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SURVIVABILITY OF THE SOUTHERN CALIFORNIA SEISMIC NETWORK IN THE EVENT OF A LARGE DAMAGING EARTHQUAKE

by

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INTRODUCTION

What will be the effect of a large damaging earthquake on the Southern California Seismic Network? What equipment might be damaged by shaking and how will the telemetry and data processing systems cope with the increased data load? How will the ability of the Seismological Lab to provide meaningful data in both the short and long term be affected and what steps can be taken to minimize the impact of a strong earthquake? Clearly the answers to these questions are dependent on the size and location of the earthquake. The anticipated magnitude 8.0+ earthquake on the San Andreas fault would have a great effect on the remote telemetry links of the network while a magnitude 6.5 event on the Raymond Hill fault in Pasadena would have a greater effect on the Seismological Lab itself. Past earthquakes in southern California (e.g. 1952 Kern County, 1971 San Fernando, 1979 Imperial Valley, 1987 Whittier Narrows) have caused damage to network components and even smaller sequences have taxed the data aquisition system to the extent that data was lost or significantly delayed.

Because a magnitude 7.0 or larger event could nucleate in many places in southern California and a magnitude 6.0 earthquake could happen almost anywhere, this report does not attempt to examine the effect of any specific scenario earthquake. Rather, it considers the consequences of the strongest shaking that is likely at the site of each telemetry link, given all credible earthquakes in southern California. Estimates of shaking are based on the work of Evernden and Thomson (1985) and Wesnousky (1986).

This report has two aims. First, to discover weaknesses in the telemetry and recording system that may lead to loss of data in the event of a large damaging earthquake in southern California and suggest remedial steps to prevent such loss of data. Second, to give emergency planning personnel, scientists and others, whose response to the earthquake will be influenced by information about its location and size, some idea of what information may be reasonably expected from the Seismological Lab.

While this report addresses the Southern California Seismic Network specifically, its observations and recommendations may be applied to other similar systems. It is also hoped that this report will encourage the recognition of network survivability as a tangible concern among those who run networks and make the issue of survival an integral part of network planning and design.

OVERVIEW OF THE NETWORK

The Southern California Seismic Network includes about 240 seismometers distributed from the Mexican border to Owens Valley and from the Pacific coast to Arizona (Figure 1). Continuous analog signals from these remote sites are telemetered by some combination of telephone, radio and microwave to the Seismological Lab at Caltech (Figure 2). At the Lab the signals are recorded in several ways. Raw analog signals from part of the Network are recorded on magnetic tape. Signals from all the stations are discriminated (separated from other signals), digitized and recorded by on-line computers (Given *et al.*, 1986). A small number of signals are also recorded on helicorders. The computer recorded signals are further processed and event locations and magnitudes are calculated on a different off-line computer (Given *et al.*, 1987).

This telemetry and recording chain is as strong as its weakest link. Each link is examined in the following sections. Recommendations presented here are, for the most part, technologically and economically realistic. More exotic measures may be possible but are probably not justified. Recommendations are listed in the general order of their cost effectiveness.

SITE INSTRUMENT PACKAGE

The equipment at seismometer sites is self contained and quite earthquake resistant. Components are generally buried in metal "tubs" in sparcely populated areas. Individual sites are powered by batteries and are, therefore, not subject to local power outages. All USGS sites have about the same configuration.

Site components include:

- Seismometer
- VCO (voltage controlled oscillator)
- Cables
- Batteries
- Solar panel (at some sites)

Caltech seismometer installations are generally older and more sensitive to strong shaking. Instruments at Pasadena, Riverside, Santa Barbara and China Lake were damaged during the magnitude 7.7 Kern County earthquake of 1952 (Richter, 1955).

Following the Imperial Valley earthquake of 1979 (M_L 6.6) the east-west horizontal component at Schaffner Ranch (SNRE) was damaged in such a way that its gain was effectively decreased. As a result, it recorded large aftershocks without clipping and provided very useful records. The problem of instrument gain is discussed in a separate section.

Loss of a small number of sites will not have a significant impact on our ability to analyze the earthquake. However, the most valuable sites, those in the the epicentral area, will be the most likely to sustain damage. Loss of records at the Caltech sites will degrade our ability to calibrate magnitudes for aftershocks.

Recommendations:

1) Secure all electrical components, especially batteries and solar panels, at sites.

RADIO TRANSMITTER/RECEIVER PAIRS

111 (47%) of the network stations are carried by radio somewhere along their telemetry path. These are VHF FM radios operated in the band from 162.5 to 173.2 Mhz. Individual site transmitters are collocated with the seismometer instrument packages. Some seismometer sites also function as radio receive sites; collecting signals from other stations, multiplexing (summing) them and either retransmitting them by radio or transferring them to telephone line.

Radio telemetry components include:

Antenna and mast
Radio transmitter and/or receiver
Summing amplifier (at some sites)
Batteries
Solar panel (at some sites)

Antenna masts are generally guyed to withstand high winds. The radio signals are directional but quite broad (about 15°) and not very sensitive to misalignment. Radio sites are individually powered by batteries augmented by solar panels and are not subject to power outages.

Recommendations:

1) Secure antennas and solar cells to withstand high horizontal accelerations (> 1.0g ?).
2) If site bedrock is difficult to excavate use guy wires to secure masts.

LEASED TELEPHONE LINES

218 (93%) of the network stations are carried by voice grade leased telephone lines somewhere along their telemetry path. For 81 (34%) of network stations the telephone system is the sole carrier of the signal. For the sake of economy, up to eight separate signals are multiplexed on a single phone line. Therefore, loss of a single phone line would result in the loss of up to eight signals from the same geographic area. This type of failure seems most likely near the epicenter where continued recording is particularly important to constrain depths of hypocenters.

We have virtually no control over the equipment used to transmit data signals over commercial telephone lines. Because our data lines are dedicated lines they bypass switching equipment and thus do not pass through the most fragile part of the telephone system (switching equipment racks and computers). They are also not subject to "call saturation"; the overload of trunk lines by increased system use as is expected in the aftermath of a large earthquake.

