Proceedings of the

GOLDEN ANNIVERSARY WORKSHOP ON STRONG MOTION SEISMOMETRY

March 30-31, 1983

Sponsored by the
University of Southern California
and the
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Introduction

March 10, 1983 was the 50th anniversary of the first strong motion accelerograms which were obtained during the Long Beach Earthquake of 1933. This was the first time that destructive earthquake ground motion had been directly measured and represents a most important milestone in the development of Earthquake Engineering.

To commemorate this notable event a two-day invitational meeting on Strong Motion Seismometry was held at the University of Southern California under the sponsorship of the National Science Foundation. Featured at this meeting were historical papers on the development of the subject presented by a number of pioneers in the field, an exhibit of early instruments together with examples of the latest technology, and a series of five panel discussions concentrating on current problems and future prospects.

The present proceedings volume contains the complete text of the historical papers, and of the technical review papers which supplied background material for the panel discussions. A description of the exhibits is also included, with a selection of pictures illustrating the evolution of the instrumentation. Finally, the panel discussions are summarized, with the main conclusions being given, based on a transcript of a complete tape recording of the sessions.

The instrumental side of earthquake engineering has profited much from the cooperation of three different types of organizations -- government agencies, universities, and instrument manufacturing companies. All of these groups were well represented at the workshop. A number of the early field staff personnel from the old U.S. Coast and Geodetic Survey were participants, as well as representatives of the present activities centered in the U.S. Geological Survey. The National Oceanic and Atmospheric Administration presented information on its current data archiving and dissemination of basic data in the field.

Of utmost importance to our subject has been the role played by the National Science Foundation, which has been for the past 20 years or so the main source of research support. The efforts of a devoted group of NSF program directors who have taken a personal as well as professional interest in the work should be specially mentioned. Among them are several persons often mentioned in the course of the workshop business -- M.P. Gaus W.N. Hakala, S.C. Lui, and J.B. Scalzi. Without the direct participation and sponsorship of NSF it would not have been feasible to organize the workshop.

It is a pleasure to acknowledge the assistance of many people who helped with various phases of the meeting. We are much indebted to Professor Bruce A. Bolt, Professor Wilfred D. Iwan, and to Mr. Harry T. Halverson for their interesting and informative talks at our evening dinner session. In addition, Professor Bolt added significantly to our instrument exhibit by displaying during the evening a beautifully made working model of the first instrument for measuring earthquakes -- the seismometer of Chang Heng which dates from 132 AD -- which he had just brought back from China. Thanks are also due to Dr. Melvin Gerstein, Dean of the School of Engineering at the University of Southern California for his support and participation, and to the staff of the

Davidson Conference Center for their assistance with many details of the conference planning. Professor M.D. Trifunac and his students were a mainstay in many aspects of the meeting. Special appreciation is expressed to Professor Sami F. Masri for assistance with the arrangements for the meeting and for publication of the proceedings.

GENERAL PROGRAM

GOLDEN ANNIVERSARY WORKSHOP
on
STRONG MOTION SEISMOMETRY

March 30-31, 1983

Davidson Conference Center, University of Southern California

<u>Wednesday, March 30, 1983</u>

8:30 a.m.	Registration
9:00 a.m.	Opening Session - Introduction to the Workshop
9:30 a.m.	The First Accelerograms
	Historical Background The Long Beach Earthquake The USCGS Strong Motion Program
10:30 a.m.	Introduction to the Exhibits - Break
10:45 a.m.	History of Accelerograph Development
11:15 a.m.	History of Accelerogram Data Processing
11:45 a.m.	Lunch - Town and Gown Foyer
2:00 p.m.	Background Papers for Workshop Topics
	I Strong Motion Instrumentation Systems II Existing Networks and Arrays in the U.S. III Field Reliability and Maintenance
3:30 p.m.	Break
3:45 p.m.	IV Data Processing
	V Data Storage, Retrieval, and Dissemination
5:30 p.m.	Informal Reception - Faculty Center
6:30 p.m.	Dinner - Faculty Center

Thursday, March 31, 1983

9:00 a.m.	Workshop Panel Sessions	
	I	Strong Motion Instrumentation Systems
10:00 a.m.	II	Existing Networks and Arrays in the U.S.
11:00 a.m.	Break	
11:30 a.m.	III	Field Reliability and Maintenance
12:45 p.m.	Lunch - Town and Gown Foyer	
2:00 p.m.	IV	Data Processing
3:00 p.m.	V	Data Storage, Retrieval and Dissemination
4:00 p.m.	General Summary and Conclusions	

Meeting concluded by 4:30 p.m.

