# Optical Instrument Survival In A Major Earthquake

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# Optical instrument survival in a major earthquake

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## Abstract

Many organizations presently are evaluating the potential loss to plant, equipment and production capability in event of a major earthquake in their area. Often it is found that equipment can be protected at a fraction of the replacement cost. The paper discusses ground accelerations, seismic probability and certain characteristics of earthquake ground motion. Methods for determining loads from the Uniform Building Code and acceleration response spectrums are explained. Protection techniques for optical equipment are presented including rigid anchors, snubbers and sensing systems. The paper is for optical engineers and managers, with no particular background in seismology or structural engineering required.

## Introduction

The devastation caused by earthquakes has been recorded throughout man's history. However, it was not until the San Francisco earthquake of 1906 that it was clearly recognized that earthquakes were caused by slippage along a fault in the earth's crust. Since that time a great deal of information has been gathered to help us better understand the earthquake mechanism, and to protect lives and property. Most of the emphasis in the area of protection has been in the design and construction of structures. Less attention has been given to the protection of machinery and equipment, but the monetary loss for repair and down time of these items can approach that for structures.

Many optical devices are particularly vulnerable to seismic damage. Included in this category are telescopes, collimators, solar concentrators, heliostats, solar simulators, test instruments, mask making equipment, Schlieren systems in wind tunnels and ground based laser systems. In evaluating the potential monetary loss it is necessary to consider both cost of replacement or repair as well as loss in down time. Usually the latter item is more significant, because of the long lead times required to replace a large lens or mirror. Even if components are undamaged, it is often very time consuming to realign a precision optical device and return it to working order. Adequate seismic protection can be provided to these items during design at relatively insignificant cost. Many devices that are insufficiently protected at present can be retrofitted quite easily. Some understanding of the forces experienced during a seismic event will be discussed, and generalized design techniques for resisting these forces will be examined.

## Seismology

An earthquake occurs when internal stresses within the earth's crust increase to the point where the rock can no longer withstand the imposed loads. Rupture generally occurs along a plane. Large earthquakes are associated with slippage planes of great area, and also have a long duration. The Richter magnitude is a measure of the total amount of energy released during an earthquake. The Richter scale is logarithmic to the base ten so a difference of one on the magnitude scale corresponds to a tenfold difference in energy release. The 1964 Alaska earthquake had a magnitude of 8.4 on the Richter scale and a fault slippage length of approximately 450 miles.[1] Earthquakes of this magnitude may exhibit severe shaking for a time interval of the order of thirty seconds. If an earthquake is below magnitude 5.0 the occurrence of structural damage is unlikely. Such an event might have a fault length of a few miles and a duration of only two to three seconds.[1]

It is interesting to estimate the frequency of occurrence of earthquakes in various regions. Table 1[1] shows the number of earthquakes to be expected in California, an area of about 150,000 square miles, as a function of Richter magnitude. The high magnitude earthquakes, upon which design criteria are based, are from worldwide frequencies, because data on large magnitude quakes in the United States is sparse.

It can be argued that because of the size of California, the chances of being effected by one of these earthquakes at a particular location is even more remote. However, if that location is in an area of high seismicity the chances will correspondingly increase.

Table 1. Expectation of Earthquakes in California (150,000 sq. mi.)[1]

| Magnitude | Number per hundred years |
|---|---|
| 4.75-5.25 | 250 |
| 5.25-5.75 | 140 |
| 5.75-6.25 | 78 |
| 6.25-6.75 | 40 |
| 6.75-7.25 | 19 |
| 7.25-7.75 | 7.6 |
| 7.75-8.25 | 2.1 |
| 8.25-8.75 | 0.6 |

It is a well known fact that certain areas of the continental United States are more likely to experience seismic activity than other areas. Figure 1[2] is a "seismic risk" map of the United States identifying five different zones of seismic activity. Zone zero is an area where little damage from earthquakes is expected to occur. Zone 4 is an area near major fault systems where severe damage may be expected to occur with reasonable frequency. Most of urban California, parts of Nevada and the area around Anchorage, Alaska (not shown) are in zone 4.