Commercial telephone companies use a combination of buried and suspended cables and microwave to transmit signals. In almost all cases the physical paths of the telephone circuits are unknown to us. Telephone companies are often unable or unwilling to provide that information. However, the physical path of the circuit from Lake Isabella to Bakersfield is known (Figure 3). It is approximately ten times longer than the line-of-sight path and takes the signal through six switching facilities. The path crosses the Sierra Frontal fault, the Transverse Range frontal fault, the Garlock fault, San Andreas fault, San Jacinto fault, Newport-Inglewood fault, and White Wolf fault; in short, every major Quaternary fault in southern California. Some of these faults are crossed multiple times. While the ability of the components of this signal path to survive a large earthquake cannot be accurately assessed, it is clear that circuitous paths like this one increase the likelihood of loss of signal due to a failure somewhere along the path.

All AT&T facilities have backup systems for their leased lines; 80% are automatic. The likelihood of failure of primary systems and the efficacy of backup systems is unknown. Telephone facilities also have backup power systems.

Priority repair service is available at additional cost from AT&T. It is unlikely that this service would be cost effective because telephone company personnel will be severely overtaxed after a large event and may not be able to honor priority service contracts.

Recommendations:

1) Where possible, choose telephone companys that offers physical routing to minimize path length, number of switching stations involved and number of fault crossings.
2) Explore cost and desirability of priority repair.

MICROWAVE TELEMETRY

101 (43%) of the network stations are carried by the USGS owned and operated microwave system somewhere along their telemetry path. Individual signals are multiplexed, as on the telephone lines, and transmitted at a frequency of 1725 or 1800 MHz. There are a total of five microwave sites chained serially from Randsburg to Pasdena (Figure 4).

Microwave system components include:

Towers
Dishes
Electronics building (reinforced concrete block)
Receiver/transmitter electronics
Equipment racks and cables
Batteries, AC power

Table 1 lists estimated Modified Mercalli Intensities (*MMI*) at the southern California microwave sites, published by Evernden and Thomson (1985) for 87 postulated events. Because local geologic conditions were generalized for cells with dimensions of about 0.76 km by 0.91 km, these estimates do not take into account very localized site conditions. Local site conditions can cause the intensity to vary by up to three units. Maximum horizontal accelerations were estimates by Wesnousky (1986) for Quaternary faults at the 10% probability level for a 50 year period. Site geology was not considered at all by Wesnousky and neither study considered such effects as directivity or focusing.

▪ Table 1. ESTIMATED GROUND MOTION AT MICROWAVE SITES

SITE	INTENSITY (*MMI*)	MAX. ACCELERATION (g)
Randsburg	N/A	0.20 - 0.29
Edwards	N/A	0.10 - 0.19
Strawberry	VII	>0.50
Santiago	<VI	0.30 - 0.49
Pasadena	VII +	0.20 - 0.29

Microwave towers and dishes are built to withstand the high winds that are common at their mountain-top locations, but one microwave mast has failed in high winds in central California. It is difficult to predict their performance during strong ground shaking. The USGS microwave telemetry system employs both eight and ten foot dishes. Transmit and receive dishes are always paired by size. Response curves from the manufacturer of the microwave dishes indicate that they are sensitive to alignment (Table 2). Larger dishes are more sensitive to alignment because the signal energy is more tightly focused. As a result the signal strength falls off rapidly as you move away from center. Generally, a signal loss of 20 dB would cause the signal to drop below the noise level.

▪ Table 2. MICROWAVE DISH ALIGNMENT TOLERANCE

Microwave Dish Size	Deflection to 20 dB loss
8 ft.	4°
10 ft.	3°

During the Morgan Hill earthquake of April 24, 1984 (M_L 6.0) there was no loss of signal on the USGS central California microwave system. The microwave relay site nearest to the epicenter was at Monument Peak, about 20 km away. Based on the isoseismal map of Stover (1984) this site probably experienced a *MMI* of V–VI. There was no loss of microwave signal due to the *MMI* VII shaking at the Pasadena receive site during the Whittier Narrows earthquake.

The continuation of microwave telemetry is particularly important because it carries a large number of signals. Signals are added to the microwave system at Randsburg, Edwards and Strawberry Peak; Santiago serves as a repeater and Pasadena is a receive site only. Therefore, the loss of the receiver at Caltech, the transmitter or receiver at Santiago Peak or the transmitter at Strawberry Peak, would result in the loss of all 101 stations; that is 43% of the network and essentially all stations north of the San Andreas fault zone. There are plans to carry even more stations on the microwave system in the future.

In order to overcome problems of atmospheric interference in its central California microwave system the USGS has erected a second set of microwave dishes about 60 feet from the existing dishes at some sites. This "spatially differentiates" the signals of the two parallel systems, that is, gives them significantly different paths and thereby minimizes signal loss due to atmospheric deflection. The signals from the two systems are summed by site electronics and are much less sensitive to atmospheric interference. As a windfall, this scheme adds redundancy to microwave masts and dishes and improves the system's earthquake survivability. Atmospheric problems have not been severe in the southern California microwave system and a parallel system has not been installed and is not being seriously considered.

Microwave electronics are powered by local AC power. Backup power is provided by on-site batteries that should provide three days of continued transmission if other site components are undamaged. Microwave sites are equipped with redundant receive and transmit electronic components that will switch over automatically in the event of failure.

Trouble-shooting microwave system problems is currently a difficult chore. In the event of failure it is impossible to know if the problem is with a receiver or with the next transmitter down the line. The USGS is currently working on a system that would transmit information about the condition of microwave electronic components and facilitate trouble diagnosis. In the absence of such a system technicians cannot even be sure which site to visit during a failure, thus lengthening down time.

Access to the microwave sites may present a problem to technicians attempting repair. Access to both Strawberry Peak and Santiago Peak is by mountain roads that will be susceptible to rockslides. Winter access may be complicated by snowfall. Depending on the extent of regional damage, purchase of gasoline may be a problem and, thus, limit the range of accessible areas. Helicopter service will not be available due to increased demand by relief efforts.

Recommendations:

1) Secure all components to withstand high horizontal accelerations (1.0g ?).
2) Maintain adequate supply of spare microwave components.
3) Purchase and install microwave self diagnostic system.
4) Explore cost effectivenes of spatially differentiated system in southern California to provide redundency of critical microwave components.
5) Keep vehicle fuel tanks full.

SOUTH MUDD BUILDING, CALTECH

The three story South Mudd building that houses the Seismological Laboratory is located on the south-west corner of the Caltech campus in Pasadena. It was designed to meet 1.5 times the seismic loading factor of the Unified Building Code at that time. The structure was built in 1972–73, immediately after the San Fernando earthquake of 1971. That event produced a *MMI* of VI on the Caltech campus (Evenden and Thomson, 1985; Table 24). Construction was overseen by Paul Jennings who added or moved shear walls to increase its seismic resistance.