* * * * * *

HISTORICAL BACKGROUND

EARTHQUAKE ENGINEERING - SOME EARLY HISTORY

by

George W. Housner
California Institute of Technology

I should like to talk today about the founding father of the strong motion program in the United States - John R. Freeman. He was a remarkable man, and the more I have learned about him the more impressed I have become. Figure 1 depicts him at the age of 70 and it shows you the sort of person he was - clearly not the type to take no for an answer. He really pushed something if he became interested in it. He was particularly friendly with Prof. Kyoji Suyehiro, the first Director of the Earthquake Research Institute at Tokyo University (Fig. 2), and with Prof. R. R. Martel of Caltech. Figure 3 is a picture taken at Caltech in 1932, at the time Prof. Suyehiro was visiting the United States, and it shows Martel, Suyehiro, Beno Gutenberg and John Anderson. John Freeman was really a very remarkable fellow. In earthquake engineering he had many accomplishments. He wrote a big book "Earthquake Damage and Earthquake Insurance." He said that he got really interested in earthquakes in 1925. It was the Tokyo earthquake of 1923 that awakened interest in this country, and then in 1925 came the Santa Barbara earthquake. Also, in 1925 an earthquake on the East Coast centered near Quebec was felt in Boston where John Freeman lived, which he said was what got him interested. He then sent his assistant to the public library to bring back all the textbooks on structural engineering and he looked through them and found that there was only one book that even mentioned earthquake forces. He said that it was clear to him that the subject was in real bad shape.

In the late 1920's there was a big engineering conference in Tokyo and this was attended by John R. Freeman and Prof. Martel, and it was at this time that they met Suyehiro, and these three seemed to have hit it off very well. As a consequence, John Freeman arranged, and paid for Suyehiro to come to the U.S. and give his lectures and he paid to have the Suyahiro lectures published by the American Society of Civil Engineers. At this time he also tried to get Prof. Naito's book on earthquake engineering published. He had the translated parts reproduced and circulated. Unfortunately, he was never able to arrange for the complete translation and publication. When he was in Japan, JRF saw a tiltmeter which he thought looked like a very informative instrument for monitoring earthquake precursors. He immediately ordered one which he bought and had sent to the U.S. He also saw in Japan Prof. Suyehiro's vibration analyzer which impressed him so much that he talked the U.S. Coast and Geodetic Survey into building one. Finally, he saw the urgent need for a strong motion accelerograph and it was his persistent effort that actually got the instrument developed by the Coast and Geodetic Survey. It is very interesting to note that in spite of all of his notable contributions to earthquake engineering, the subject was not even mentioned in Freeman's obituary, which listed all the other things that he did. He began his professional life as a Civil Engineer from M.I.T. Later he became the president of an insurance company (Factory Mutual). He arranged to work only half time at the insurance business and the other half he devoted to his own research and to consulting. He did significant research on the hydraulics of fire hoses and the design of fire nozzles. If you talk to people in the fire insurance business you will find that John R. Freeman is known as the man who put the subject on a scientific basis. He served as a consultant on many major projects, for example on the Panama Canal, on the Hetch-Hetchy water project for San Francisco, on the silting of the Yangtse River in China and others. He saw the need for a hydraulics research laboratory in the U.S. and pressed the Corps of Engineers to set up the laboratory. He talked to congressmen and at one stage he thought he had it all set when it came up to Congress for an appropriation, but the Corps of Engineers said they didn't want it and that killed it. This didn't stop him, he kept right after it and eventually it was set up as a laboratory at Vicksburg, Mississippi, now the well-known U.S. Army Engineer Waterways Experiment Station. He endowed three Freeman scholarships for sending young engineers to Europe to spend a year at Hydraulic Laboratories.

If you look in his book on earthquake damage and earthquake insurance you will find that he mentions the need for an accelerograph to measure destructive ground motion and he tells what properties it should have. It should record on a continuous belt of paper, which should move at about a half inch per second or about a centimeter per second. He laid out the basic design and specifications and was responsible for getting it built. To give you a better idea of the man himself, I have reproduced at the end of these remarks a facsimile of a letter which he wrote to Prof. Martel in 1930. This letter covers so many topics which later assume great importance in the field that it is worth studying.

