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A Proposal to Upgrade the Northern California Seismic Network

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Table of Contents

List of Tables

List of Figures

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Executive Summary

Substantial progress has been made over the past two decades in reducing the hazard from earthquakes in northern California using data recorded by seismic networks. Notably, seismologists and geologists can now identify seismogenic faults that are likely to rupture in damaging earthquakes. Using wave propagation theory and knowledge of local geologic conditions, seismologists can predict the level of shaking from these future quakes. Urban planners and engineers use these predictions to guide land-use decisions and revise seismic design specifications in building codes. Automated systems continuously analyze telemetered seismometer signals and issue alerts when significant earthquake activity is detected. Rapid earthquake locations provide disaster officials with authoritative information on magnitude and extent of rupture, thus aiding in their direction of emergency response. In addition, volcanic unrest at five regions in northern California can be detected by seismic networks well in advance of eruptions. These efforts, as well as many others, all result from a long-term research effort to understand these hazards and from an investment in continued seismic monitoring.

Because of hardware limitations when seismic networks were first installed, both strong- and weak-motion networks were deployed to record earthquakes. Strong ground motion networks consisting of accelerometers reliably record the full waveforms of large earthquakes, but the infrequent recordings must be manually retrieved from the on-site recorder. Weak-motion networks use analog telemetry to continuously transmit data from seismometers to a central processing site. This enables seismologists to rapidly report the size and location of earthquakes above magnitude (*M*) 1.0, but the waveforms are "clipped" for earthquakes above *M* 3 for most stations in the networks due to the method of telemetry and the type of instruments installed in the field. This limits the utility of the telemetered data for many applications.

If the functions of these two networks were merged together, both fundamental earthquake research efforts and public safety would benefit. For example, most earthquake damage is the result of seismic waves that travel from the fault and shake the earth. The first energy to arrive is in the form of *P*-waves, which travel at typical velocities of 5-6 km/s, but the more damaging, larger amplitude *S*-waves travel at almost half the speed of the *P*-waves. Because seismic data can be continuously telemetered to a central network site at the speed of light (300,000 km/s), it is possible for seismic networks to provide advance warning of the imminent arrival of strong ground motion at distances beyond where the first seismometers detect the quake. Computer programs that continuously analyze the telemetered data could identify when a large earthquake is occurring and issue a brief radio broadcast of the magnitude and location of the earthquake. Depending on the location of the recipient of the warning and type of facility to be affected, users could take action such as warning people in poorly designed structures, protecting electrical equipment, stopping trains and automotive traffic, and opening fire stations garage doors. To provide this service, however, requires continuous telemetry to a central site of on-scale waveforms of large earthquakes.

On-scale, telemetered data offers a second benefit to public safety. Within minutes after a large earthquake, emergency services coordinators could have access to maps that show where the earthquake has occurred, the observed shaking intensity as recorded by seismic instrumentation, and predicted damage patterns based on the location of the event and the local geology. This information can be used to efficiently deploy fire fighting, rescue, and medical services before calls for help can be made through an overloaded phone service. Preliminary information on the location and magnitude of the mainshock can be available within seconds of occurrence, refined estimates within 10 minutes, and the extent of the aftershock zone imaged within 30-60 minutes. Telemetered strong-motion data will make it possible for emergency officials to quickly see exactly where strong ground motion occurred, and also assess the reliability of the ground shaking predicted by the automated procedures.

Because of advances in communications technology, it is now feasible to transmit data from the existing stations of the Northern California Seismic Network (NCSN) to Menlo Park using digital instead of analog telemetry. Engineers in Menlo Park have developed inexpensive, solar-powered, digital telemetry hardware that can utilize the existing system of radio and microwave telemetry. Installation of this hardware at existing analog sites of the network provides a non-disruptive, evolutionary upgrade path for all the seismic instrumentation in the NCSN. These systems are now capable of transmitting three components of 16-bit data at speeds of 9600 kbaud, and tests are underway for transmitting four components of 24-bit data via 14.4 kbaud communication hardware. With three accelerometers and one vertical seismometer at each field site, it is possible to obtain on-scale recording of ground motion from earthquakes ranging from M 1 to M 8.

Though a continuously telemetered seismic network can provide strong ground motion observations in real-time to Menlo Park, there are too few sites in the network to provide an adequate spatial representation of strong ground motion that reliably could guide disaster response. Given the wide range of site conditions within the San Francisco Bay region, an increase in the number of seismic stations in this region is clearly warranted. However, many soft-rock sites and sites in urban environments are not optimal for routine monitoring using continuous telemetry. Thus, a more cost-effective means of recording and telemetering infrequent ground motion data is proposed. A prototype system, called "TREMOR", has been developed that uses inexpensive ($50) accelerometers that produce accurate information for all potentially damaging earthquakes. Upon triggering, estimates of the ground shaking from several hundred TREMOR sites could be simultaneously transmitted via spread-spectrum radio telemetry to the USGS, California Office of Emergency Services, and CalTrans for incorporation into maps of observed ground motion.

Seismic networks are a cornerstone of the USGS earthquake program, but USGS networks that were installed 20 years ago do not adequately meet the needs of the program today. The network upgrade described in this proposal provides a conservative plan that meets these needs while utilizing the investment in existing telemetry infrastructure. The upgrade requires a substantial investment of funds, about $4 million, over a 5-year period, but we believe that this modernized network will prove its worth immediately. Better data will greatly improve our efforts to understand the earthquake process and will have immediate impact on public safety for the millions of people who live along the San Andreas fault system in northern California.

Introduction

Helping people live safely with earthquakes is the goal of the National Earthquake Hazards Reduction program. A key element of this program is the operation of seismic networks which are used to measure the shaking during earthquakes and provide data for earthquake research. The data recorded on these seismic networks is currently used in formulating seismic design criteria in building codes and understanding where and when damaging earthquakes may occur. For the past 25 years seismologists have operated two different networks to fulfill these missions because of limitations of recording technology. On-scale recordings of strong ground motion, which are of great interest to the engineering community, are typically obtained from non-telemetered event recorders. These instruments only record ground acceleration during the infrequent large earthquakes and therefore provide no information on the more frequently occurring, but smaller quakes. Weak-motion seismic networks fulfill the need for real-time recording of earthquakes of all magnitudes by relying on continuous analog telemetry to transmit a seismometer output to a central recording site. However, analog telemetry invariably produces a clipped record for any earthquake exceeding magnitude (M) 2 at distances less than 25 km and $M > 3.5$ at distances less than 100 km.

While there were compelling reasons to use this technology two decades ago, the requirements on seismic networks are rapidly changing. In northern California the primary mission of the weak-motion seismic network has been to report on felt earthquakes, monitor volcanic seismicity, and record data for research topics such as earthquake prediction, earth structure, stresses that cause earthquakes, and geothermal phenomena. However, new mandates to the seismological community emphasize urban hazard mitigation and rapid damage assessment following large earthquakes. In northern California a situation exists where neither weak- or strong-ground motion networks are able to fulfill satisfactorily the expanded mission. This proposal provides a plan for upgrading the 1969-era hardware of the USGS Northern California Seismic Network (NCSN) (Figure 1) with equipment that will enable us to address the new mandates. We begin by briefly reviewing the rationale for operating regional seismic networks. We discuss how society can benefit immediately from network operations as well as from the long term research efforts based on data recorded by the networks. We then identify the technology that we believe best meets the complex requirements and provide a preliminary budget and time frame for implementing this plan.

The Role of Seismic Networks in Public Safety

In 1969 seismologists had a relatively limited understanding of the earthquake problem in comparison to what we know today. Fundamental topics like the statistical behavior of earthquakes was rudimentary; the catalog of seismicity was incomplete, inaçcurate, and limited in both space and time. The role of stress interaction between earthquakes was undeveloped. The role of local geologic conditions on amplification of strong ground motion was hampered by a lack of seismological recordings. Few examples of the pre-eruptive behavior of volcanoes were available to guide hazard notices. Realistic modeling of strong-ground motion data in terms of variable slip models and wave propagation were impossible because of limited computer resources. The role of fault creep in strain accumulation was poorly understood. We have learned much about the earthquake process as a result of this long-term investment in basic research, and as a result we are now able to apply this knowledge toward reducing the hazards from earthquakes. In the following discussion we identify the contributions to public safety that can be provided by seismic networks and the instrumentation required to make these contributions.

Warning of impending shaking.

Most earthquake damage is the result of seismic waves that travel from the fault and shake the earth. The first energy to arrive is in the form of *P*-waves, which travel at typical velocities of 5-6 km/s, but the more damaging, larger amplitude *S*-waves travel at almost half the speed of the *P*-waves. Because seismic data can be continuously telemetered to a central network site at the speed of light (300,000 km/s), it is possible for seismic networks to provide advance warning of the imminent arrival of strong ground motion at distances beyond where the first seismometers detect the quake. Computer programs that continuously analyze the telemetered data could identify when a large earthquake is occurring and issue a brief radio broadcast of the magnitude and location of the earthquake (Heaton, 1985; Holden *et al.*, 1989; National Research Council, 1991). Depending on the location of the recipient of the warning and type of facility to be affected, end-users could take appropriate action. For example, early warning broadcasts could warn people in poorly designed structures, protect equipment such as electrical power substations, stop trains and automotive traffic. Communications equipment could momentarily be halted to prevent damage during the earthquake and ensure that power and communication system are intact for subsequent rescue operations. Fire station garage doors could automatically be opened so that fire fighting vehicles would not be trapped if the building were to shift.

The length of the advance warning increases with the distance between the quake and the recipient of the warning, but the shaking generally attenuates with increasing epicentral distance. However, there are often critical damage zones well away from the fault. For instance, the 1989 Loma Prieta earthquake created significant damage and mortality in the San Francisco Marina district and at the Cypress freeway structure in Oakland. These areas were 90-100 km from the earthquake and could have been given only 8 seconds warning in advance of the *P* wave arrival, but as much as 19 seconds warning in advance of the arrival of the damaging *S*-wave.