Evernden and Thomson (1985) suggest a maximum *MMI* of VII+ in Pasadena due to any of 87 postulated earthquakes. This predicted maximum *MMI* for Pasadena was realized during the M_L 5.9 Whittier Narrows earthquake of October 1, 1987 (Hauksson *et al.*, 1987). Wesnousky (1986) estimated maximum accelerations for Pasadena of 0.20–0.29g. The peak acceleration at the Millikan Library on the Caltech campus during the

Whittier Narrows event was 0.19g on the north-south component (Paul Jennings, written communication). The epicenter was only 10 km from the lab but the duration of strong shaking was short and it caused only minor damage to the South Mudd building and its contents. The greatest damage was to ceiling tiles, unsecured furniture and the elevator. There was no interuption of power or chilled water (for computer room cooling). An adjacent building had to be evacuated due to a chemical spill. Had that evacuation included the South Mudd building network equipment and data would have been inaccessible for hours after the event. It is unlikey that the building will sustain any major structural damage.

That event and the occurrence of a M_L 4.9 earthquake on the Raymond Hill fault right under the campus on December 3, 1988 attest to the high level of seismic risk at the Lab. It is reasonable to assume that higher intensity and longer duration of shaking are possible.

The rooms that house the telemetry and computer systems have suspended lights and acoustic panel ceilings. This type of ceiling is susceptible to damage during strong shaking. There is extensive ductwork and plumbing in the ceiling space above the computer rooms. This presents a falling hazard and the possibility of water damage to computer equipment.

Telemetry cables take a variety of routes in the South Mudd building; from commercial telephone equipment and the microwave receive dish on the roof to the telemetry room on the second floor, from the telemetry room to the computer room, and between points within the telemetry room. They pass through conduits, wall spaces, false floors, false ceilings and along overhead ladder-type racks. The most likely source of cable failure is separation at connectors, especially where cables do not have enough slack to accommodate differential movement of the components on either end.

Recommendations:

1) Where possible fix cable connections with clips or screws.
2) Allow adequate slack in cables and wires to accomodate motion of terminal components.
3) Secure racks, shelves, cabinets, etc. to prevent cables pulling away and object falling on exposed cables.
4) Add diagonal wire braces to the suspended ceilings, pipes and ductwork overhead in computer rooms.

ELECTRICAL POWER TO THE SEISMOLOGICAL LABORATORY

Power to Caltech is provided by the Pasadena Department of Water and Power (PDWP) and is augmented by an on-campus 1 megawatt cogeneration facility that burns natural gas. The 1 megawatt on-campus cogeneration facility is not capable of starting in the absence of municipal power. Computer operations are, therefore, completely dependant on the continuity of the Pasadena municipal power supply. Power to Caltech is provided through a dedicated 34 kV line. The PDWP is tied into the southern California power grid and imports an average of 45% of the city's power needs. This figure, however, is determined by economics; PDWP has the capability of generating sufficient power for all the city's need except during periods of exceptionally high usage. PDWP in cooperation with other utilities has developed a plan to "shed power" in the event of diminished capacity of the power grid. This means that noncritical areas can be selectively blacked out if available electrical power is limited. The Caltech campus is not subject to these black outs.

The South Mudd building that houses the Seismological Laboratory has a "rough stand-by" capability. This alternate power source consists of a generator that will autostart in the event of power interuption. The generator can burn either natural gas or gasoline. This stand-by power is only sufficient to power selected building lights, the discriminators, FM tape drives and helicorders. The "rough stand-by" generator in the South Mudd building is not capable of providing power to the computers.

Caltech is currently constructing a four megawatt cogeneration facility on campus. It will have the ability to start and run in the absence of municipal power and will provide about 60% of Caltech's electricity needs. Should municipal power be lost the power generated on-campus will be preferentially supplied to campus laboratories. This facility should be completed soon.

FM TAPE DRIVES

Two Ampex "FM" (frequency modulated) analog tape drives record the raw signal that is received at Pasadena. These signals are recorded before they are discriminated. The units are capable of recording 32 channels with a maximum of 9 stations per channel. This yields a total analog recording capacity of 288 stations, however, signals must be multiplexed by circuit and circuits cannot be mixed. Because not all circuits are completely filled, only 207 stations (88% of the network) are recorded in analog form. The FM tape drives are old and prone to data loss even under normal working conditions. Because the tapes are not routinely read soon after they are recorded, some types of recording failures may go unnoticed for extended periods.

The drives record on reels of one inch tape, each of which holds 24 hours of data. These tape drives provide long term backup to digital recording but, because of the length of the tapes and the difficulty of reading them, they do not allow timely access to data.

The stability of the FM tape drive cabinets and their susceptibility to shaking damage are comparable to those for computer hardware. Damage mitigation measures discussed in the section entitled COMPUTER HARDWARE can, therefore, be effectively applied to the FM tape drives.

The FM drives are routinely powered by batteries that are continuously recharged by standard AC power. These batteries are also connected to the "rough stand-by" power of the South Mudd building.

The usefulness of the backup data provided by the FM tapes is reduced by the lack of a simple, convenient means of retrieving the data in digital form. A prototype system exist at the USGS Regional Headquarters in Menlo Park, but there is no such system in Pasadena.

Because of their age the FM drives are expensive to run and maintain. Breakdowns are frequent, parts difficult to obtain and replacement tapes are expensive. It is technically feasible to replace the FM drives with continuous digital recording on high density tape.

This scheme would also allow quick playback on existing computers eliminating the need for an FM playback system. It would also allow the recording of every station in the network.

Recommendations:

1) Secure FM tape drive cabinets with tether systems.
2) Secure cabinets used to store FM tapes, batteries and cables to walls and/or floor.
3) Install FM to digital playback system in Pasadena.
4) Initiate routine periodic checking of FM data tapes to insure drives are functioning properly.
5) Periodically check battery backup and backup generator system.
6) Evaluate phone lines recorded on FM tape for good regional distribution and recording of high quality stations.
7) Prioritize phone circuits so that if one that is recorded on FM tape is lost its place can be quickly filled with another circuit.

OR

1a) Replace current FM backup system with digital backup system.

DISCRIMINATORS

Each multiplexed station signal coming in on the telemetry system is separated from other signals on the same carrier by a discriminator. This process is required before the individual signals can be digitized by the computer system or recorded on helicorders. Discriminators are powered by batteries that are continuously recharged by standard AC power. Batteries are also connected to the "rough stand-by" power of the South Mudd building.