There are many other letters of interest from Freeman in Prof. Martel's files. For example, he sent Prof. Martel copies of the letters that he wrote to N. H. Heck, the chief seismologist at the Coast and Geodetic Survey, who he said was not a good listener. He wrote a lot of letters to Captain Patton, who was in charge of the Coast and Geodetic Survey, who he said was a good listener. He talked to him and also to the Secretary of Commerce, Mr. Lamont, and occasionally even to the President, Herbert Hoover, and he explained to them the need for doing something about earthquakes. He said in one of the letters, "I think we're making headway, I'm getting a letter from Captain Patton almost every day" and so he kept after the USGS until the accelerograph was developed. Certainly, he was the father of the strong motion accelerograph.

I think it is unfortunate that his contributions to earthquake engineering haven't been given the recognition they deserve. It is especially surprising to realize that when he started thinking about earthquakes in 1925 he was 70 years old. So this shows what you can do after 70; JRF didn't slow down at all. I think that the original accelerograph should have been called the Freeman accelerograph in recognition of the big contribution that he made. JRF's book on earthquake engineering was the first sensible one that came out in English. Those of you who have looked at it know that its typography is rather odd. In his letters he was given to underlining a statement that he wanted the reader to especially notice and in his book instead of underlining he used capital letters whenever he wanted something to be noted. Apparently, his book was criticized on this because in one of his letters he said, "Well, people criticized the typography, but I wrote the book, I edited it, I paid to have it published, I paid to have it distributed and that's the way I wanted it." I will make one additional comment about the earthquake engineering field. When I was a student in the 1930's and had to decide on doing my Ph.D. research, I said to Prof. Martel that I wanted to do something in the earthquake engineering line because that was very interesting, and he said to me, "Well, that is a very interesting subject, but I don't know if it will ever amount to anything. We have tried and tried to get things done but it has been very difficult to get anything accomplished; people seem not to be interested in the earthquake problem." I'm sorry that he didn't live to see the things that have now been done, the many instruments built and the many changes incorporated in the code.

JOHN R. FREEMAN,
CONSULTING ENGINEER,
Room 815, Grosvenor Building,
PROVIDENCE, RHODE ISLAND.

Water Supply,
Water Power,
Fire Protection,
Factory Construction

File Subject

Date January 7,1930.

In reply to yours of

Professor Romeo R. Martel,
Structural Engineering Dept.,
Pasadena, California.

air mail

Dear Professor Martel:

You will be interested to learn of my activities in earthquake matters since we parted company.

I returned to Tokyo, put in another day with Professors Suyehiro, Imamura and Ishimoto, got various other pamphlets including data on earth-tilt and copies of seismograms, and was so impressed by what was shown me about earth-tilt and the apparent confidence of these three eminent gentlemen that they had a valuable indicator in Ishimoto's new clinometer, that I placed an order for one of these to be built in the highest type of the art at their earliest convenience and delivered in good order in San Francisco to such a representative of the Seismological Society as I might advise later.

On the steamboat I loaned my collection of pamphlets to George Otis Smith, Chief of the U. S. Geological Survey and asked him to give particular attention to the demonstrations on earth-tilt and to the fact that these seismologists were focusing their attention on the tilting of the big fault blocks rather than upon single rifts, with the suggestion there might be cosmic forces at work down at the level of the plastic layer in which our isostatic friends are so deeply interested.

I urged friend Smith that his Department should undertake five or ten lines of precise levels with standard first-class bench marks at approximately right angles to the California coast line in places to be carefully selected.

At Stanford University I had a long conference with Dean Hoover and Dr. Townley, Secretary of the Seismological Society, in which I displayed various pages from my Japanese pamphlets emphasizing the fact, that whereas the American studies had been directed in the direction of pure science, geophysics and mathematical analysis of elastic wave transmission, that the Japanese had proceeded from the opposite end of the picture by putting their investigations in charge of an engineer who understood structures, stresses, waves and impacts, from having been trained as a naval constructor and as a professor of naval architecture. That, whereas, in America <u>no</u> particular study had been given to effects <u>within</u> the epicentral area or within the area of damage to structures, all of their studies commonly began a hundred miles or more away from this disturbed area (in considering their elastic waves) and with their instruments for nearby study were all set on solid rock and of such great delicacy as to be

M. JAN. 1927

To Prof. R.R.Martel,
California Tech,
Pasadena, Calif.