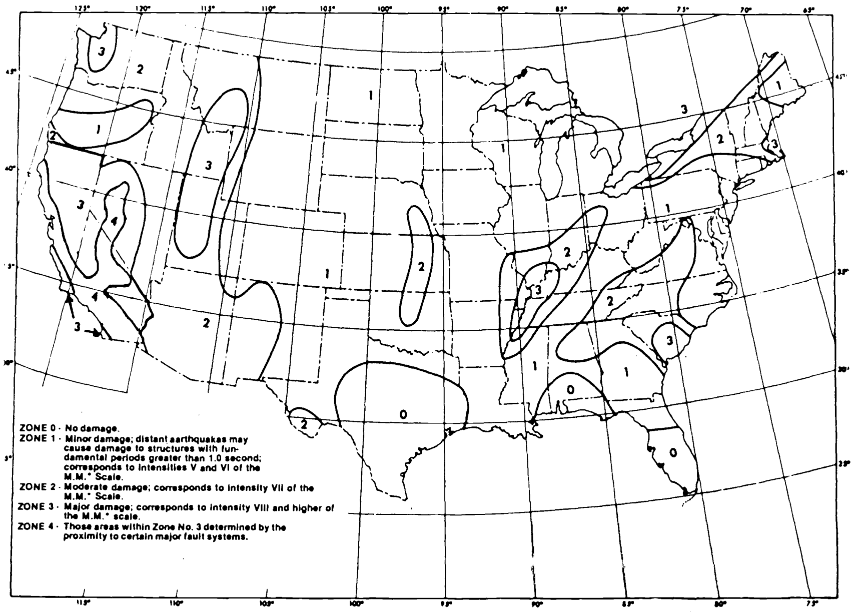


Figure 1. Seismic risk map of the United States.[2]

An accelerograph is a recording instrument that measures acceleration as a function of time during an earthquake. The record produced is called an accelerogram. Figure 2[3] is an accelerogram for two orthogonal horizontal components and the vertical component of the 1971 San Fernando, California earthquake recorded on the first floor of a building in downtown Los Angeles, approximately twenty-six miles from the epicenter. This earthquake was of magnitude 6.4. A maximum horizontal acceleration of 0.16g and vertical acceleration of 0.03g was observed at this station. Notice that the vertical motion is relatively regular for the strong motion duration, while the horizontal motions are initially low, increase abruptly to near maximum and then gradually decay until the activity subsides. This "signature" of the horizontal motion is typical of most strong earthquakes.

When a fault below the ground slips, the energy released is transmitted through neighboring rock material by seismic waves. These waves are in two forms, P or pressure waves and S or shear waves. The P waves travel faster through the rock than the S waves, and therefore arrive at a distant accelerograph sooner. The P waves are also of generally lower magnitude than the S waves. The vertical motion tends to be dominated by the P waves, while the horizontal motion is dominated by the S waves. The time lag between the arrival of the P and S waves is illustrated clearly on the accelerogram of Figure 2. This time difference allows the seismologist to estimate the distance from the recording station to the earthquake epicenter. It is important to note that the faster moving P waves can

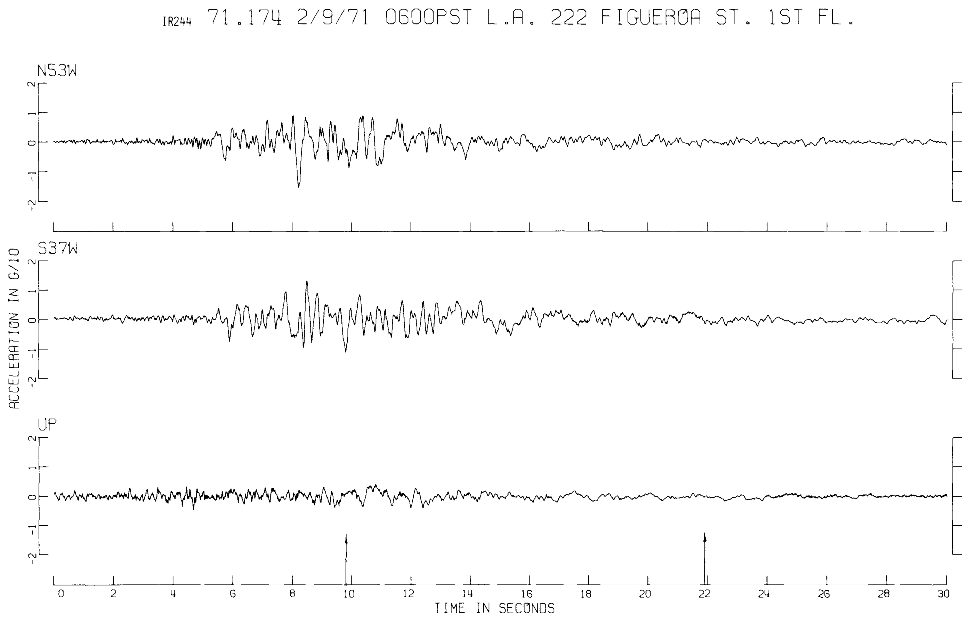


Figure 2. Typical accelerograph record.[3]