One discriminator was jarred loose by the strong shaking of the Whittier Narrows earthquake. Discriminators should be secured to prevent similar problems in the future.

Recommendations:

1) Secure cabinets, batteries and cables to walls and/or floor.
2) Secure discriminators in their racks.

HELICORDERS

Helicorders are the standard ink-on-paper drum recorders that have been in use in seismology for more than 50 years. About 20 stations continue to be recorded in this manner to maintain continuity with historic recordings. The helicorders are powered by batteries that are continuously recharged by standard AC power. They are also connected to the "rough stand-by" power of the South Mudd building.

Intense shaking of the recording units will be transmitted to the pens and obscure the records. This occurred during the Whittier Narrows earthquake of October 1, 1987. This is of little consequence because the instrumental record during this period of strong shaking will be clipped and of little value. During the San Fernando earthquake of 1971 (M_L 6.4), helicorders recorded both the arrivals at the stations and the arrivals at the Seismological Laboratory. Heavy shaking may also cause the pen assemblies to jump on the helical screws that transport them across the paper resulting in a loss of timing synchronization. It will be important to check all the helicorders soon after the event.

These records are of particular importance because they have been the basis for comparing and calibrating earthquake records in southern California for the last 55 years. Therefore, it is important that the intruments do not sustain any long-term damage.

Recommendations:

1) Secure cabinets, batteries and cables to walls and/or floor.
2) Bolt helicorders to their racks.
3) Secure helicorder cabinets with tether systems.
4) Maintain adequate supply of spares and parts.

COMPUTER HARDWARE

The discriminated signals are digitized by a Tustin A/D converter and continuously recorded on two different Digital Equipment Corporation (DEC) minicomputers; one PDP 11/34 and one MicroVAX II. These computers also do event detection. Both systems use DEC RA–81 disk drives as their primary storage media.

The PDP 11/34 is mounted in standard six foot high computer cabinets and the MicroVAX is mounted in cabinets of half that height making it less likely to topple during shaking. Both are located in an environmentally controlled room along with the microwave receiver electronics, FM tape drives and discriminators. Cabling is routed on a suspended ladder-type track overhead.

Off-line processing of seismic data is done on a DEC VAX 11/750. This computer system is located in a separate room from the on-line computers but is subject to the same problems of power supply and shaking as the on-line computers. In addition, the off-line computer is partially supported by a false floor. It is unknown how this false floor will perform during heavy shaking, however, at least three such raised floors collapsed during the San Fernando earthquake of 1971 (Gates and Scawthorn, 1983).

A second VAX 11/750 is located in the two-story, wood frame house that houses the USGS office across the street from the Lab. The chimney of that building was damaged by the Whittier Narrows earthquake but it was otherwise unaffected.

All of these computers are linked by an Ethernet coaxial cable. Networking is acheived using DECnet and LAVc (Local Area VAXcluster) software.

The computer manufacturer (DEC) has not vibration tested the equipment at seismic frequencies but does claim that the Head Disk Assembly (HDA) of the RA–81 disk drive (the most sensitive part of the system) can withstand 0.25g in the range 22–500Hz. This is a much higher frequency than that of seismic waves but is much closer to the natural frequency of the HDA. Iwan (1983) states that most rotating mechanical equipment can survive accelerations of 3-4g without failure but that other components of disk drives may be more fragile. He further points out that accelerations in excess of 4g are possible if equipment topples or impacts other equipment.

Two DEC VAX 750's with RA–81 disk drives were in place at the USGS Hawaiian Volcano Observatory on Kilauea during the Kaoiki earthquake of November 16, 1983. This earthquake was assigned an M_S of 6.6 and was centered only about 15 km from the observatory. The computers, which were free standing and not secured, "walked" across the room, disconnecting their umbilicals. Tape racks and shelves fell causing some damage to cables. However, once power was restored and the computers were reconnected they functioned normally. There was no damage to computer equipment at the Lab as a result of the Whittier Narrows earthquake.

Shake table research done by IBM (Morgan, 1983; Gates and Scawthorn, 1983) indicates that the "dog-on-a-leash" method is the most effective in minimizing damage to computer equipment. Cabinets are allowed to move on casters or low friction feet but are tethered to prevents toppling or colliding with other equipment or walls. By lowering the coefficient of friction between the cabinets and the floor less horizontal force is transferred to the cabinets and toppling is less likely. Adjacent cabinets are either separated far enough apart to allow movement, bolted together so they will respond as a unit or separated by some energy absorbing material. Sufficient slack is provided in umbilical cables to accomodate movement within the the limits of the tethers. Cabinets are less likely to overturn if their center-of-gravity is low and the ratio of height-to-base is less than 1.0 (Gates and Scawthorn, 1983).

Electrical power is provided by Caltech and PDWP and the computers systems have no backup power source. They are also sensitive to power surges and glitches. Uninterruptible power source (UPS) systems are commercially available from a number of vendors. However, these systems are generally intended to provide battery power for only a brief time to allow the system to be properly shutdown. Such systems cost from about $12,000 to over $100,000.

Room environmental control is dependent on a supply of chilled water that is piped throughout the campus by the Caltech physical plant. This chilled water supply is subject to interuption by loss of power, damage to the main facility or damage to the network of pipes that distribute the water. If chilled water is lost on a warm day it may be necessary to shut down computer systems to avoid overheating damage.

Current plans call for replacing the 11/34 computer with another MicroVAX computer. Not only are MicroVAX computers more powerful but they are smaller and can be placed in a "low profile" stable configuration. Second, they have smaller power requirements making installation of an UPS system cheaper. Third, they produce less heat making computer room enviornmental control unnecessary.

Recommendations:

1) Remove or secure tape racks, book shelves, stacks of boxes, etc.
2) Replace PDP 11/34 with second MicroVAX system.
3) Provide computer equipment cabinets with tether restraints, connect or isolate individual cabinets, where possible lower center of gravity of equipment cabinets.
4) Add shear bracing to false floor supporting computer.
5) Maintain current system backups in secure location.
6) Install automatic Halon fire suppression systems in telemetry and computer rooms.

7) Explore usefullness of room air conditioners to use in event of loss of chilled water supply.
8) Explore electrical surge and spike protection.
9) Explore cost effectiveness of CPU battery backup.

COMPUTER SOFTWARE

Similar real-time detection and recording software runs on the PDP 11/34 and MicroVAX II computer systems. They are compatible with and considered part of the larger earthquake processing software system that is collectively referred to as **CUSP** (Caltech–USGS Seismic Processing).