Subject Earthquakes

Date 1/7/30

Sheet No. 2

utterly incapable of recording the effects in any destructive earthquake; on the other hand the Japanese were concentrating their efforts within epicentral areas and to the territory within which buildings had been injured.

I told Dean Hoover that their new shaking-table at Stanford was the best and the most practical piece of earthquake apparatus that I had yet seen in America, and that I regretted to find it idle, particularly as Jacobson had made such an excellent beginning. That at Stanford was the one spot in California where no one would deny the actuality of earthquake occurrence and since it was situated only 3 miles from the greatest known active fault in America, therefore it would be a good place to make observations; and I would present this clinometer (which cost me 1000 Yen) to either the Seismological Society, or to the University if they would set it up and give it an earnest trial.

I found Dean Hoover very responsive to my suggestions that our American Engineering Colleges, particularly in California, should maintain research and give instruction in the science and art of earth resisting construction. I had expected to find Professor Bailey Willis back from his world tour and hoped to also enlist his enthusiastic aid.

The next day at the University of California, I was a guest of the Faculty Club, where, when called upon to speak I made bold to discuss the unpopular topic of earthquakes, particularly as Professors Lawson and Joseph Lecont were present.

I stated that the data which had been given to structural engineers on acceleration and limits of motion in earthquakes as a basis for their designs were all based on guesswork, that there had never yet been a precise measurement of acceleration made. That of the five seismographs around San Francisco Bay which tried to record the earthquake of 1906 not one was able to tell the truth. I told of Suyehiro's demonstration of rocking motion for rigid buildings and of his demonstration that the best ordinary seismographs gave erroneous records as to limits of motion when affected by a sidewise tilt, etc. etc.

By way of starting a little rivalry in research as well as in athletics, I told of my conference with Dean Hoover and his hearty response in favor of finding out accurately some of these things on which structural engineers must base their designs.

Next, I had talks with Huber and a particularly long and interesting talk with Dewell, showing Dewell my Japanese pamphlets and turning the pages of the proof of my forthcoming book. Dewell loaned me his translation of Naito's book on earthquake resisting structures, and I have had this blue printed for distribution among a small group of interested engineers. I am sending you a copy and am sorry that the original typewriting did not permit clearer blue prints.

I have suggested to Dewell, that you and he ought each try your hand at writing a preliminary introductory chapter to this book, making plain that it is not forbidding or incomprehensible, as a quick turning of the pages might lead the ordinary non-mathematical prodidgy of an engineer to suspect. (This copying has cost me about $160. which seems absurdly

To Prof. R. R. Martel,
California Technology,
Pasadena, California.

Subject: Earthquakes | Date: 1/7/30 | Sheet No. 3

high, but I am glad to contribute anything in reason to the promotion of this good cause).

Sunday, I lunched with Dr. and Mrs. Millikan at Pasadena, and showed Dr. Millikan the interesting pages of my Japanese pamphlets, and made plain to him that the engineer could hope for little from the geophysical organization, since they had a definite line of problems all mapped out, which called for more money than they had in sight. I urged that we had got to arouse research on the practical side, particularly among the engineering schools of California, and expressed my appreciation of what you had been doing and of the work by Jacobson at the Stanford shaking-table.

Dr. Millikan told me that he had kept close watch on the procedures of the Seismological Association at its recent conference at Wood's laboratory. That he now had funds in sight for undertaking some practical researches, and that your trip to Japan had been fostered as a first step in this direction. (I congratulate you heartily on your opportunity).

Next, I called again on Harry Wood at his laboratory, and outlined the situation as I had found it in Japan, and asked if it were not in some way practicable to interest the geophysical laboratory and the Carnegie Institute on the practical side of the field. He told me what I had surmised, that they had a definite line of research all mapped out, for which they had scant funds, and to which it would be doubtless found advisable that they confine all their energies, or, in brief, that for our practical Japanese type of investigations of conditions within the area which is damaged and for the measurement of acceleration, limits of motion, rocking motion and keynote of mobile basins of mud, such as revealed by Suyehiro's seismic analyzer, we must seek funds from those engaged in the structural arts.