provide a warning of up to several seconds before the more destructive S waves arrive. The warning time increases as the distance from the epicenter increases.

The nature of seismic waves can also be used to explain why some areas may receive severe surface shaking while other nearby areas might receive less shaking from the same earthquake. The rock in the earth's crust acts as a transmission path for the waves generated by the release of energy associated with an earthquake. The waves travel through the rock until they reach the surface or until they encounter a softer alluvium layer. The wave speed in the alluvium is considerably slower than in rock, and the nature of the associated ground displacement is changed. Local soil conditions may have a strong influence on the severity of ground shaking during an earthquake.

Of more concern than the Richter magnitude of an earthquake to the engineer or designer is the magnitude of the ground motion during an event. One measure of the magnitude of ground motion is the maximum acceleration experienced during the shaking. Table 2[1] shows the maximum ground acceleration that might be expected to occur in the vicinity of fault slippage for earthquakes of varying Richter magnitude. The values given are based on historical observations which are quite limited in the case of larger magnitudes. Indeed, some recently recorded earthquakes have exhibited maximum accelerations in excess of the values given. Accelerations are commonly expressed in "g's", where one g is an acceleration that generates a force on an object equal to the weight of the object. Ground accelerations generally decrease as the distance from the causative fault increases.

Table 2. Maximum Ground Accelerations During an Earthquake[1]

| Magnitude | Maximum Acceleration (g's) |
|---|---|
| 5.0 | .09 |
| 5.5 | .15 |
| 6.0 | .22 |
| 6.5 | .29 |
| 7.0 | .37 |
| 7.5 | .45 |
| 8.0 | .50 |
| 8.5 | .50 |

The maximum ground acceleration does not provide an adequate description of an earthquake for design purposes. To become meaningful the maximum acceleration must be associated with some measure of the frequency content of the ground motion. The predominate frequencies for earthquake ground motion generally lie in the range of 0.05 to 10 Hz.

Design to resist earthquake damage

It is important to understand how a piece of equipment behaves when the floor on which it rests begins to vibrate. Items of equipment can often be modeled as a mass, m, attached to a support having a stiffness, k, as shown in Figure 3. If the floor beneath the spring vibrates with an acceleration time history, a(t), a relative displacement time history, x(t), will occur, and the support will exert a restoring force on the mass. The maximum restoring force will occur when the displacement is maximum, and this is the force used in design. Associated with every system which can be modeled as in Figure 3 is a natural frequency and damping which are independent of the excitation. The natural frequency is the frequency at which the mass will vibrate if it is deflected and suddenly released. Damping is a measure of the energy dissipated by the system during its motion and is usually expressed as a percent of critical damping.