The real-time portion of the system will accept data from up to 300 channels at 12 bits per channel. The primary system digitizes incoming signals at a rate of 100 samples/second yielding a total data rate of about 45,000 bytes/second.

On the PDP 11/34 computer system this raw data is continuously written to a disk buffer that can hold up to 30 minutes of data. The event detector cannot operate on this volume of data in real-time and, therefore, examines only every fourth 1/4 second of the data in the buffer. During periods of high activity the work of creating event data files increases, making it possible for the data buffer to "wrap around". When this occurs previously buffered data is overwritten before event detection has been performed on it and data is lost. This situation occurred in July of 1986 during the North Palm Springs earthquake (M_L 5.6) when six hours of digital data after the main shock was lost.

In order to mitigate this problem to some extent the backup on-line system (the PDP 11/34) is routinely run at a sample rate of only 62.5 samples/second. This reduces the data rate by about 1/3 and extends the data buffering time to about 40 minutes. It also reduces the volume of data that must be written and handled by other system modules.

The newer MicroVAX II system buffers data in memory and only writes to disk when an event is detected. This scheme reduces I/O and disk space usage. Once the raw digital files are written they are demultiplexed. This process also deletes data for individual stations that were not triggered, thus compressing the saved data. Once this is complete the event is available to the off-line processing VAX via LAVc.

The systems' triggering algorithm recognizes earthquakes by comparing the short term average of station amplitudes over the past five seconds to their long term averages over the last 60 seconds. If the short term average is twice the long term average on four closely spaced stations the system is triggered. In the coda of a large quake the whole network will be clipped for an extended period and the short term average will never exceed the long term average. Triggering will become erratic or cease.

Continuity of operations will depend on the intervention of laboratory personnel. The high volume of data generated by a large event will require writing data out to magnetic tape because sufficient disk space is not available. This will require the continuous attention of an operator to mount and dismount tapes.

If the off-line computer is inoperative for any reason but phase data is still available, either from the on-line system or from paper records, it is possible to use the VAX 750 in the USGS office to locate events. If both VAX's are inoperative it is possible to calculate locations on desk-top microcomputers in the Lab. At least one such computer should have a standby power source. In the absence of a computer for earthquake locations, crude locations can be obtained using manual methods.

Recommendations:

1) Continue aquisition of MicroVAX computer hardware and install improved on-line system software.
2) Maintain adequate supply of magnetic tapes for data buffering.
3) Obtain standby power source for at least one desk-top microcomputer.

INTRUMENT GAIN — SIGNAL CLIPPING

Network stations currently have attenuation settings of from 0 to 36 dB (Given *et al.*, 1986). Ten of the network stations are being run at low gain (48 dB). There are also four force balance accelerometers at various sites and a Streckeisen broad-band instrument at Pasadena that stay on scale during strong shaking. Network stations currently clip if they are near the epicenter of a magnitude 2.5 earthquake. The whole network (with the exception of the low gain stations) will clip during a magnitude 4.0. Larger events can be expected to clip for long periods of time. During the period of signal saturation phase arrivals for aftershocks and events elsewhere in the network will be lost. Amplitude saturation is presently the the most common and potentially the most serious source of data loss for the Network.

This problem may be solved slowly by the evolution of the Network sites to high dynamic range, broad-band instruments such as those being developed for the National Network. Such sites will have the ability to record ground motion from background noise up to more than 1.0 g without clipping.

Recommendations:

1) Reduce station gains
2) Pursue conversion to wide dynamic range seismometers and telemetry

COMMUNICATIONS WITH THE SEISMOLOGICAL LAB

Regular telephone communications with the Seismological Lab will be very difficult due to increased call load on the regional telephone system in general and the Caltech switchboard in particular. Commercial telephone systems routinely run at or near full capacity and will be easily saturated by an excited populous (Davis *et al.*,1982) and by hand sets being knocked off their cradles by a large earthquake. Because of this call saturation, telephone communications will be significantly impaired in the aftermath of a large damaging earthquake, even in the absence of physical damage to the system. This situation may persist for several days after the event. Loss of communications with other offices of the USGS may make it necessary for some critical decisions to be make without approval of management.

The Federal Telephone System (FTS) operates over lines leased from commercial telephone companies. It operates routinely at about 90% of capacity. The FTS system will also be subject to increased traffic after a big earthquake.

After the Whittier Narrows earthquake telephone communications at the Lab were significantly impaired by call saturation. No outgoing calls were possible on either commercial or FTS lines for several hours after the event. Only sporatic incoming calls were received. A service is available from commercial phone companies that gives subscribers priority access during times of system saturation. This service will be purchased for a phone at the Lab in the near future.

The Pasadena office of the USGS has mobil radio units in its vehicles and a base station in its office. These radios are in the government band and have a limited range. The system is capable of tying into the Bureau of Land Management (BLM) repeater network. The extent of the BLM network and the possibility of using it to communicate with other USGS offices are unknown but probably limited. Repeater networks in general are expected by Davis *et al.* (1982) to remain 60% effective immediately after an 8.3 on the San Andreas but decline to 40% effectiveness in the first 24 hours as backup batteries become exhausted.

The USGS in Pasadena also has a ham radio that is capable of reaching the Menlo Park office. This radio may provide an independent means of communication if other channels are not available. It may also be a valuable source of damage information from the epicentral area. However, this radio is currently dependent on an AC power source.

Electronic media (television and radio) will be of some help in distributing seismic information. Past experience, however, has shown the media to be capable of distributing distorted or false information in crisis situations. It is probably not wise to expect the media to provide the accurate data required by scientists and emergency management personnel.

Recommendations:

1) Purchase priority access for at least one Lab phone.
2) Coordinate with BLM on extent of repeater network and availability of channels in event of earthquake.
3) Explore California Office of Emergency Services radio communication link.
4) Provide battery power source for USGS ham radio.

PERSONNEL

Lab personnel are severely taxed by large events. First priority is usually given to the location of the mainshock and aftershocks to monitor the progress of the sequence and evaluate its implications for emergency management organizations. The large data influx requires checking of data acquisition systems and telemetry to prevent data loss. Responding to public and media inquiries causes a substantial drain on personnel resources.

After a very large event some staff member may be unable (or unwilling) to reach the Lab. It is assumed the laboratory staff will be distracted by concerns about the safety of family and friends and damage to personal property.