Consider the occurrence of a large earthquake occurring at a depth of 9 km on the Rodgers Creek fault near the city of Santa Rosa. For reliability, the network would only issue an alert after strong ground motion has been recorded by 5 seismic stations, about 8 seconds after the origin time. Clearly, citizens of Santa Rosa would be subject to shaking by the *S*-wave before the *P*-wave was recorded by the 5th station, but the city of Richmond in the east San Francisco bay region would have as much as 12 seconds of advance warning before the arrival of the *S*-wave and San Francisco 15 seconds. Conversely, an earthquake nucleating near San Leandro at a depth of 7 km on the Hayward would allow only 2 seconds of warning before the *S*-wave arrived at San Francisco, but as much as 22 seconds for Santa Rosa.

Even more elaborate warning systems are possible. Consider, for example, the operators in a control room of a public utility or railroad. Upon receiving the above "early warning", they must make rapid decisions about the continued operation of power plants or rail systems. Seismic networks could transmit via dedicated communication channels to these clients the 1-second average of ground motion amplitude at each station of the seismic network for local generation of a shaking map. This map would provide visual confirmation of an alert message, since the operator would observe the wavefront propagate across the network at speeds of 5-8 km/s. For example, it would take more than 60 seconds for the energy to propagate from a large quake in the San Francisco bay region to the Oregon border, and nearly 90 seconds for energy for a Parkfield event to reach the border. Prototypes of this system are operational in Menlo Park, but implementation of this service awaits an upgrade of the network hardware.

Early warning of strong ground motion and the above wavefront expansion display require 1) a network of sensors (accelerometers) sited along active faults that records the ground motion with high fidelity, 2) telemetry that transmits with minimal delay the full dynamic range of these signals back to a central network site, 3) real-time software at the central site that reports on significant earthquakes during rupture, and 4) a dedicated broadcast system to distribute this information to the public. Later in this proposal we discuss these requirements in more detail. However, the siting of the network deserves special comment at this time. Although the risk from earthquakes is greatest to urban areas, earthquakes that occur in sparsely populated regions can also pose a hazard to urbanized areas. The M 7.0 Loma Prieta quake, which occurred beneath the Santa Cruz mountains, illustrated this point quite effectively to the residents of San Francisco and Oakland. Moreover, during the last decade some of the most significant earthquakes to yield information about the earthquake process have occurred in rural areas (*e.g.*, Coalinga, Landers, Imperial Valley, Petrolia). Recordings of strong ground motion from these earthquakes has been translated into improved building codes for urban areas. Because we learn most quickly from well recorded earthquake sequences, it is good scientific and public policy to operate seismic networks where earthquakes are likely to occur. A network restricted only to urban areas will observe strong ground motion too late to be applicable, whereas the lessons we learn from earthquakes in sparsely populated regions can be directly applied to urban areas.

Maps of shaking

After an earthquake the ability to rapidly deploy rescue equipment can save not only lives but also property. Accurate rapid deployment is currently hindered because it is difficult for a centralized command center to compile damage reports from a wide region. This occurs because citizens frequently cannot report damage and fires due to overloaded telephone systems; consequently, the initial damage reports are often distributed via radio and television broadcasts. This information may misrepresent the full scale of the crisis, because local site conditions influence the amplitude of earthquake ground motion, the population distribution governs the location where ground motion is reported, and communications can be disrupted in the epicentral region. A notable example occurred for the 1989 Loma Prieta earthquake. Aerial television coverage of the World Series being played at Candlestick Park south of San Francisco immediately diverted from the stadium to the sites of earthquake damage in San Francisco and Oakland. However, the earthquake occurred 100 km to the southeast in the Santa Cruz mountains and the heavily damaged cities of Watsonville and Santa Cruz close to the epicenter received comparatively little media attention for several days.

Within minutes after a large earthquake, emergency services coordinators could have access to automatically generated maps that show observed shaking intensity and predicted damage patterns. This information can be used to efficiently deploy fire fighting, rescue, and medical services. Regional seismic networks provide the basic parameters needed to predict the ground motion throughout the affected region - hypocentral coordinates, earthquake magnitude, mechanism, and rupture zone extent (from aftershock locations). In northern California the combined contributions of the existing USGS network of analog, high-gain vertical-component seismometers and the University of California at Berkeley (UCB) network of digital, broadband instruments are well suited for calculating these parameters. Preliminary information on location and magnitude will soon be available within seconds of occurrence, refined estimates of magnitude and mechanism within 10 minutes, and the extent of the aftershock zone imaged by aftershock locations within 30-60 minutes.

Observations from strong-motion instrumentation can be integrated into the above maps of predicted ground shaking. Various estimates of ground motion, such as peak ground acceleration, velocity, shaking duration, energy content, or spectral values (Rojahn *et al.*, 1994), can be calculated in real-time. By combining this observed data with the predicted ground motions, it will be possible to immediately see where strong ground motion occurred, and to assess the reliability of the forecast model of ground shaking. As we discuss below, the current instrumentation of the networks operated by the NCSN, USGS Strong Motion Program (NSMP), California Division of Mines and Geology (CDMG), and the UCB only begins to address this need. There are more than 80 free-field sites in the San Francisco Bay region (Figure 2) that have strong-ground motion sensors, but 60 of them have no telemetry. To provide a significant set of observations for rapid response requires that these data be telemetered in real-time to a central network site and that more stations be installed.

Post-earthquake advisories

Immediately after a significant earthquake, the public wants to know from the seismological community if more earthquakes should be anticipated. The rate of aftershock decay enables seismologists to calculate the probability of the expected rate of damaging aftershocks and the probability for even larger events (Reasenberg and Jones, 1989, 1994). Initially, each earthquake sequence is assumed to behave like the "average" earthquake sequence in California, and "generic" probabilities are immediately reported for earthquakes above M 5 during, typically, the next week. With time the network locates a sufficient number of aftershocks such that the decay rate can be estimated for this particular sequence, and more accurate aftershock probabilities are then reported to the public. This information can be used to guide rescue response and the repair of infrastructure immediately following an earthquake. Entry into damaged structures at risk of total failure may be postponed until the probability of aftershocks declines to an acceptable level. The NCSN has reported earthquake locations and magnitudes within minutes of occurrence since 1981, and probability reports have been issued to the public since 1989.

In addition, the same parameters that seismologists utilize in forecasting shaking intensity (location, magnitude, mechanism, and rupture zone extent) are utilized in calculating the change in stress on faults of the region surrounding the mainshock (*e.g.*, Stein *et al.*, 1994). Where the stress has increased on faults that have been identified as having a significant probability for a M 7 quake (Working Group on California Earthquake Probabilities, 1990) advisories could be issued about an increased hazard on specific faults. Conversely, where the model indicates that stress is relieved, seismologists could advise that the risk, though still present, has not increased. These calculations are now routinely computed within hours following an earthquake.

Improving estimates of future shaking

Long after the shaking has stopped, seismologists analyze the recordings of the mainshock to improve their ability to predict ground motion for future earthquakes. They attempt to match the observed motion recorded by seismic networks using computer methods that model seismic wave propagation through the earth, complexities in the earthquake rupture process, and the effects of local geology. This is a key aspect of improving earthquake safety because these models guide revisions to the seismic design in building codes. Observations of strong ground motion ultimately form the basis for engineering decisions that reduce loss of life and property in future quakes. Acquiring this seismic information requires a network of seismometers along active faults, particularly in urban areas where there is a need to know the level of ground motion responsible for causing a structure to fail. This aspect of earthquake research has traditionally been based on recordings obtained from non-telemetered, strong ground-motion, event recorders that reliably recorded the infrequent main shock. Since this effort is not conducted in real-time, there has been no requirement for continuous telemetry. However, a telemetered network of strong ground motion data is desirable for issuing early warnings and rapidly producing maps of shaking.

Volcano monitoring

Seismic networks provide one of the first indications of volcanic unrest because earthquakes frequently accompany magmatic movement. In northern California there are five active volcanic regions that threaten public safety - Long Valley Caldera, The Geysers-Clear Lake, Mt. Shasta, Mt. Lassen, and Medicine Lakes (Figure 1). While an eruption clearly constitutes a local emergency, attendant ash eruptions pose a threat to a wide region including many urban areas. Consequently, the NCSN monitors these volcanoes quite carefully for unusual earthquake activity like changes in rates, swarms, and harmonic tremor. It is worth noting that the particular behavior of each volcano is observed only through continuous, long-term monitoring. As we have learned at Mammoth Lakes, unusual earthquake activity may indicate subsurface magmatic movement, but it does not necessarily indicate imminent eruption.

The Role of Seismic Networks in Earthquake Hazard Reduction

Seismologists are now applying their knowledge of the earthquake process, based on the decades of data recorded by seismic networks, toward reducing the hazard from earthquakes. However, significant earthquakes have recurrence times much longer than decades, ranging from 100's to 1000's of years. This stands in contrast to the history of seismic networks in California, which were first installed during the early 20th century. Before 1970 only earthquakes with $M > 3$ were located, and before 1960 the locations were determined by graphical methods. This incomplete catalog of earthquakes greatly limits our understanding of the seismic hazard in California.