Next, I visited the Bureau of Standards at Washington and went into conference with Dr. Burgess and Dr. Wenner, the inventor of their new, beautiful seismograph, and urged that their attention be given toward devising an accelerometer, and described the one which I saw under construction in the laboratory at the Imperial University, having a pendulum weighing apparently more than a ton, and which Ishimoto apparently feared would not be a success. I also urged the importance of an instrument which would measure accurately the vertical motion which accompanies the horizontal motion, and which Suyehiro seemed to think played an important part in overturning monuments.

Then, I called at the Coast Survey, got Dr. Bowie, Chief Geodesist and Dr. Heck, Chief of Seismology together and repeated my story, again exhibiting the Japanese pamphlets and urging that Dr. Heck in particular should get busy in the practical end of the field, instead of working only with the geophyscists and high-brows. I don't think I made very much of a dent in the armor of these two friends, but shall keep on trying.

I am sending to you herewith a copy of Dr. Naito's paper on the reconstruction in Japan after the quake of 1923, and will mail the blue print of Naito's book as soon as copying the figures is completed.

To Prof. R. R. Martel,
California Tech.
Pasadena, California.

Subject Earthquakes

Date 1/7/30

Sheet No. 4

Meanwhile Seabury tells me that he has been following up my suggestion of obtaining contributions from the National Board of Fire Underwriters for printing the A.S. C. E. Earthquake Committee Report, which he had estimated would cost $25,000. The Underwriters promised $5,000. the Steel Construction Association another $5,000. The Mutual Insurance Companies with which I am connected will give $500. and he has some more in sight. Thus, it seems the book is in a fair way toward early publication.

I shall confer with Mr. Seabury about this in New York next week, and also will try to find some means of promoting an American edition of Naito's book.

I earnestly hope that you and Mr. Dewell each can be prevailed upon to prefix introductory chapters to this book, so that we can get something out and into the hands of our technical schools without waiting until the "spirit moves you" to write a book of your own, after you have made further researches.

I also had a two hours talk with Dr. Keith, the specialist of the U. S. Geological Survey on Earthquakes.

If you, Dewell, Huber and a half a dozen others of the structural engineers of the Pacific coast will keep stirring this matter up, I am sure we shall get something started that will make structures safer and be of great public service

These eminent Japanese experts were so strongly in favor of earth-tilt measurements that I am trying to devise or get someone else to devise an apparatus less delicate than the Ishimoto clinometer, which, like it, will show differences of 1/10th of a second of arc. A fused quartz disc ground like a concave lens of great radius forming the top of a cup containing a bubble, offers one possibility.

Also, I am trying to get the Bureau of Standard people and some others to devise a reliable accelerometer. I suggest you put this problem up to your friends of the Mt. Wilson Workshops.

Dr. Millikan had the impression that the Coast Survey was already trying out some lines of precise levels for detecting earth-tilt, but Dr. ~~Bouise~~ said that they had merely established their bench marks and run over them for the first time.