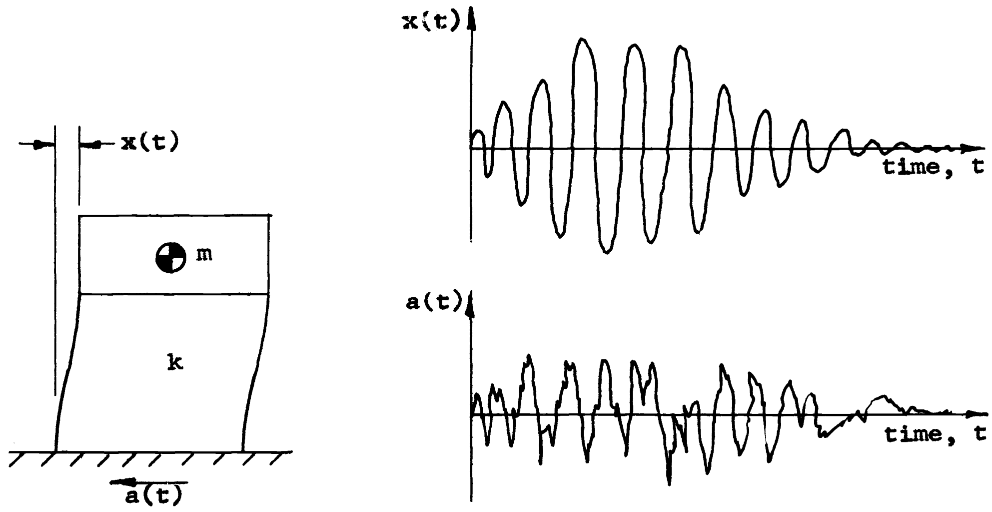


Figure 3. Excitation of a spring mass system.

Several design techniques are available for determining the maximum restoring force that an optical device will experience during an earthquake. One of the most commonly used is the design formula presented in the Uniform Building Code.[2] In this code a static lateral force is specified to be applied to the center of mass of the equipment. This force is given by the formula:

$$F_h = ZICW \qquad (1)$$

In this formula Z is a factor for the seismic zone taken from Figure 1. Factor Z has a value of 0, 3/16, 3/8, 3/4 or 1 for zones 0, 1, 2, 3 and 4 respectively. The factor I is an importance factor, and is assigned a value of 1.0 or 1.5 depending upon whether or not the equipment must remain operational immediately after the earthquake. Factor C is the horizontal force factor having a value of 0.3. The weight of the equipment is represented by W. The force $F_h$ is to be applied in any horizontal direction at the center of mass of the equipment. The largest force was revised downward from 0.75W when the Uniform Building Code was revised in 1979.

Another design technique that is coming into wider use is the response spectrum approach. This method more closely simulates actual dynamic conditions by taking into consideration the natural frequency and damping of the piece of equipment being considered. If a piece of equipment such as that shown in Figure 3 were subjected to an earthquake excitation, it would experience a certain maximum response acceleration. Another system having a different natural frequency and subjected to the same excitation would experience a different maximum response acceleration. If many systems having a wide range of natural frequencies were excited and all their maximum response accelerations were plotted, a graph called an acceleration response spectrum would be generated. A typical smoothed acceleration response spectrum plotted with log-log scales is shown in Figure 4.[4] A family of curves is created by varying the damping as well as the natural frequency.

To use this graph it is first necessary to determine the natural frequency and fraction of critical damping of the piece of equipment under consideration. The maximum response acceleration can then be read from the graph. Since the acceleration of the equipment center of mass is directly related to the total force acting on the mass through Newton's

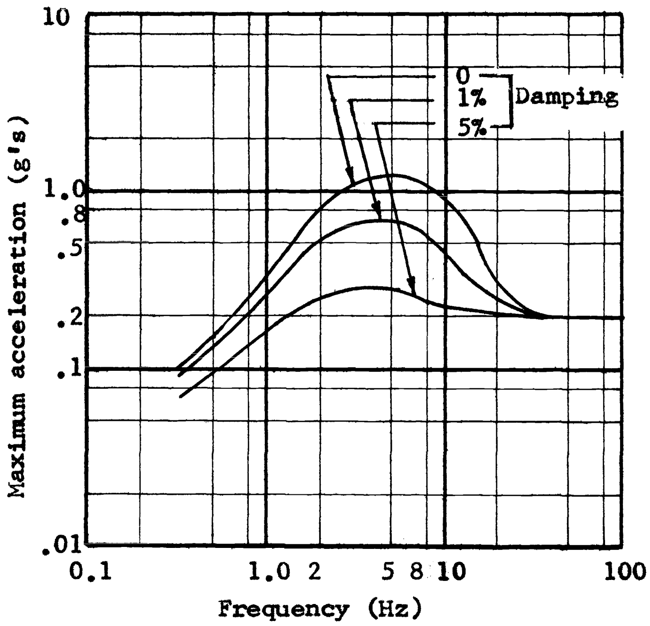


Figure 4. Acceleration response spectrum.[4]

Second Law, the total effective horizontal force, $F_h$, which must be carried by the equipment support will be

$$F_h = Wa_{max} \tag{2}$$

where $a_{max}$ is the maximum acceleration in g's and W is the equipment weight. If the response spectrum for the equipment location is known, equation (2) may be used in place of equation (1) to determine the design loads on the equipment support anchorage. It is noted from the response spectrum of Figure 4 that the design lateral load of an item of equipment may be greater than the weight of the equipment. Also the lowest loads are experienced by either very rigid or very flexible systems, with the highest loads occurring in the frequency range of 1.0 to 10 Hz.