Consider, for example, the 1906 M 7.8 San Francisco earthquake sequence. It is represented in the catalog by only 26 events, including the mainshock. Only 4 events have estimates of magnitude and all the aftershock locations are presumably based on isoseismal methods. In contrast, the NCSN located 10,243 aftershocks from the 1989 M 7 Loma Prieta earthquake. Our understanding of the 1906 rupture properties, such as rupture length, depth, and the slip distribution, is quite

Table 1. Seismic Networks in Northern California

Net	# of Sites	Objective	Sensors	Telemetry	3-Comp?	Typical Site
NCSN	370	Locate all N. CA eqs above ambient background noise	L4	Real-time analog for entire net	~30 sites	Remote, free-field, "hard-rock"
CSMIP	~70	CA program to provide seismic data for building codes	FBA23	16 sites w/ digital auto dial-up	Yes	Structures and free-field
BDSN	12	On-scale recording of all M>3.5 in N. CA, Moment tensor soltns Global studies	STS1 STS2 FBA23	Packetized digital for entire net	Yes	Remote, free-field, "hard-rock"
NSMP	~23	US program to provide seismic data for building codes	FBA23	None Analog + Digital	Yes	Structures and free-field

The reason for these separate networks is that each performs a unique, though limited, function. The telemetry and sensors that the NCSN operates enable it to locate small earthquakes quite accurately, but it does not have sufficient dynamic range to record the complete range of shaking that occurs in large events. Consequently, most signals recorded by the NCSN for large earthquakes are "clipped", which makes it difficult to use the data for reliable early estimation of magnitude or for reporting post-earthquake shaking levels. The broadband sensors and digital telemetry of the BDSN enable it to record the full range of earthquake motion, but the network has few sites. Consequently, the BDSN can routinely locate only earthquakes with $M > 3$, and it cannot effectively provide early warning or an adequate representation of the distribution of shaking. The CSMIP program has only 16 sites that report in near-real time via telephone, eliminating the possibility of reporting early warnings and closely sampled observations of post-earthquake shaking levels. Moreover, experience shows there is the possibility that land-line or cellular telephone service may be unavailable immediately after a large earthquake. Finally the NSMP program has no telemetry capability.

Recent improvements to the NCSN real-time software enable the network to compute an initial location within 10 seconds of the origin time for quakes occurring in the middle of the network. However, the NCSN cannot estimate a reliable magnitude from the first few seconds of the waveform because of the fidelity problems described above. Recognizing this limitation, the NCSN and BDSN computers have linked their network software together via the Internet so that the NCSN computes the initial location and magnitude from its dense short-period network, and the BDSN then computes a moment tensor solution from the broadband waveforms 8-10 minutes later. Even so, this combined network is still incapable of providing credible magnitudes for early warning or useful maps of shaking.

In summary, seismologists can rapidly tell where an earthquake of $M > 1.5$ occurred anywhere in northern California (NCSN) and how large it was (BDSN), but they can not rapidly map the shaking that occurred in detail. Instruments are deployed which can record the full range of earthquake shaking (CSMIP and NSMP) at selected sites, but the data from these instruments are not rapidly relayed to a central recording site. This disjoint mix of network capabilities, mandated by the technology of the 1970's, should be consolidated Addressing these deficiencies in seismic network infrastructure, despite the difficult financial times, is critical if rapid progress is to be made in reducing the hazard from earthquakes.

A Pragmatic Approach for Upgrading the Network

Four factors govern the type of seismic network proposed below. First and foremost, we wish to record earthquake data that fulfills the objectives for early warning, rapid response, and seismological research. These objectives dictate the appropriate type of sensors, telemetry, and network facilities. Second, we want to reliably and consistently record data. We will have failed to design a useful network if it fails to operate during a large quake. Third, we have attempted to find the most cost-effective solution that meets the above goals. Finally, we do not want to interrupt the monitoring of earthquakes as a result of the network upgrade and thus require that we can simultaneously record signals transmitted by the existing analog hardware as well as the new hardware.

It is possible to operate one network that will fulfill most of the above objectives, but such a network will not be cost-effective. Consequently, in the following sections we propose operating three different seismic networks to record the full range of local earthquake data: 1) a network of stations that continuously telemeter data into a central facility, 2) a network of non-telemetered event recorders that trigger only during mainshocks, and 3) a network of inexpensive sensors that report parametric information by spread spectrum radio telemetry shortly after detection of strong ground motion. Each type of network records a specific type of seismic information not readily obtainable by the others. We believe that operation of all three networks best addresses the network objectives described above, meets the need for reliability, and is the most cost-effective plan.

Continuous telemetry to a central analysis site

Sensors

Several tasks require that the network have the ability to routinely locate and record earthquakes as small as M 1 in some regions. The locations of small magnitude aftershocks rapidly map out the extent of a mainshock rupture, which is needed by the emergency response community for responding to a crisis. Small earthquakes are sensitive barometers of volcanic unrest and provide a baseline for future activity. Third, the number of quakes increases by a factor of 10 for each unit of magnitude decrease, so that small earthquakes provide an accelerated picture of the seismotectonics of a region. This information enables seismologists to map out the seismogenic region of future earthquakes.

We also require that the network be able to record on-scale waveforms of M 8+ earthquakes that could occur within northern California. Although we would like to obtain three-component waveforms for every earthquake, large or small, we recognize there is a significant cost in terms of telemetry bandwidth, money, and human effort to record and process all of this data. Generally, we analyze the waveforms of the smaller (M <3.5) quakes to obtain only the traveltimes and amplitude measurements for calculating the earthquake location and magnitude. Because there are no sensors that span the complete range of possible ground motions (10^{-7} - 2 g) (Figure 3), we propose at each site a four-component installation - a vertical component velocity transducer for recording small quakes and a three component accelerometer package to record large quakes. Assuming existing sites in the network only require the addition of a 3-component FBA package, the added sensor costs are approximately $4000/site.

Field digitizer

We require digitization at the sensor because the 40 db dynamic range of analog telemetry is not sufficient to preserve the full range of ground motion recorded by seismometers or accelerometers. To address this requirement, the engineering staff in Menlo Park has developed a low-power field unit that can digitize and telemeter 16-bit data at 9600 baud using one-way radio communication (Gray Jensen, pers. commun.). These units, hereafter referred to as "digital seismic telemetry" (DST) units, currently allow us to transmit 3-components of information at 100 sps from anywhere in the network over existing radio, telephone, or microwave communications. Thus, we can upgrade our existing analog network to digital simply by installing these units at our existing NCSN sites at a cost of approximately $1500/site.

The 16-bit DST units are a first-generation design and have two factors that limit their utility. Because they only have the bandwidth to transmit 3 components of information at 100 sps, they do not meet our requirements for a vertical component seismometer and 3-component accelerometer at each site. Even where we increase the transmission speed to greater than 9600 baud, the 16-bit digital telemetry may not be sufficient to ensure an overlapping range for a dual-sensor network of L4C seismometers and FBA23 accelerometers (Eaton, 1995). Therefore, we are testing a second generation model that utilizes a 24-bit A/D with a 14.4 kbaud modem, which will make it possible to transmit 4 components of information spanning the full dynamic range of each sensor. Tests are expected to be completed by the end of summer, but preliminary results indicate that this level of throughput is achievable. Costs for the 24-bit DST units are not anticipated to be much greater than the 16-bit DST units.

Unlike two-way modes of communication which ensure against loss of data by requesting the field unit to re-transmit when data are not successfully received, the DST units operate only in one-way (broadcast) mode. This mode will result in lost data if not successfully received at the central site, but has compensating advantages which are discussed below in the section on telemetry. Four sites in the San Francisco Bay region are currently transmitting first-generation DSTS data by direct radio communications to Menlo Park and a fifth site is transmitting from Bakersfield using the microwave system. A DST network is also operating at Kilauea, Hawaii, with broadband instruments for recording harmonic tremor.

Telemetry

We require "real-time" data transmission to a centralized site so that the network can provide early warning of earthquake shaking. The term "real-time" is often casually used, in that some systems have built in delays of 8-10 seconds, and other systems transmit packets of digital data in time-stamped, 1-second blocks. For an early-warning system it is desirable that the maximum transmission delay be less than 1 second. In addition, the network, including field sites, telemetry, and central facilities, must operate successfully during the largest anticipated earthquake. As yet, no regional network has been subjected to the duration and amplitude of shaking imposed by a *M* 8 earthquake. However, we have had limited experience during two strong earthquakes, the 1989 Loma Prieta and 1993 Northridge earthquakes. In both instances, portions of the network utilizing telephone telemetry were disrupted, whereas radio and microwave telemetry systems continued to function.

In southern California the upgrade effort is shifting the operation of telemetry to telephone companies, which have more experience and expertise in this area. The Southern California Seismic Network (SCSN) is beginning to utilize a new, high-speed communications network provided by Pacific Telephone for real-time data transmission. We recognize the merit in this approach, but opt for an alternate means of telemetry for the following reasons. First and foremost, the PacTel network does not provide digital service where most of our existing field instruments are sited. Even were we to utilize this high-speed network, we would still need to provide some form of digital communications from our remote field sites to the PacTel network because many of our sites have no telephone access or AC power. Since the PacTel network is not yet widely available outside urban areas, this is a partial solution, at best, for the NCSN. Second, the telemetry is being provided without cost to the SCSN through the PacTel Calren Project through 6/96, but the future costs are unknown. A decade ago when the telephone monopoly was deregulated, the NCSN migrated from telephone to radio telemetry because the cost of telephone telemetry quickly became prohibitive. If the cost of high-speed commercial telemetry becomes too expensive as it did in the past, we fear that future operation of the seismic network could be jeopardized. Third, connection to the high-speed telephone network requires additional communications hardware at each site that significantly increases the upgrade cost. Finally, there is a possibility that the telephone company may not reliably deliver digital information in real-time during a major earthquake. As mentioned above, telephone communications have failed during the Loma Prieta and Northridge earthquakes. Moreover, the telephone companies have throttled back network access immediately after large earthquakes to avoid network overload, though it is not clear if this will be a factor in the high-speed network.

The USGS National Seismic Network (USNSN) utilizes satellite telemetry to transmit their digital data from the field to Golden, CO. This approach is probably the most reliable means of transmission, in that there are no telemetry links that are likely to fail during an earthquake. However, the data rates used by the USNSN are too slow to make this approach suitable for a early-warning system. The USNSN transmits continuous data from all of its stations at 1 sps. When an earthquake triggers the field unit, it subsequently transmits 20 sps data. If higher bandwidths were continuously available at acceptable costs, satellite communications would clearly be a desirable means of telemetry, with the caveat that the satellite is a single point of failure that could conceivably shut down the network.