Bowie

Very truly yours,

John R. Freeman

John R. Freeman/OF

cc Mr. Walter L. Huber,
Dr. Macelwane
S. W. Stratton,
Dr. Hodgson

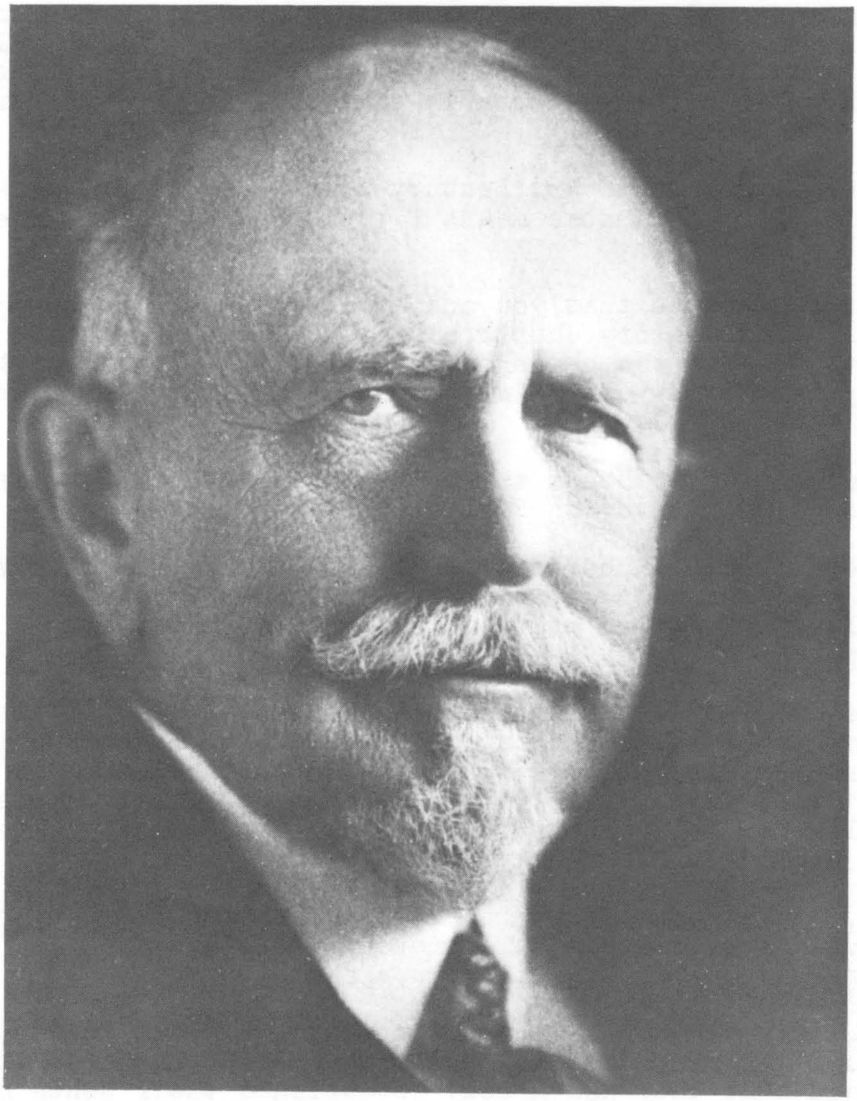

Figure 1: John R. Freeman 1855-1932

Figure 2: Kyoji Suyehiro 1877–1932

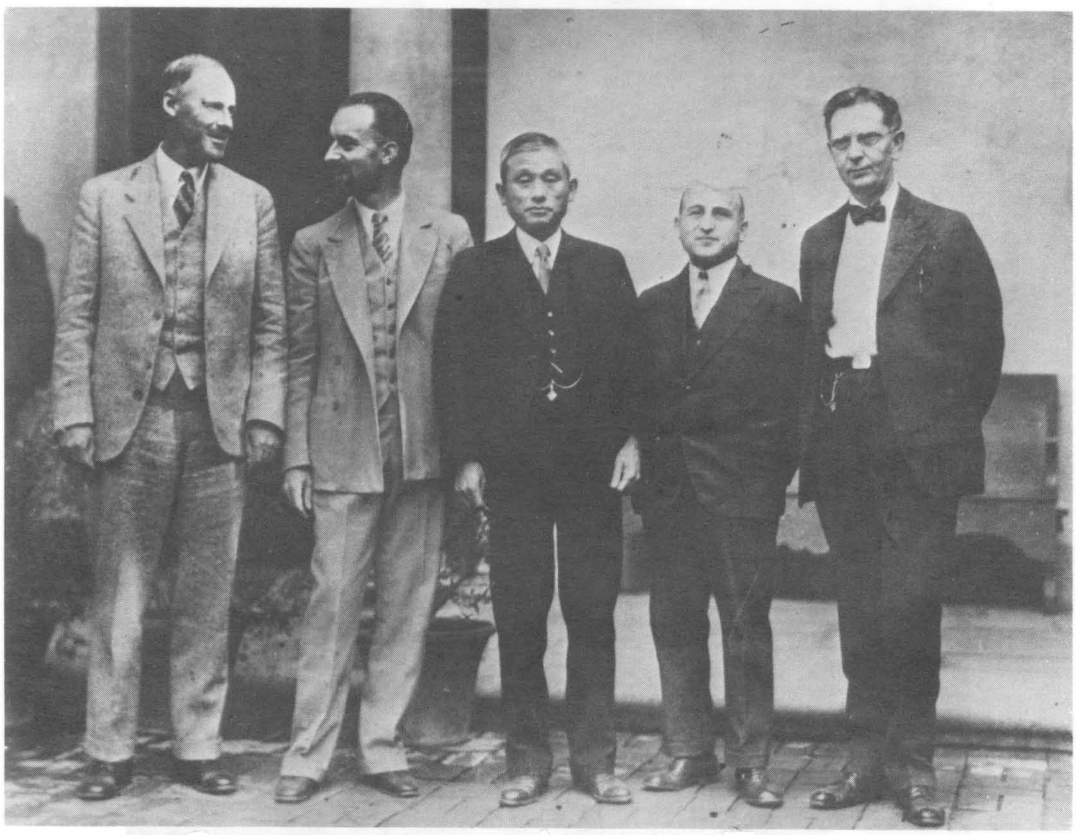

Figure 3: Left to Right: J.P. Buwalda, R.R. Martel, K. Suyehiro, B. Gutenberg, John Anderson. California Institute of Technology - 1932. Suyehiro was in the United States to give the "Suyehiro Lectures" on earthquake engineering.

THE LONG BEACH EARTHQUAKE

As a background for the story of the accelerograms of the March 10, 1933 Long Beach earthquake, a short moving picture was presented which had been filmed the day after the event, and showed typical scenes of destruction. We are indebted to Professor Paul C. Jennings of Caltech for loaning us this historic film.

The film was introduced and commented on by Mr. Edward M. O'Connor, who was for many years the Director of Building for the City of Long Beach. He is the person mainly responsible for the pioneering Long Beach program for the repair and rehabilitation of hazardous old structures. Without the example of this notable program, it is unlikely that Los Angeles could have achieved its recent progress in the development of building code requirements for the strengthening and repair of certain types of hazardous structures.

In introducing the film, Mr. O'Connor made the following remarks. "The movie was taken by an employee of the local newspaper. He went out with a 16 mm camera the day following the earthquake and shot this unedited, untitled movie. I stumbled on it through an employee of the Building Department who attended a training session. He said – say, have you ever seen this movie that Jack Emery of the Long Beach Fire Department has? I said – no – so I got interested and approached Emery. Emery was the son of the newspaper reporter who took the movie. He ended up, when his dad died, with the movie. He said that he almost threw it away. It looked in pretty bad shape so he made a decision at that time to have it refurbished, and thank God he did. It really helped me when I was really in need of something ... it was just the thing I needed at the time to reinforce my position in doing something about those old buildings."

The film proved to be an interesting and informative background for the story of the retrieval of the first significant accelerograms of destructive earthquake ground motion, made during the Long Beach earthquake. That story was presented next by Mr. Ralph S. McLean, who at that time was with the field staff of the U.S. Coast and Geodetic Survey. Mr. McLean had installed and serviced the accelerographs, and was the first man to visit the instruments after the earthquake.

THE LONG BEACH EARTHQUAKE AND THE FIRST ACCELEROGRAMS

by

Ralph S. McLean
McLean and Schultz, Consulting Engineers