DISCUSSION

Given the hypothetical nature of this study, our limited experience with very large earthquakes in this country, and the diversity of included elements, it is impossible to provide quantitative results. It is possible, however, to gain some valuable insight into the tenuous chain of telemetry components and discover clear weaknesses. Identification of these weaknesses is a necessary first step in taking remedial action. Before any remedial action is taken, it should be examined in the context of the whole telemetry system to determine if that action would be cost effective. Factors to be considered include: cost, level of expected shaking at the site, number of signals dependent on that component, accessibility and speed with which it could be replaced or repaired and interrelation of components. For example; it would not be cost effective to make the computer systems significantly more durable than their power source.

Given the foregoing discussion, it is possible to construct an estimate of the relative vulnerability of the system components (Figure 5). Such a scheme is rather subjective and is only intended as an aid in deciding on a resonable course of remedial action by identifing the most fragile links. Frail components should be strengthened first.

The last two lines in Figure 5 estimate the degree to which data processing will be affected. These are essentially a result of the other factors on the figure. The ability of the Lab to produce reliable location and magnitude information in the short term will first be impaired by the increase in data rate that accompanies an earthquake in the magnitude 6.5 and larger range. Computer systems will be overloaded, aftershocks and codas will be inextricably mixed and amplitudes will be clipped. Network personnel will also be over taxed at that point. It is likely that a location, rough mainshock magnitude and incomplete count of large aftershocks will be all that can be provided. Little information about focal mechanism or aftershock distribution or migration can be expected in the first hours. At even larger magnitude levels telemetry failures and power outages may further reduce data processing to the point that only a very crude mainshock location and magnitude are available.

Long term data processing will be heavily affected at lower magnitude levels. The large number of events will require a great deal of analyst and computer time to locate. Even a relatively small event ($M_L \simeq 5.0$–6.0) with a copious aftershock sequence can delay data reduction for months. Larger events can cause telemetry or computer hardware failures or overload the system to the extent that data is lost and irrecoverable.

Many of the recommendations made in this report will return a great deal of system durability for a modest investment of time and money. However, some problems would be much more difficult and costly to solve. It is important that future planning for network change and expansion include serious consideration of survivability of network components and continuity of operations during and after large, damaging earthquakes.

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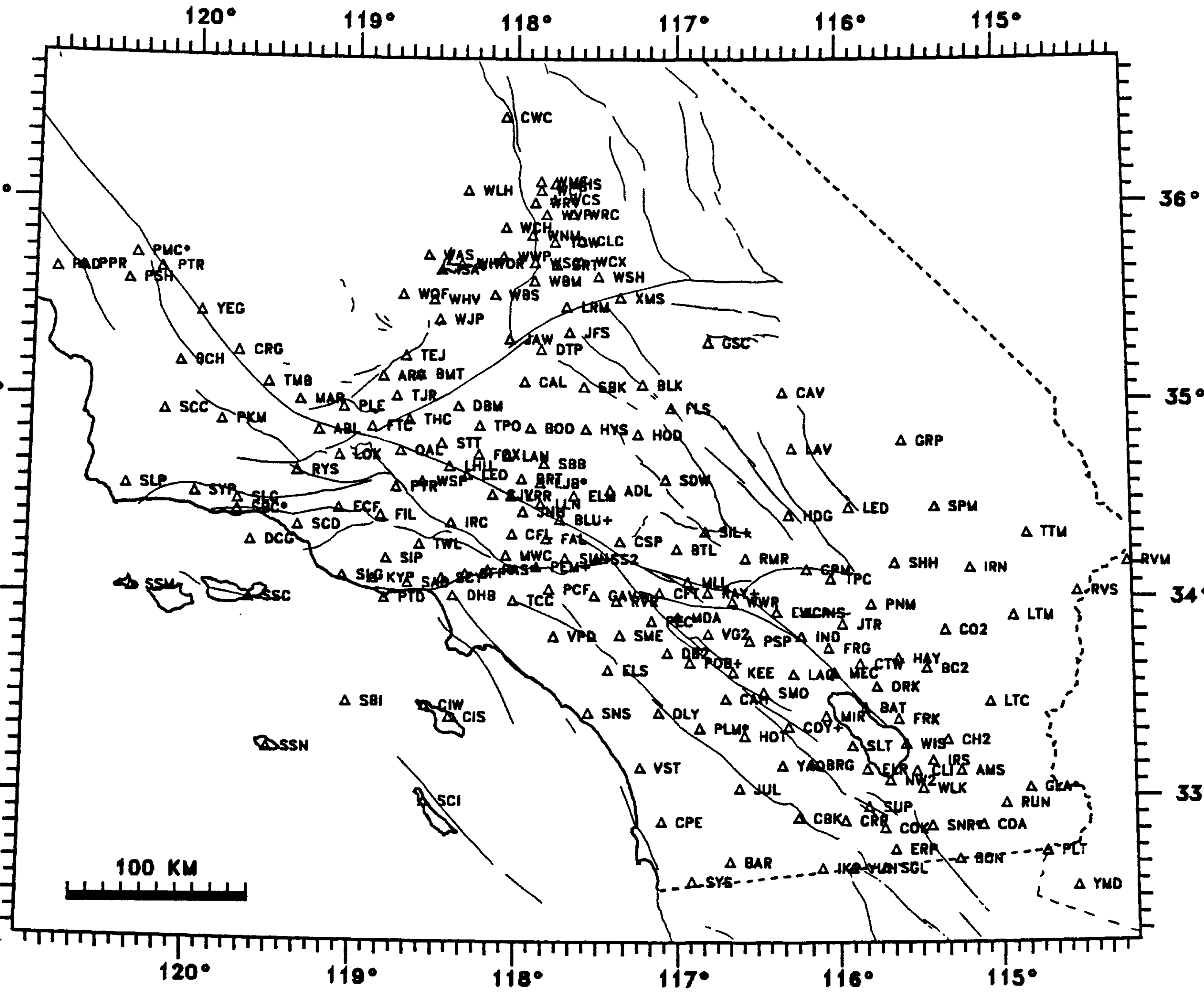

Figure 1. The Southern California Seismic Network. Station names followed by "*" have horizontal components; stations followed by "+" have a low gain component.