## Protection techniques

Once the design loads have been determined, either from code requirements or the design response spectrum, the equipment support and anchorage system must be designed to withstand these loads. Equipment support systems are often designed with insufficient regard for lateral loads and must be strengthened. Regions of potentially high load should be determined and these regions reinforced by appropriate measures. Consideration may also be given to stiffening the support structure so as to increase the system natural frequency, and thereby reduce the required load carrying capacity of the support structure.

In the design of anchorage systems both horizontal and vertical loads must be considered. A simple model of an equipment system is shown in Figure 5. Let it be assumed that there are four points of anchorage in a rectangular pattern. Then, the maximum anchorage reaction forces at each support are generally assumed to be given by the following relationships (assuming no slipping at the anchors):

$$H_a = H_b = F_h/4 \qquad \text{(Maximum Shear)} \tag{3}$$

$$V_a = \frac{1}{2(b+c)}\left[F_h h + (F_v - W)c\right] \qquad \text{(Maximum Uplift)} \tag{4}$$

$$V_b = \frac{1}{2(b+c)}\left[F_h h + (F_v + W)b\right] \qquad \text{(Maximum Down Force)} \tag{5}$$

In equation (5) the vertical force, $F_v$, has been assumed to act downward instead of upward as shown in Figure 5.

The two components of horizontal force which result from this formula should be combined in an appropriate manner. The vertical force is assumed to act simultaneously with the horizontal forces. The value of $F_v$ is variously taken to be between zero and 0.67 $F_h$ depending on the design approach adopted.

Optical devices that are extremely fragile or have sensitive alignment systems often can not be rigidly anchored to the floor. If they are, the motion of the floor will be transferred directly to the instrument, possibly causing internal damage. One way of solving this problem is to mount the unit on swivel casters. During an earthquake the floor will move beneath the casters while the equipment remains relatively stationary. Vertical motion will still be transmitted, however, and must be taken into account. A limitation to this design approach is that the device must be some distance from walls or other objects that move with the floor, otherwise the equipment may impact these objects and sustain damage.

Some optical instruments are mounted on air or other low frequency isolators to prevent extraneous vibrations from disturbing their operation. Such instruments cannot be tied down rigidly or mounted on casters. In these cases snubbers may be used. A snubber is a restraint mounted in close proximity to the instrument, usually having a neoprene or similar contact surface. During normal instrument operation the snubber will not contact the device. However, during an earthquake the snubber will constrain the device while limiting the transmitted forces. The design of a snubber system is a nonlinear vibration problem, and is best solved by the use of a computer. In general the smaller the gap between snubber and instrument, the lower the contact force. A typical snubber design is shown in Figure 6.

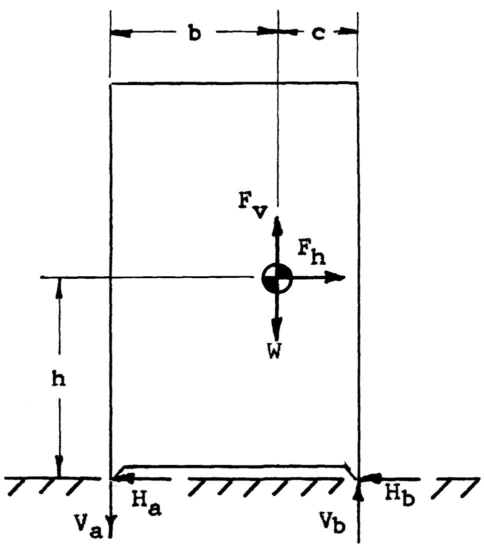


Figure 5. Loads on equipment supports.

