes that occurred during this grant period included: 1) Ocotillo Wells, CA, February 9, 2007, M_L=4.2, distance=233 km, 2) Coso Junction, CA, March 30, 2007, M_L =4.0, distance=226 km, 3) Ocotillo, CA, April 15, 2007, M_L =4.3, distance=269 km, 4) Devore, CA, May 24, 2007, M_L =3.9, distance=98 km, 5) Indio, CA, June 2, 2007, M_L =4.2, distance=207 km, 5) Chatsworth, CA, August 9, 2007, M_L =4.6, distance=31 km, 6) Lake Elsinore, CA, September 2, 2007, M_L =4.7, distance=97 km, 7) Wrightwood, CA, October 16, 2007, M_L =4.2, distance=82 km, and 8) Chino Hills, CA, July 29, 2008, M_L =5.4, distance=64 km. Fig. 3 shows accel-

eration time series data recorded by most channels in the Factor building in response to the August 9, 2007 Chatsworth earthquake.

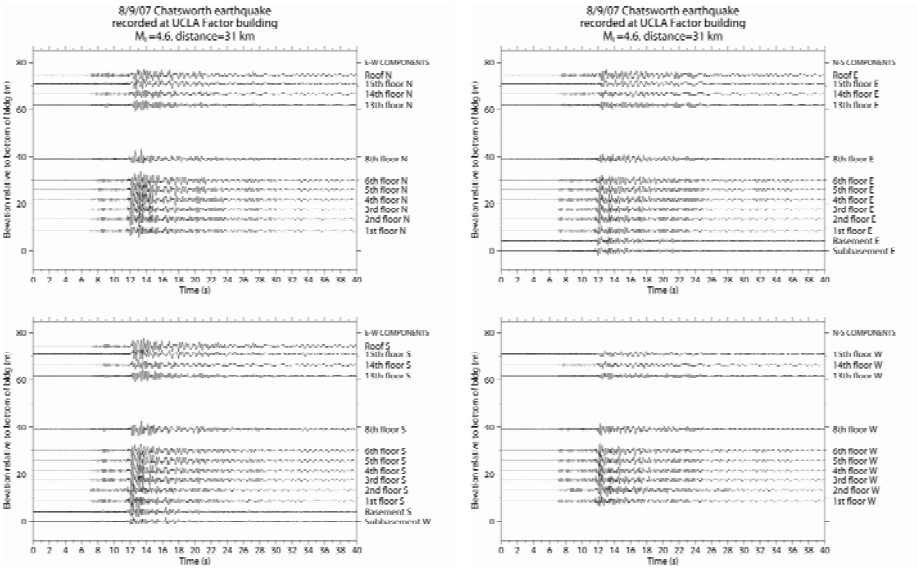

Figure 3. Acceleration time series recorded by the Factor building array in response to the Chatsworth, CA, earthquake that occured on August 9, 2007, M_L = 4.6, at a distance of 31 km from the array. Gaps are due to non-functioning sensors.

We also continued to produce displacement animations of significant earthquakes (Fig. 4) recorded by the array for a variety of frequency ranges. We completed this aspect of Factor Array products for all significant 2007 earthquakes and for one large 2008 earthquake as we regularly receive requests to show the animations as unique illustrations of what dense structural arrays can record. The animations were created in AVI format and are also available for immediate download from factor.gps.caltech.edu/animations. They are viewable by any standard animation/movie-viewing software (e.g., QuickTime). The animations show displacements in four views: head-on view of N-S wall, head-on view of E-W wall, oblique view of entire building profile, and plan view.

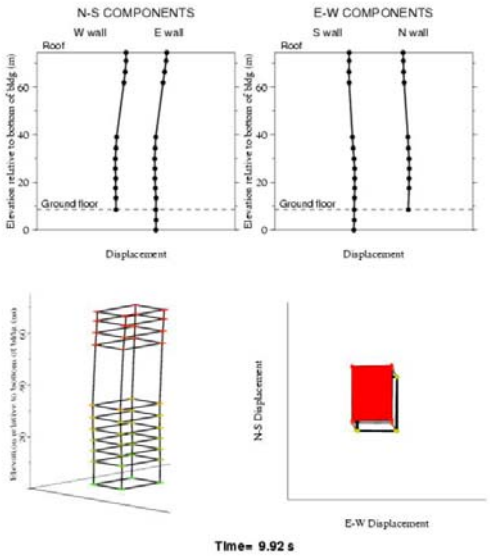

Figure 4. Actual 2D displacement of the Factor building during the August 19, 2008 Chino Hills, CA earthquake (0.45-5.0 Hz). This frame is from a 32-second animation. Filled circles show locations of sensors contributing data to the displacement measurements.

Animation files show displacements of the building floors relative to the base using the recorded data. See Figure 4 for a sample single-frame displacement frame that was part of the August

19, 2008 Chino Hills, CA earthquake's animation. The displacements were bandpass filtered for frequencies between 0.45 Hz and 5.0 Hz (limits vary depending on earthquake size). The density of the stations makes it possible to view the dominant frequencies of building response, and how the dominant frequencies vary depending on the size and distance of the earthquake. These animations are unique tools for both academic research and educational purposes. Furthermore, the animations provide additional information about the state of health of the sensors because their measurements can be compared with nearest neighbor measurements. These animations are unique tools for both academic research and educational purposes.