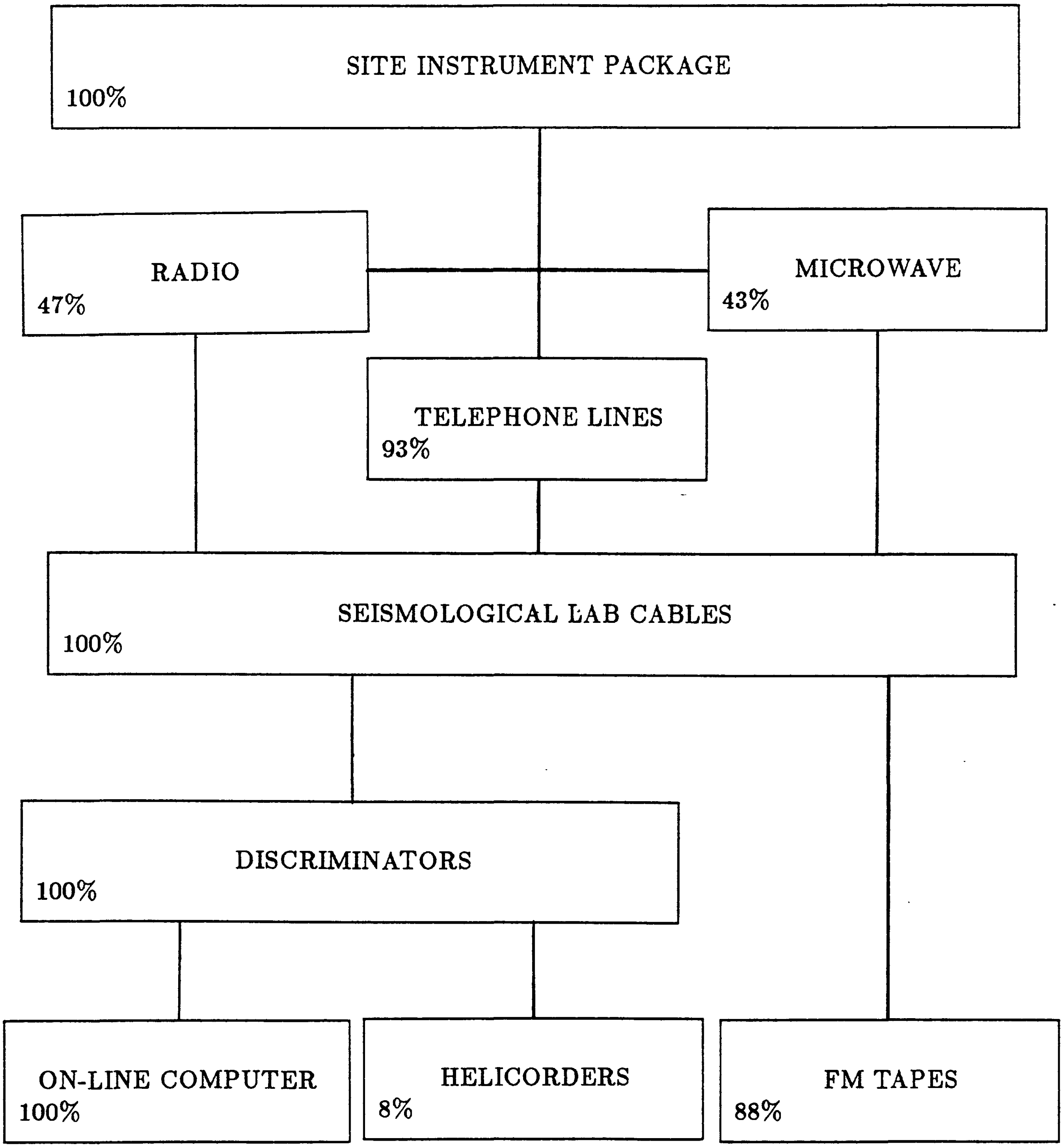

Figure 2. Schematic diagram of the Network telemetry path. Data flows from the top toward the bottom. Numbers in lower left-hand corners of boxed represent percentage of all Network signals passing through each node in the chart.