The Coast and Geodetic Survey was originally responsible for the Strong Motion Program and the work of the Survey in seismology began in 1925 when the work was transferred from the Weather Bureau to the Coast and Geodetic Survey. However, the Survey had operated seismographs at its magnetic stations for 25 years before that but recording of strong ground motion wasn't undertaken until quite a few years later. At that time there were not really many engineers that were much interested in earthquake resistant design.

Earthquake insurance was being written on buildings and some insurance companies took a terrible beating in the Santa Barbara earthquake. It may perhaps be as an outgrowth of this that Freeman published his book about earthquake damage and earthquake insurance. That was in 1932 and in the book he made a very strong pitch for earthquake resistant design. As a senior at Caltech in 1929 our structures class for the first term of the year was not taught by Prof. Martel because he was in Japan to learn what he could from the Japanese who had suffered so terribly in the earthquakes of 1923 and 1927. On his return he sought support from engineers and seismologists. George Housner has told us about the correspondence with Freeman. At that time, of course, there had never been any measurements available to aid in seismic design. Of course there were a lot of other persons that were active in this field too, and I think of such people as Perry Byerly at UC Berkeley, Lydick S. Jacobsen at Stanford and Harry Wood at Pasadena at the Seismological Laboratory. The members of the Structural Engineers Association of California were also anxious to get information on earthquakes and their appeal was successful. Congress made funds available for the program in 1932. New instruments had to be designed and this was done by the Survey with the aid of various cooperating institutions, notably the National Bureau of Standards, MIT, and the University of Virginia. The automatic recorders were developed by the Coast Survey with its own personnel. One of the men involved in this work was Edward C. Robison who later came to California to install and operate the instruments. There were three types of instruments developed and there are samples of them in the display upstairs - accelerographs, displacement meters and the Weed seismographs. You can see them in the exhibit so there is no need for me to try to describe them. The instruments did not operate continuously, of course. The starters at that time were what were called Braunlich starters and you can see a couple of these in the Weed instrument in the exhibit. The starters, designed by Mr. M. W. Braunlich of MIT, were little inverted pendulums with electrical contacts at each end and they were undamped. They were not very good starters because they could be affected by things other than earthquakes and they were quite difficult to adjust. No vertical component sensors were used. At one place, however, at the subway terminal building in Los Angeles, we had a different type of starter because there the instruments were located within about ten feet of the car tracks where the heavy red cars came into the terminal.