We believe that continued use of analog microwave telemetry is the appropriate technology for upgrading the NCSN. The NCSN has generally had very good results transmitting analog data via microwave telemetry. We operate our own microwave systems and also have access to spare capacity on the US Army Corps of Engineers and Federal Aviation Administration microwave systems (Figure 1). We have in-house staff that maintains both the USGS and USACOE systems. More important, we have demonstrated that we can successfully transmit digital data over the analog microwave systems both in broadcast mode using the 16-bit DST units and also in two-way communication mode. The BDSN successfully uses the latter telemetry mode over our microwave system to continuously transmit digital data at 20 sps from 5 sites at 9600 baud and 80sps data for triggered events. In particular, microwave telemetry has the following advantages:

- The NCSN microwave system has line-of-site visibility to a large portion of the network. This enables us to broadcast the DST data to the microwave system via radio communication. This provides us with ability to operate a statewide digital network from remote locations instead of from sites requiring AC power and telephone access.
- The microwave system is cost effective after the initial investment. We can predict our maintenance expenses in future years and be confident that we will have the resources to continue operation.
- A microwave system provides guaranteed rates of data throughput because there is no competition for bandwidth with other users. We can therefore transmit the digital data sample-by-sample, which is preferable for an early-warning system because it eliminates network delays and the inherent delay introduced by packetization.
- All microwave sites are supplied by uninterruptable power systems and are designed to withstand substantial wind loads. The performance of these towers in the epicentral region of the Loma Prieta earthquake suggests that the system should remain operational during and following significant earthquakes.
- The NCSN and SCSN could each receive subsets of each other's networks over the microwave, providing a backup if either the Menlo Park or Pasadena offices became inoperable due to a major quake.
- We can simultaneously transmit analog and digital information via the microwave network, so no interruption of monitoring capability is anticipated as a result of the upgrade.

A critical issue facing all regional seismic networks utilizing radio telemetry is the FCC (IRAC) requirement that we relinquish our existing radio frequencies for auction to the private sector. Consequently, we must purchase replacement radio pairs for all sites in the network at a cost of $1200/pair in the next 2 years. Replacement of the radios at the nearly 390 sites in the NCSN (including UNR and Livermore, and DWR) will result in a one-time hardware cost of about $470,000 plus the associated travel and field expenses. **We emphasize that all radios must be replaced regardless of any upgrade plans for the NCSN. Otherwise, we will be forced to revert to commercial telephone telemetry where available and cease operation of at least 60% of the stations in the network, including virtually all of the network in the Coast Ranges north of San Francisco.**

In order to convert the network telemetry to digital, we will have to expand the capacity of the microwave system. Beyond the San Francisco Bay area the capacity of the system is sufficient to convert the network to digital. However, all of these signals ultimately converge into Menlo Park, and the system capacity in the region from Sonoma Mt. in the north to Fremont Peak in the south (Figure 1) must be expanded to support 600 channels. The initial upgrade will be installed in the San Francisco Bay region because of ease of access, relevance to urban hazard reduction, and the high likelihood for *M* 7 earthquakes (Working Group on California Earthquake Probabilities, 1990). Following conversion of the Bay Area stations to digital telemetry, we will expand the effort to Parkfield, Cape Mendocino, Mammoth Lakes, and more remote sites in the network. This one-time investment in microwave hardware will cost approximately $350K, not including installation costs.

Non-telemetered event recording

In the event of a catastrophic telemetry failure (*i.e.*, Menlo Park is disabled or microwave towers collapse), we would still be able to record the earthquake if some of the stations in the network were operated with non-telemetered, digital, event recorders. The SCSN upgrade addresses this issue by installing digital data loggers at every site of their telemetered network, so that the data could ultimately be recovered in the event of telemetry failure. Given available funds, we would like to have the same capability, but the cost of event recorders at every sites in the NCSN could approach an additional $5 million. We hope that the proposed DST/microwave system will be sufficiently robust to make it unnecessary to install event recorders at each NCSN site, but it is good policy to install these recorders at critical sites.

There are other reasons to install non-telemetered event digital recorders. Not all sites that are desirable from the point of recording strong ground motion are desirable for continuous monitoring. For example, sites located in urban areas, like the Marina district of San Francisco, will yield strong ground motion information that are likely to be important for studying local site response during large earthquakes. However, these sites are generally far too noisy to be useful for continuous monitoring, require costly telephone telemetry, and are difficult to protect from vandals when sited as a free-field instrument. We propose that digital event recorders be deployed in urban locales where it is imperative that strong ground motion be reliably recorded. A complementary and cooperative program with CSMIP should be undertaken to ensure that adequate strong ground motion recording is obtained throughout urban areas of northern California.

In contrast to the need to record ground motion in urban areas, it is difficult to justify the costs of operating a *dense*, telemetered network in regions where the rate of seismicity and the population density is low. However, large earthquakes, like the 1992 *M*7.3 Landers or *M*5.8 Klamath Falls quakes, may occur in these regions, and seismologists may want to operate a temporary network of instruments to record aftershocks. Several types of instruments could be deployed in these situations. If radio telemetry is available, then temporary, telemetered DST sites can be installed, as has been done by the SCSN with their analog "coffin" hardware. Alternatively, digital event recorders could be deployed. Although PASSCAL now has almost 400 field instruments, they may be committed to ongoing experiments and not be available for rapid deployment in the hours following a significant earthquake in northern California. The Seismology branch maintains 15-20 GEOS event recorders, which were designed in the late 1970's, available for immediate deployment to record aftershocks. These instruments have a 16-bit dynamic range and limited data storage capacity compared to recorders that are now commercially available. As happens with all electronic devices, it is now becoming impossible to obtain replacement components for the GEOS recorders. While, this proposal addresses only the telemetered portion of the network, we recognize the need for this type of instrumentation and advocate that the NCSN have the capability to record aftershocks with portable event recorders.

Occasional telemetry to multiple recipients

The third component of the proposed network upgrade will provide rapid estimates of ground shaking, but only after the significant ground motion has been detected. Though the continuously telemetered seismic network provides strong ground motion estimates in real-time to Menlo Park, there are too few sites in the network to provide an adequate spatial representation of strong ground motion that reliably could guide disaster response. The existing NCSN station spacing ranges from about 15 km in the Central Coast ranges to 35 km in northern California, but station spacing on the order of 6 km or less is desirable to reliably depict variations in ground motion (D. Boore and W. Joyner, personal commun., 1995). Given the wide range of site conditions within the San Francisco Bay region, an increase in the number of seismic stations in this region is clearly warranted. However, as we note above, many soft-rock sites and sites in urban environments are not optimal for routine monitoring using continuous telemetry. In addition, it would be very expensive to increase the number of telemetered stations to achieve 6 km spacing. Thus, a more cost-effective means of recording and telemetering infrequent ground motion data is desired.

A prototype system called "TREMOR" has been developed to provide a detailed map of the strength and characteristics of ground motions in an urban area (Figure 4) (Spudich and Evans, written commun.). The TREMOR system records ground acceleration time histories using inexpensive ($50) accelerometers developed for a broad range of commercial applications. Tests of these sensors demonstrate their adequacy for strong-motion applications in engineering and emergency response (Evans and Rogers, 1995). The accelerometers have flat response spectra from <0.5 to >20 Hz, a dynamic range from below 3 mg to greater than 3 g, and a noise level which is 1 to 2 orders of magnitude below the level of ground motion expected for a magnitude 5 earthquake at 100 km on soil A (hard rock) (Boore et al., 1993) (Figure 5). In other words, these sensors would produce accurate information for all potentially damaging earthquakes.

Recently developed spread-spectrum radio technology makes it possible to send, without an FCC license, information from these accelerometers, such as response-spectrum values, peak acceleration, or even the time series, over distances up to tens of miles using inexpensive transmitters powered by solar-charged batteries. The reliability and cost of these systems are quite variable and still under test. However, two systems have been identified with immediate utility: $100 transmit-only units applicable to very short-range mass telemetry, and $1200 intelligent network nodes applicable as a telemetry backbone for the TREMOR system.

The former ($100 units) are quite reliable to 200 m at ground level and reasonably reliable to 1 km. Beyond that distance, elevating the receiver may be of assistance. These transmitters, originally developed for reading water meters, would be used to instrument freeway interchanges and major public structures, relaying damage information to a nearby "cell site" equipped with one of the network nodes. The low-cost transmitters would also be applicable to local ultra-dense accelerograph networks of inexpensive instruments used to study ground shaking variability over 100- to 1000-m scales.

The more expensive network-node radios (comparable in cost to a current NCSN radio) are in wide use by utilities, railroads, and oil companies. Several tens of thousands are installed and operating, with some links as long as 100 to 130 km. This technology is purported to have greater transmission range due to use of a different type of spectrum-spreading algorithm (frequency hopping). These radios are nearly identical to commercial cellular telephone technology in power, frequency, and operating algorithms. They provide a highly redundant, self healing, error correcting, solar powered telemetry network that can transmit data to several users from each of many data sources. Data from several hundred TREMOR sites could be simultaneously transmitted to USGS, OES, CalTrans, and the USGS microwave towers for redundant relay on that network. USGS transmission tests are planned for these radios by the end of FY95. The total cost of an installed station, including telemetry, sensors, installed tower, and signal processing hardware, is estimated at $4400. Redesign of the signal processing unit may bring down the cost by $1000; use of existing towers and high points would reduce costs an additional $1500.