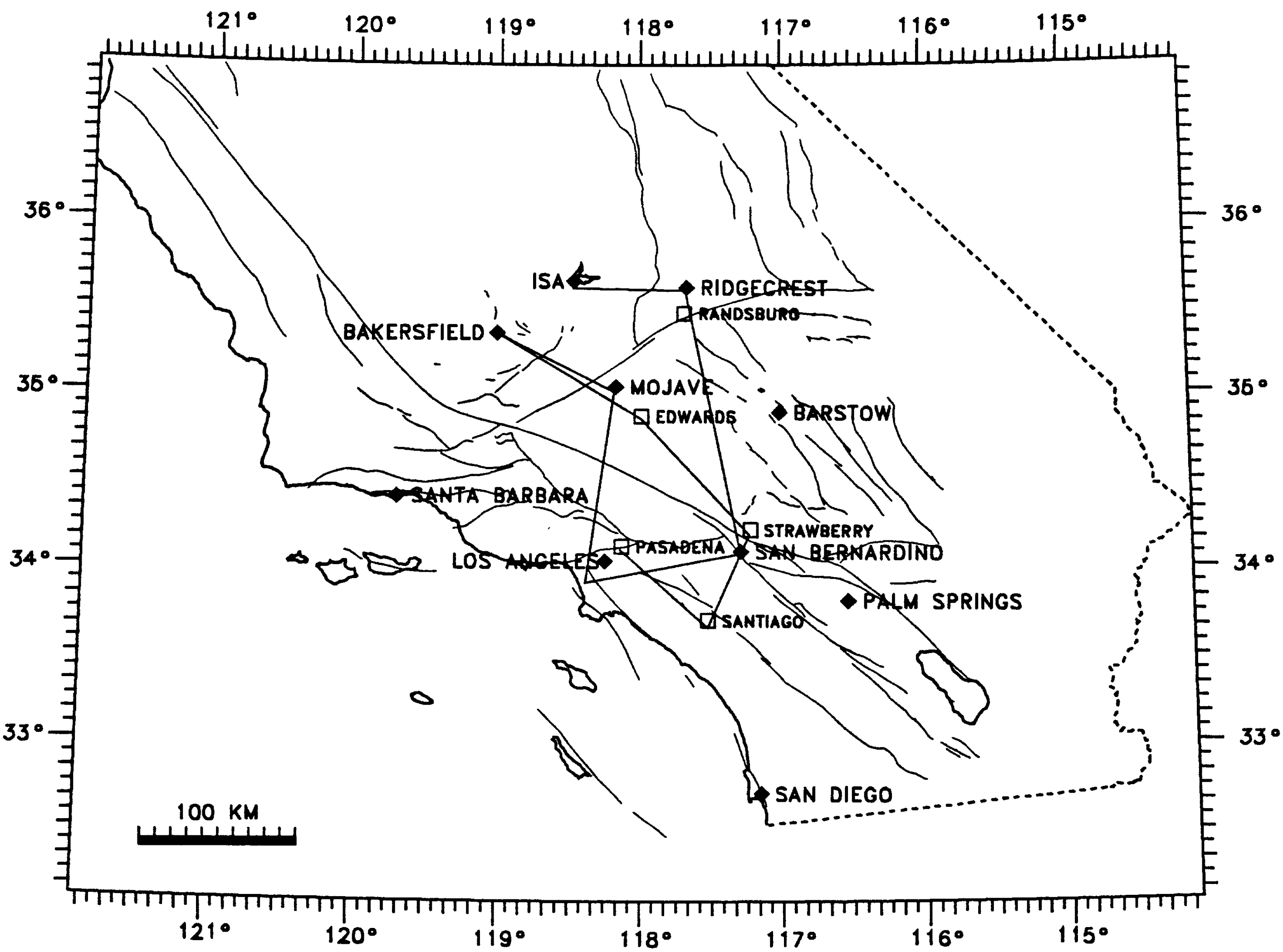

Figure 3. Physical data path of signal from station ISA to Pasadena. The signal is carried by leased telephone line from ISA to Edwards. From Edwards it is carried on the U.S.G.S. microwave (open boxes). The physical distance traveled is about ten times the line-or-site path.

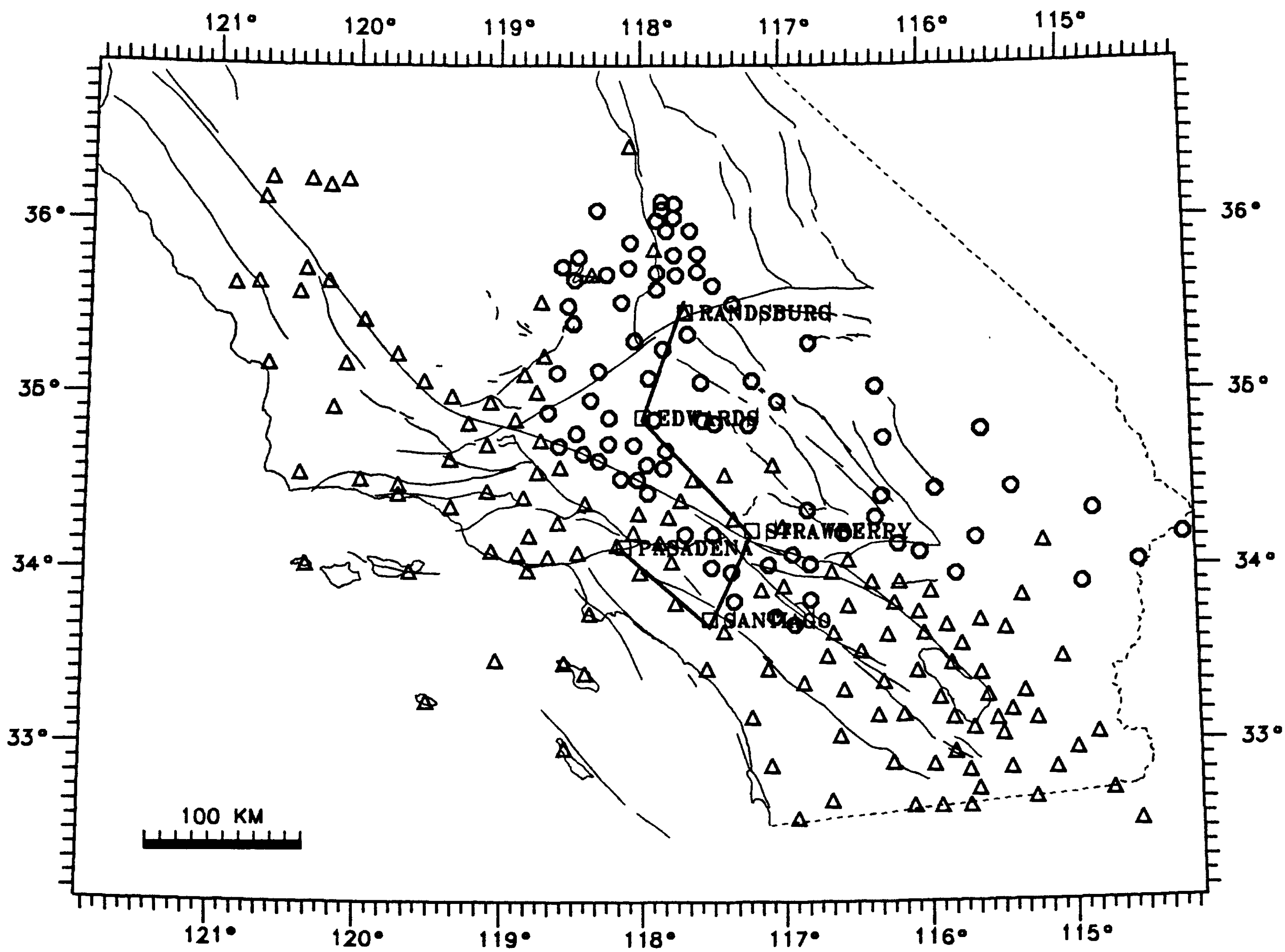

Figure 4. U.S.G.S. Microwave network in southern California. Open squares represent microwave relay sites. Stations indicated by circles are carried on the microwave system for at least part of the distance to Pasadena (43% of the network). Triangles represent stations that are not dependent on the microwave.

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        ESTIMATED PERFORMANCE OF CRITICAL DATA LINKS

   MAGNITUDE OF EVENT            5.0  5.5  6.0  6.5  7.0  7.5  8.0  8.5
.....................................................................

SITE INSTRUMENTATION             -----------------------------========

RADIO TELEMETRY                  --------------------------===========

TELEPHONE TELEMETRY              ---------------============#########

MICROWAVE TELEMETRY              ---------------=====#################

SEISMOLOGICAL LAB HARDWARE       -----------------============########

LABORATORY POWER                 ----------------============#########

AMPLITUDE SATURATION             =================####################

DATA RATE SATURATION             ---------============################


SHORT TERM DATA PROCESSING       ---------------==============########

LONG TERM DATA PROCESSING        =============########################
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Figure 5. Graph of estimate of performance of various network components in the event of earthquakes of different magnitudes. (-) = no impairment, (=) = some impairment, (#) = significant impairment.