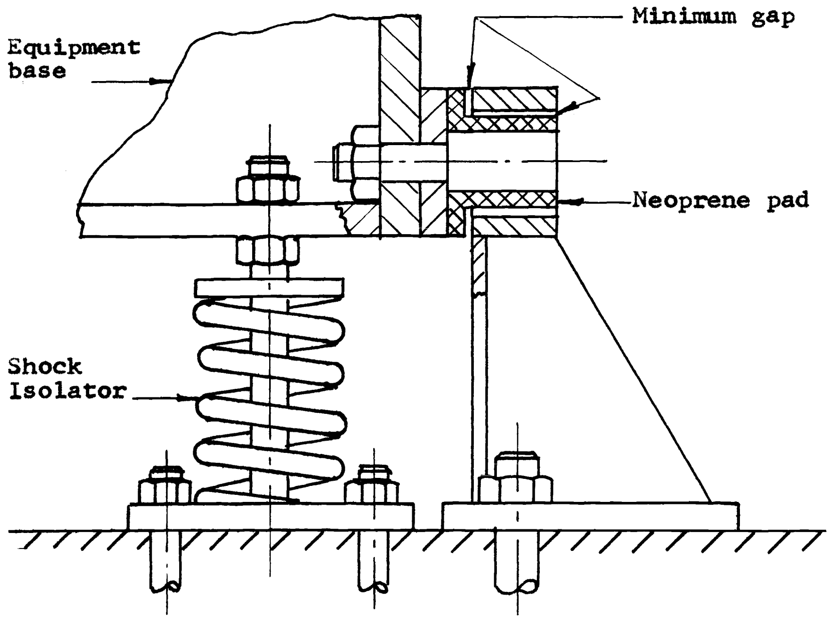


Figure 6. Snubber design.

The methods just discussed are categorized as passive protection techniques. There is one active protection technique that has attracted some attention. If the fast moving, low magnitude P wave is detected, there may be sufficient warning to shut down any critical processes, disconnect high voltage power systems, close pipeline valves or activate snubbing systems before the destructive S wave hits. With the wide use of microprocessors, many instrument functions are now computer controlled so that the only new equipment required would be a ground motion sensor. These sensors are called seismic triggers. Their threshold is set above the level of ambient vibrations induced by passing trains, starting machinery or other noise sources; but low enough to detect the P wave of a reasonably large earthquake. The limitation of these devices is that they would be relatively ineffective for very nearby events where the warning time is short.

The cost of providing seismic protection varies greatly. For new designs the cost is usually negligible compared to the cost of the instrument. For existing equipment, if supports are accessible and foundations adequate, it can be a simple matter to provide adequate anchors or install casters. However, if the supports are inaccessible or specialized snubbers are required, the time and cost of retrofitting may be substantial. This cost must be weighed against the probability of an earthquake occurring, and the cost of replacement or repair in event it does occur. In determining replacement or repair costs the most significant factor is usually the down time.

Of more importance than the equipment, of course, is the possibility of injury or death to personnel. Many injuries in earthquakes are from falling structures or objects. Instruments with high centers of mass and narrow bases may tip and fall on workers in the immediate vicinity. High voltage power systems and caustic chemicals are also potential safety hazards. A well designed seismic bracing and anchorage system may pay for itself many times in the event of a severe earthquake, and will provide a safer environment in which to work.

## References


1. Housner, G. W., "Strong Ground Motion." Chapter from Earthquake Engineering, Prentice Hall, 1970.
2. Uniform Building Code, 1979 Edition. Published by the International Conference of Building Officials, Whittier, California.
3. "Strong Motion Earthquake Accelerograms," Report No. EERL 73-23, California Institute of Technology, July 1974.
4. Housner, G. W., "Design Spectrum." Chapter from Earthquake Engineering, Prentice Hall, 1970.


**Question:** When you talk about a design recommendation for snubbers as something we could use, do you have any more relative to the use of analytical models for things like large ground base telescopes (i.e., NMMT) to see how well they would perform in earthquake environments?

**Answer:** Well, I worked on a 100 inch Dupont telescope for Carnegie. We used the snubbing technique for the mirrors you're talking about. A 16th of an inch away from the mirror surface we put a stop with a nylon pad and this is one approach you can use.

**Question:** Have any large optics been monitored under an earthquake?

**Answer:** There was a small earthquake at Big Bear that caused some structural damage on a solar telescope about 8 months ago. I didn't find out what the details on that were. There were no mirrors broken. Also, in 1971 there was an earthquake that did some damage to a solar telescope.

**Question:** The laser fusion project in Livermore—I understand some mirror mounts were recently damaged?

**Answer:** I haven't heard much about that, it's so recent there hasn't been anything published on it. We've been doing some work in the San Jose area. I was up in San Jose when the earthquake occurred and it was quite mild. Apparently it wasn't so mild at Livermore.