The same technology used by the TREMOR system can be used to identify structures that are so badly damaged that lives may be at risk. This system, referred to as "SOS", measures the earthquake-induced permanent tilt of the structure or its components. Structural components having static tilts exceeding the UBC tilt limit of 0.26° indicate that the structure may be damaged and may present life safety hazards. Larger tilts would induce a higher-priority signal. The philosophy of these devices is like that of the smoke detector. As they will be fairly cheap, the structure owner can buy as many or as few as needed for the level of protection desired and for adequate monitoring of the particular type of structure. Users would install these detectors on vulnerable components of such obvious candidate structures as a) structures with soft first-stories, b) bridges and overpasses, c) high occupancy structures such as stadiums, auditoriums, shopping malls, and d) walls of tilt-up buildings. Upon installing these devices, the user would register the device with a local receiver facility, which would forward all information to regional response facilities via the TREMOR/SOS telemetry network. As an alternate to the early-warning system, SOS receivers could also be deployed at unmanned sites where computer-initiated action, such as closing of a bridge or illuminating a freeway warning sign, would be desired in the event of an earthquake.

It is premature to propose a large installation of these devices until we have demonstrated that the telemetry is feasible and that software is in place to utilize this information. Achieving uniform 6 km station spacing in the San Francisco Bay Area's urbanized region from Gilroy to Santa Rosa would require about 100 TREMOR sites. At 3 km spacing, about 450 sites are needed. The potential cost ranges from $250k to $2M, depending on site cost and station density. In the first year of this proposal we request funds to install 10 TREMOR network node sites and develop supporting software. We anticipate siting them in a "redundant linear array" from Menlo Park northwest along the Peninsula's densely populated region, and use the telemetry network for a parallel SOS demonstration funded by CalTrans. If the pilot system proves successful, we will seek additional funding from OES, public transportation agencies, and utilities for expansion of the system.

Data Acquisition, Analysis and Distribution

A seismic network is comprised of three fundamental components: hardware, software, and people. The NCSN has extensive experience in the development of network software for the acquisition, analysis, distribution, and archiving of seismic data. In this section of the proposal we review the current status of our real-time software, collaborative efforts to share this data with other seismological institutions in California and the U.S., and our plans for enhanced data distribution. We are confident that we have the software platforms and the programming talent to immediately begin utilization of the digital data stream to be generated by an upgraded NCSN.

Earthworm

Over the past 3 years the programming staff in Menlo Park has been developing software to provide rapid earthquake information about on-going earthquake sequences. The initial goals of this project, called Earthworm, were to replace the aging "real-time picker" (RTP) machines which provided automated earthquake locations, origin times, and magnitudes within 4 minutes of occurrence. The replacement software is now able to provide the same information as the RTP's, but with the additional feature that the information is available within seconds following the arrival of energy at the fourth station (Johnson *et al.*, 1994). As the earthquake energy propagates across the network, this arrival time information is dynamically integrated into the solution. Thus, the Earthworm system provides the ability to issue early, but preliminary, information and subsequently improve the reliability with time.

Because the Earthworm system was designed to be modular and platform-independent, its processing functions are installed on the most cost-effective and appropriate machine for the task. For instance, the A/D function operates on a computer running a DOS operating system, but the earthquake detection and association software operates on computers running either DOS, OS/2, or Unix operating systems. The system is currently able to integrate diverse data sets in real time, including 12-bit data digitized from the analog telemetered network and 24-bit data from the Southern Hayward digital network. Because of this modular design, the system can be easily expanded to integrate data from other diverse sources, such as the DST, SOS/TREMOR, CSMIP, BDSN, and USNSN networks.

This system is the software platform for future network development in Menlo Park. Thus, data from the proposed network upgrade will be processed in real-time with Earthworm software. Moreover, other regional seismic networks (Washington, Utah, Alaska, Memphis) have expressed interest in replacing their systems with Earthworm because they recognize the advantages of this architecture, wish to operate compatible software environments, want to link their networks in real-time via the Internet, and no longer have the resources to develop or support their own, unique seismic software system. We are pleased that other networks recognize the advantage of the Earthworm architecture, and we believe it is in the best interests of the NEHRP program for regional networks to utilize the same software. In order to provide ongoing support to other regional networks, we are requesting a new staff position for a professional programmer.

Principal tasks to be addressed by the Earthworm development team in the next two years are

- Improve system performance so that aging RTP machines can be replaced
- Integrate the 16-bit and 24-bit DST data into Earthworm system.
- Unify the NCSN and UC Berkeley networks by integrating BDSN and Northern Hayward Network data into the system via a dedicated T1 line to UC Berkeley.
- Develop software to issue interim earthquake reports via email and pagers.
- Develop graphical display software to depict interim locations and expansion of earthquake arrivals across network.
- Couple analysis software like the IRIS-supported DataScope to Earthworm so that review and data archival is possible for regional networks that do not use CUSP software.
- Provide software support for other regional networks operating Earthworm environments.

Cooperation with the University of California at Berkeley

The NCSN and Seismographic Stations of the University of California at Berkeley have operated separate, overlapping networks since the late 1960's. In 1991 the UCB network began a network upgrade, installing broadband and FBA sensors at each site with continuous digital telemetry to Berkeley. Their network now consists of 12 sites that provide very high quality data for earthquakes above *M* 3.5. Although the relatively sparse station spacing results in greater location uncertainties and magnitude detection thresholds than those from the NCSN, the data can be used for computing moment tensor solutions for earthquakes in northern California using full waveform or surface wave methods. In addition, the data from the Berkeley Digital Seismic Network (BDSN) can be used to study earth structure, attenuation, and earthquake source properties. Though the two networks previously could be considered somewhat redundant in northern California, they now operate complementary instrumentation. The NCSN operates a dense, short-period, high-gain network for accurately locating earthquakes as small as *M* 1, and the BDSN operates a sparse, broadband network for analysis of waveforms.

Recognizing that each network contributes unique information about the earthquake process, both networks now actively cooperate in monitoring earthquakes in northern California. The BDSN system in Berkeley maintains an active Internet link to NCSN computers in Menlo Park, providing the BDSN with real-time access to NCSN arrival time and amplitude information. The BDSN software uses this information, in conjunction with its own data, to decide whether the event magnitude is sufficiently large to be adequately recorded by the BDSN. If so, it then begins to automatically calculate a moment tensor solution. Meanwhile, the Earthworm system progressively generates improved locations with the addition of each travel time observation, so that a stable hypocenter is generally available within 20 seconds. An initial magnitude is also computed by the NCSN based on the observed coda decay of the seismogram. The preliminary earthquake location and magnitude is then broadcast to the user community if the event exceeds predetermined criteria. If sufficiently large, the BDSN will also broadcast similar earthquake information, but with an M_L magnitude computed from on-scale waveforms of the BDSN and NCSN networks. After the BDSN determines that recording of the full earthquake waveform has been completed, it computes the moment tensor solution. The BDSN then rebroadcasts the earthquake hypocenter solution based on NCSN and BDSN data with their moment magnitude to the same user community. The combined response by both networks generally is complete within 12 minutes. The unified information both networks distribute eliminates public confusion over minor differences in reported magnitude that were common in the past.

The BDSN obtains parametric information from NCSN computers by an Internet link, which is not sufficiently reliable for emergency response functions. Consequently, the BDSN and NCSN are establishing a dedicated, high-speed communications link (T1) to exchange not only traveltime and location information in real-time, but also waveform data. The exchange of waveform data between the two nets will truly integrate both operations, so that each network can see each others data. To provide even more redundancy, the BDSN, NCSN, and California OES will begin exchanging parametric information (locations, traveltimes, amplitudes, *etc.*) via the OES OASIS satellite system. This will ensure that if land-line communications fail, including both the Internet and the dedicated T1 line, both networks will be able to communicate with each other and supply OES with the information that it needs to respond to ongoing earthquake emergencies. This system will expand to include the SCSN, if successful.

Data distribution

Providing rapid access to earthquake information for the emergency response community and the general public is an essential function of the NCSN. Though we already provide earthquake origin time, location and magnitude information through facilities like email, "finger quake", World-Wide-Web (WWW) sites, and pagers, the proposed network upgrade coupled with the Earthworm environment enables us to rapidly provide additional information that is useful to the emergency response community. As discussed above, on-scale waveforms telemetered in real-time enable the network to provide early warning of the arrival of strong ground motion, maps of observed ground shaking, rapid predictions of ground motion based from the rapidly computed earthquake location, moment tensors, and the distribution of aftershocks.

Immediate delivery of early warning broadcasts requires that seismic networks have access to a dedicated radio broadcast system, since commercial paging companies may have messages already queued which could delay broadcast. We are engaged in discussions with the Lawrence Livermore National Laboratory (LLNL) to form a cooperative venture in which the Earthworm system transmits to LLNL the early warning based on analysis of telemetered NCSN and BDSN data, and LLNL issues a radio broadcast. LLNL has obtained a broadcast license and operates pager transmitters atop Mt. Diablo in the east San Francisco Bay region. A prototype effort will be directed toward demonstration of feasibility using historic waveforms, on-line testing at lower magnitude thresholds, and development of user interfaces for the pager receivers.

We are entering into a formal cooperative agreement with UC Berkeley for unified pager distribution of earthquake information to the public through the UCB Rapid Earthquake Data Integration (REDI) system. Emergency response personnel will be able to receive location and magnitude information about significant (M >3.5) earthquakes via alphanumeric pagers without charge, except for the monthly fee charged by the paging company. We will also issue pages of more frequent, smaller magnitude (M > 1.5) earthquakes for map display on dedicated computers connected to alphanumeric pagers. Users can either subscribe to the REDI system and obtain the proprietary CUBE/REDI mapping software or obtain a copy of the shareware SEISMIC display software. The map-display software illustrates the locations of earthquakes which occur each day, but more importantly, reveals the extent of earthquake rupture of significant quakes through the locations of the numerous aftershocks.

We plan to expand the information content of our WWW site (*http://quake.wr.usgs.gov*) by providing automated maps of the most recent earthquake using the locations produced by the Earthworm system. These maps will also show the predicted ground motion for $M \geq 4.5$ events (Perkins and Boatwright, 1995) with the observed ground motions observed at NCSN, BDSN, and TREMOR/SOS nets. Automated waveform plots of the latest event will show expanded views of the initial P wave and computed arrival time, and a second view of the entire wave form with the calculated coda duration. This will allow users to assess the validity of the automated solution. A similar plot will show a continuous 1-hour record of the waveforms recorded at a fixed set of stations distributed across the network. This plot, updated every 5 minutes, will visually illustrate the arrival of teleseisms, swarm activity, harmonic tremor, and the level of aftershock activity. A companion plot of the spectral content of these same stations is also planned.

Reliable user access to earthquake information on our WWW site following significant earthquakes presents a challenge. A user connection to our WWW site generally involves intermediary, though transparent, connections through many other machines on the Internet. Ultimately, a successful connection depends on the ability of each computer link to remain operational during the earthquake. While the NCSN and Menlo Park Rolm telephone network operate on uninterruptable power systems, it is unlikely that all intermediate Internet links will remain operational during a major quake. An inherent feature of the Internet is its ability to find alternative paths to establish a connection, but this redundancy is only available if the two computers at each end of the Internet have multiple, independent connections to the Internet. The Menlo Park campus has multiple connectivity to the Internet through a connection to Stanford University, Reston, Denver, Vancouver, and Sacramento. Thus we plan to maintain mirror WWW sites at locations outside of California to provide the public access should local nodes be unavailable.

For research on past earthquakes we will continue to provide on-line, public access to NCSN data via the Internet at the Northern California Earthquake Data Center (NCEDC). The NCEDC is located on the campus of the UCB and is jointly operated by the UCB and NCSN (Romanowicz *et al.*, 1994). The NCEDC archives the NCSN catalog of earthquakes since 1967, associated focal mechanisms and phase data, and all waveforms digitally recorded since 1984. The NCEDC also archives the catalog of earthquakes located by the UCB since 1910, phase data since 1984, all BDSN digital waveform data, and continuous GPS data recorded by the Bay Area Regional Deformation Network (BARD) since 1994. The NCSN and UCB are working to create a joint database that will integrate information about northern California earthquakes from both networks, as well as data pertaining to these earthquakes from other sources like NEIC and Harvard. The NCEDC is updated daily, and access to the data is offered either through a WWW-page or by individual accounts.

Projected 5-year Budget

We propose that this upgrade be implemented gradually over a 5-year period for several reasons. First, it is prudent to establish a limited, working system before proceeding with an upgrade of the entire network. The initial upgrade will be installed in the San Francisco Bay region because of ease of access, relevance to urban hazard reduction, and the higher likelihood for M 7 earthquakes (Working Group on California Earthquake Probabilities, 1990). The second reason for implementing a multi-year upgrade is the lead time for procuring hardware. The upgrade will require 7 microwave transmitter/receivers and hundreds of analog radio pairs, accelerometers, and custom building of Digital Seismic Telemetry units. Third, the costs of the hardware, shown below, are substantial, and full funding of the upgrade at one time is unrealistic.

The staff of the NCSN is considerably smaller than it was a decade ago. Consequently it is not possible to upgrade the network in a few years even if all funds were authorized. For example, simply visiting each site in the network will likely require almost 2 years given the current staffing levels. The procurement of hardware, installation of microwave communications on towers, and upgrading of power at each site (additional solar panels and batteries) are all tasks that are in addition to the current responsibilities of existing staff. We estimate that only 35 sites will be upgraded in the first year. In later years it is possible to pick up the pace if additional staff are applied to the effort.

The following costs are preliminary and are subject to significant revision. Similarly, the time-line is tentative and dependent on staffing levels. This budget serves to illustrate the scope of the project, but more detailed work plans will be submitted each year in accordance with the level of available funding. All costs are in addition to on-going network operational costs.

Year 1 - San Francisco Bay $1000

Complete tests of 24 bit digital telemetry @ 14.4 KB	10.0
Evaluate accelerometers	5.0
Purchase 200 radio pairs	240.0
Procure3 600-channel microwave systems	150.0
Procure 35 3-component accelerometer packages	140.0
Build 35 DST packages	52.5
Install new µwave hardware at Menlo Park, Vollmer Peak, and. Monument Pk.	10.0
Install upgrade at 35 sites in SF. Bay Area (batteries + solar panels)	14.0
Travel +Vehicle Costs	10.0
Procure 35 serial ports for interface of DST to Earthworm system	3.5
Procure computer hardware for data collection/picking/analysis	25.0
Complete tests off spread spectrum radios in S.F. Bay region for Tremor/SOS system	10.0
Procure hardware and install 10 Tremor/SOS systems in S.F. Bay area	45.0
Computer programmer and 2 field technicians (Term appt)	150.0
Total	**865.0**

Year 2 - San Francisco Bay/Santa Rosa

Purchase 200 radio pairs	240.0
Procure 2 600-channel microwave systems	100.0
Install microwave transmitters/receivers Loma Prieta, Sonoma Mt.	10.0
Procure 75 3-component accelerometer packages	187.5
Build 75 DST packages	112.5
Install upgrade at remain sites in SF. Bay Area and in Santa Rosa (batteries + solar panels)	30.0
Build and install 30 TREMOR systems in San Francisco Bay Area	132.0
Procure 75 serial ports for interface of DST to Earthworm system	7.5
Procure computer hardware for data collection/picking/analysis	25.0
Travel +Vehicle Costs	20.0
T1 communications to UCB	8.5
Computer programmer and 2 field technicians (Term appt)	150.0
Total	**1023.0**

Year 3 - Parkfield/Mammoth Lakes

Procure 2 600-channel microwave systems	100.0
Install microwave transmitters/receivers Fremont Pk, North Bay	10.0
Procure 75 3-component accelerometer packages	187.5
Build 75 DST packages	112.5

Install upgrade at Parkfield/Mammoth Lakes	30.0
Build and install 30 TREMOR systems in San Francisco Bay Area	132.0
Procure75 serial ports for interface of DST to Earthworm system	7.5
Procure computer hardware for data collection/picking/analysis	25.0
Travel +Vehicle Costs	30.0
T1 communications to UCB	8.5
Computer programmer and 2 field technicians (Term appt)	150.0
Total	**793.0**

Year 4 - Northern Coast Ranges/Cape Mendocino

Procure 75 3-component accelerometer packages	187.5
Build 75 DST packages	112.5
Install upgrade at sites in Northern Coast Ranges/Cape Mendocino	30.0
Build and install 30 TREMOR systems with SS radios	132.0
Procure 75 serial ports for interface of DST to Earthworm system	7.5
Procure computer hardware for data collection/picking/analysis	25.0
Travel +Vehicle Costs	30.0
T1 communications to UCB	8.5
Computer programmer and 2 field technicians (Term appt)	150.0
Total	**683.0**

Year 5 - Sierra Nevada/Modoc Plateau/Cascade Volcanos

Procure 75 3-component accelerometer packages	187.5
Build 75 DST packages	112.5
Install upgrade at sites in Sierra Nevada/Modoc Plateau/Cascade Volcanos	30.0
Build and install 30 TREMOR systems in San Francisco Bay Area	132.0
Procure 75 serial ports for interface of DST to Earthworm system	7.5
Procure computer hardware for data collection/picking/analysis	25.0
Travel +Vehicle Costs	30.0
T1 communications to UCB	8.5
Computer programmer and 2 field technicians (Term appt)	150.0
Total	**683.0**

GRAND TOTAL	**4047.0**

Summary

The Northern California Seismic Network is a cornerstone of the National Earthquake Hazard Reduction Program. Data from this network continues to provide the foundation for hazard assessment, emergency response, and earthquake research. However, without replacing much of its 1970-era recording and telemetry hardware, it will be able to fulfill only a narrow aspect of its mission. To be able to provide early warning, rapid urban hazard assessment, and on-scale data for earthquake research, it is necessary to begin recording three-component accelerometer data in addition to the existing high-gain vertical seismometers using digital telemetry. We have outlined an evolutionary approach to a network upgrade that permits us to simultaneously operate a hybrid network of analog and digital instruments. This approach builds on our extensive experience in radio and microwave telemetry and digital instrumentation design, and ensures that there is no interruption of monitoring capability during the 5-year upgrade period.

At the same time that we are upgrading the recording hardware of the network, we will continue our efforts to develop robust computer software that delivers reliable earthquake information as rapidly as possible. We now have in place the computing architecture and expertise for integrating diverse digital data sources in real-time and can easily expand the software capacity to accommodate more stations for generating shaking maps in the minutes following a large quake. Moreover, we have the computing infrastructure to provide redundant, hardened communications to reliably provide this information to the public and disaster response officials. Given the proper data, the seismological community can further reduce the risk of earthquake hazards for the millions of people who live along the San Andreas fault system in northern California.

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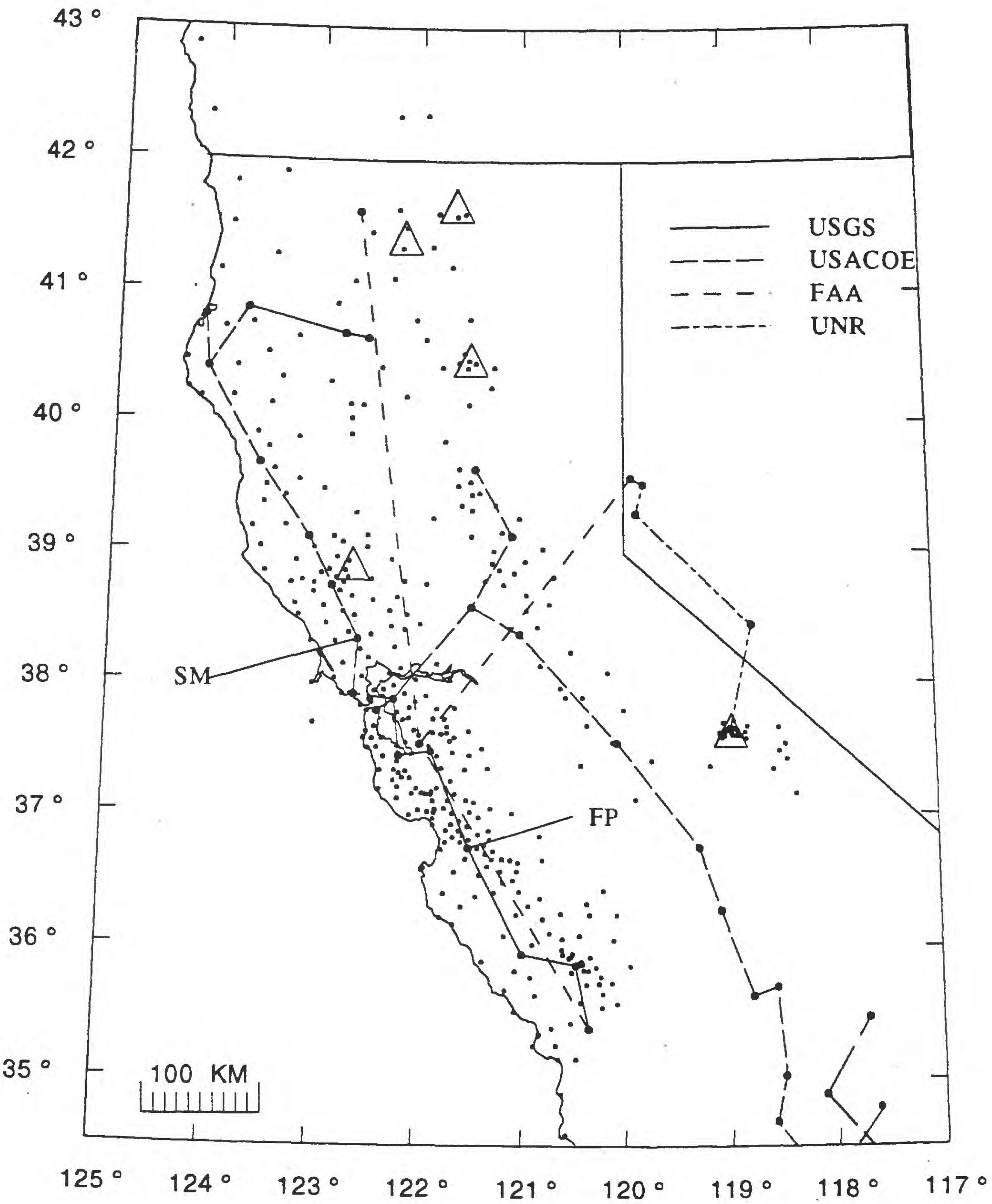

Figure 1. Location of stations operated by the Northern California Seismic Network (NCSN) and Lawrence Livermore National Laboratories (small, open circles) and microwave telemetry paths. Key depicts owner of microwave hardware currently used by NCSN. Solid circles depict locations of microwave towers. Volcanic regions depicted by open triangles. SM = Sonoma Peak, FM = Fremont Peak

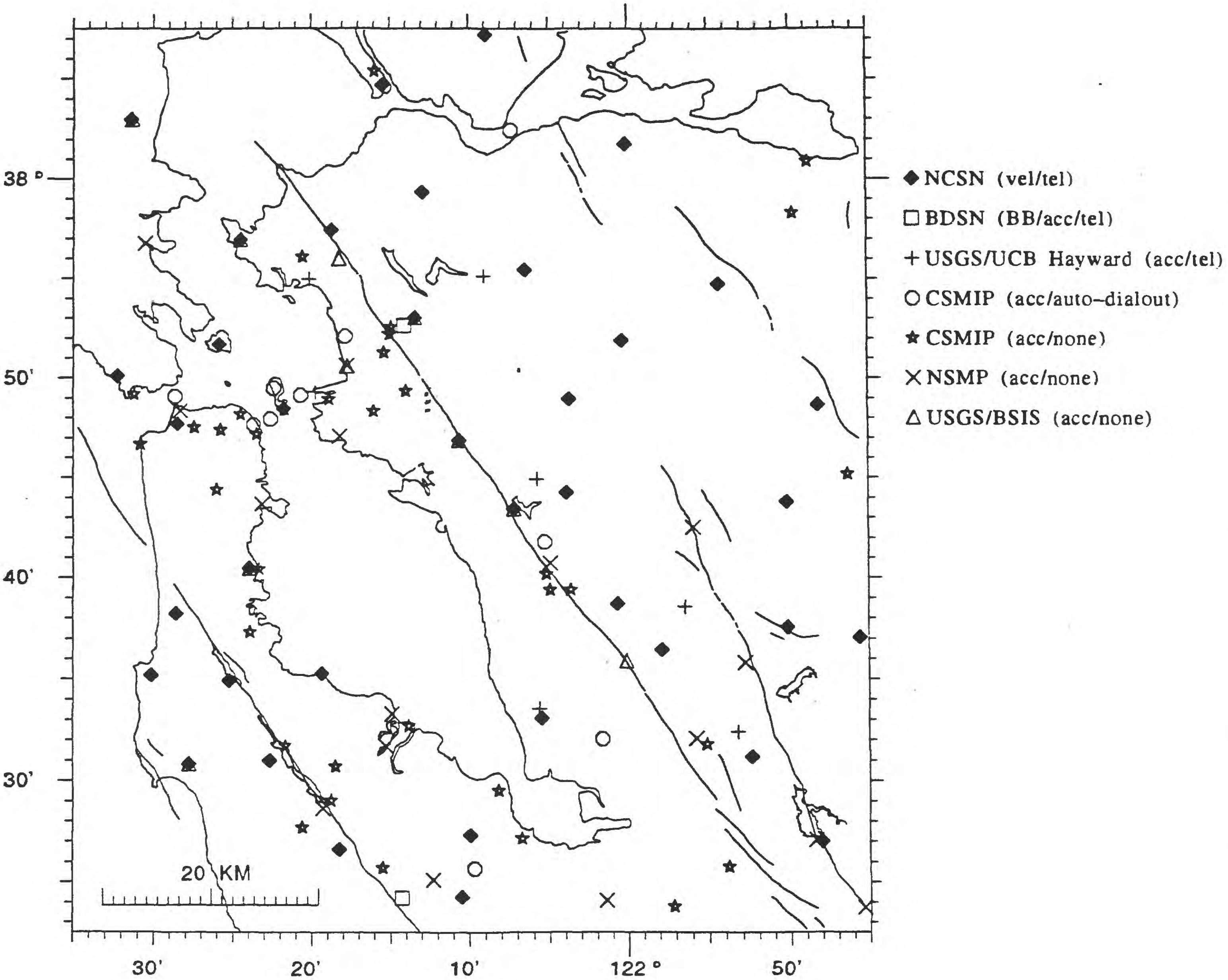

Figure 2. Locations of seismic stations currently operating in San Francisco Bay area. Symbol key depicts owner, type of motion ground recorded, and mode of telemetry at each station. acc = acceleration, vel = velocity, bb = broadband, tel = continuous telemetry, auto-dialout = delayed telemetry following triggering, none = no telemetry. BDSN = University of California Broadband Digital Seismic Network, CSMIP = California Division of Mines and Geology Strong Motion Instrumentation Program, NCSN = USGS Northern California Seismic Network, NSMP = USGS Strong Motion Program, USGS/BSIS = USGS Branch of Seismology, and USGS/UCB Hayward = cooperative down-hole, digital network on Hayward fault. Some sites have NCSN analog, USGS/BSIS and Hayward digital stations because the Hayward down-hole network is still in test mode. Faults with evidence of displacement in the last 10,000 years are from Jennings (1994).

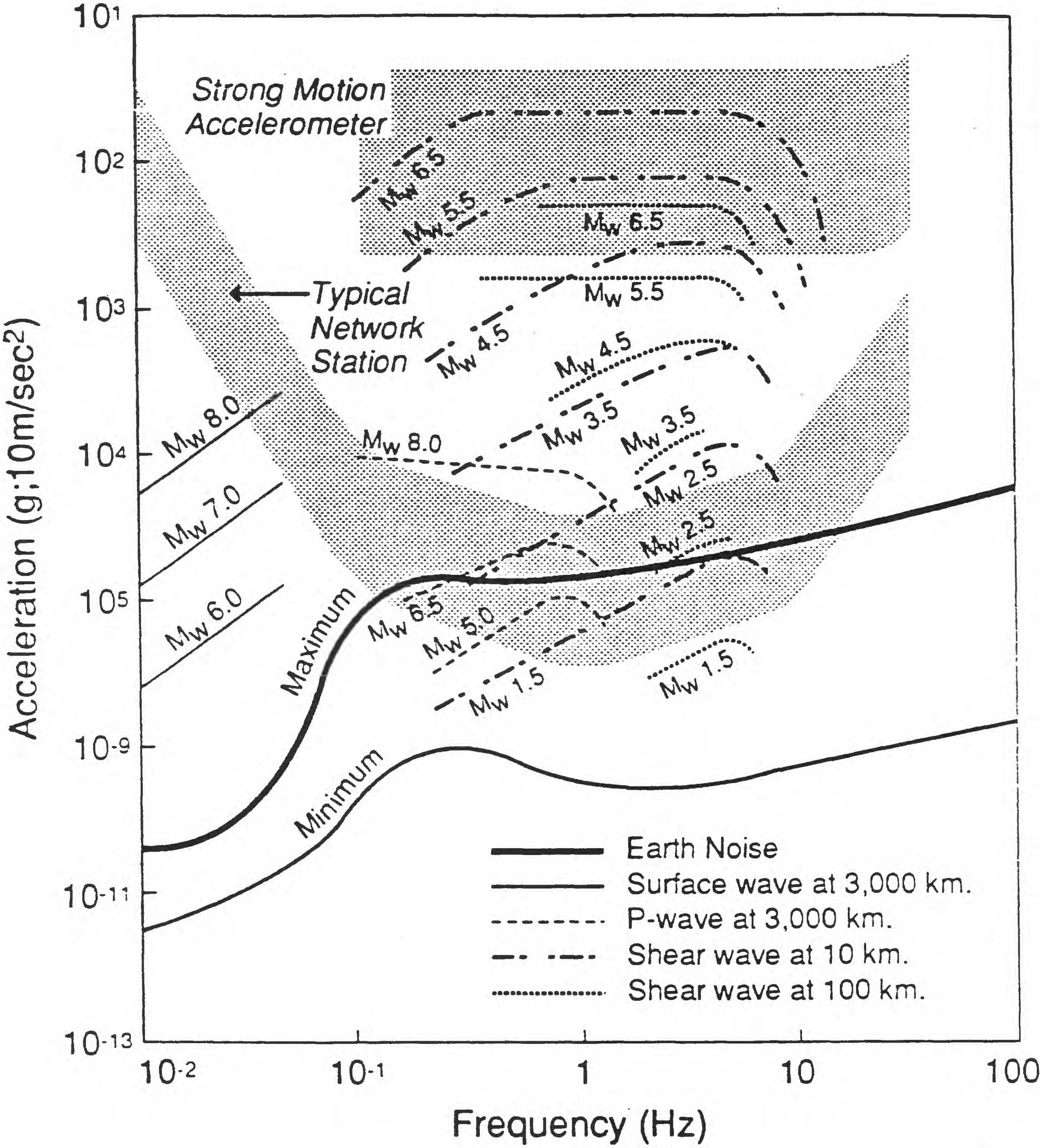

Figure 3. Expected accelerations produce by a range of magnitude earthquakes (moment magnitude M_w) as a function of frequency. The range of operation of the typical existing California network station and typical strong ground motion station is indicated by the striped area. The curves marked -120 and -160 dB indicate the constant power spectral levels of acceleration of 10^{-12} and 10^{-16} $(ms^{-2})^2/Hz$, respectively. Note that many earthquake motions are not within the range of existing instruments in the networks (after Heaton *et al.*, 1989)

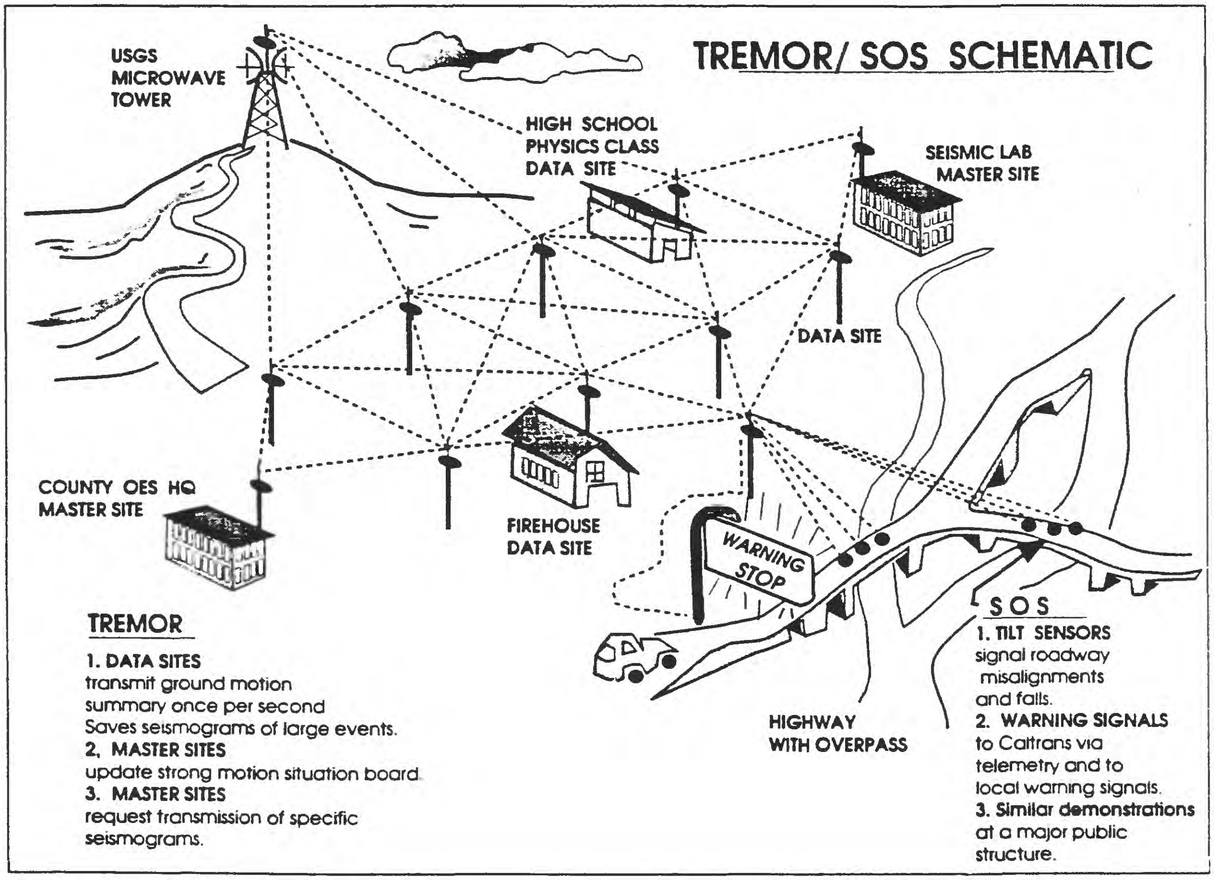

Figure 4. Schematic of TREMOR/SOS system for providing infrequent telemetry of strong ground motion in an urban area.

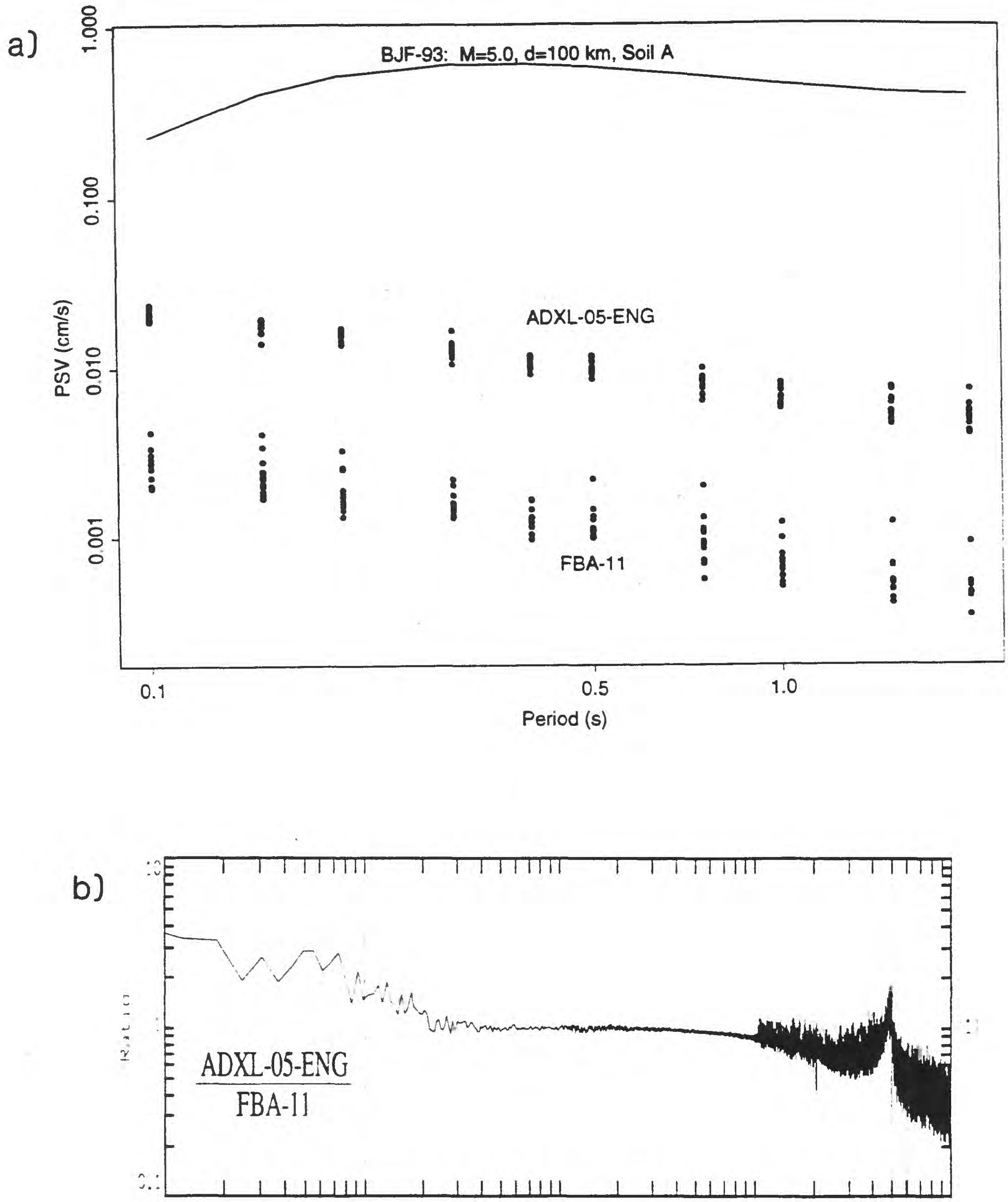

Figure 5. a) Pseudovelocity ($\omega x_{maximum}(t)$, where $x(t)$ is displacement) response spectra (5% damped) of the noise samples obtained with ADXL-05-ENG micro-machined FBA and Kinemetrics FBA-11 sensors mounted on a optical-bench isolation table. Also shown response spectrum for weakest ground shaking predicted by the Boore *et al.* (1993). b) Spectral ratio of ADL-05-ENG FBA to FBA-11 (after Evans and Rogers, 1995).