The Braunlich starters had been sensitive to the vibrations that were produced, so they were trying out a vertical pendulum of the type that you will also see on some of those in the exhibit. On the earthquake record of March 10, 1933 there also appears a record of a car going by the station at the time that the seismograph was operating. The Braunlich starters were soon replaced with the other type of starters but not until after the earthquake.

The seismographs were operated at that time by dry cells through electrical relay controls and as there was a constant drain on the batteries even when the instruments were not operating, battery life was limited. The displacement meters, which you can also see in the exhibit and the Weed seismograph that recorded on a glass plate which was translated by a clock motor, were also installed but it was the accelerographs that produced the first records.

The installation of these instruments began rather quickly considering the fact that the funds were made available in 1932, and installation was started in the summer of 1932. The ones that were actually in operation at the time of the earthquake were as follows. In Long Beach, Vernon, El Centro, and San Diego they were installed in July of 1932. The Los Angeles subway terminal building and the Suisan Bay Bridge were installed in August and in September there was an instrument installed in the basement and on the 13th floor of the San Jose Bank of America Building.

You may recall that 1932 was a bad depression year and I personally had been without work for 6 months. I guess I would have gotten a Christmas present of a job if it hadn't been for the earthquake of December 20, 1932. The 7.3 magnitude earthquake which occurred in Western Nevada affected 500,000 square miles and there was extensive faulting over an area 38 miles long and from 4 to 9 miles wide. A record of this was obtained on the Long Beach accelerograph. This earthquake was about 350 miles from Long Beach where the ground motion was barely perceptible, with very low acceleration amplitudes far below the damage range. Because he had been diverted by this earthquake, Robison was delayed in coming south, but on December 31, 1932 I got a message from Martel and met with Robison on January 3 when I was employed.

I was employed on a day to day basis for servicing and maintaining the seismographs and the work did involve some travel in which the travel expenses were paid. I think it cost the government two cents a mile on the Southern Pacific Railroad to transport us places, but meals and hotel were on me. Well, this still looked like a pretty good job to me because I was going to get $5.50 per day.

Robison taught me the things that I needed to know about servicing the instruments, testing them and installing them too, so the first thing we did was to go to Colton aboard the Southern Pacific and install an accelerograph in Colton. Then we went to El Centro and serviced the instrument down there. He returned north and I went to San Diego and serviced the accelerograph there. Then we serviced the accelerographs at Vernon and Long Beach. At Long Beach the instrument was completely inoperative because the dry cells had gone dead. We put it back in service on February 3, 1933. Then on February 17, I had word that all strong motion work was stopped until further notice and Robison was transferred to other work in the Survey. Then several interesting things happened. On March 2, Governor Rolph of California closed the banks for three days. On March 4, Franklin Roosevelt was inaugurated and on the 5th he declared a nationwide bank holiday. On March 6 in Martel's office I met Albert K. Ludy from the Tucson Seismological Observatory of the Coast Survey. He was given temporary charge of the Strong Motion Program. Franklin P. Ulrich who came down later was then in the Magnetic and Seismological Survey Observatory in Sitka, Alaska and they were not able to relieve him fast enough to bring him down until fall. So I met Ludy and understood that probably I was going to have a job again, but he went on up to San Francisco, this was March 6, to confer with Captain Maher who was in charge of the San Francisco office.

I was home at Brea on March 10 at 5:54 p.m. When I arrived in Vernon about 7:00 p.m., I found that some of the buildings had lost parapets and there were a few broken windows in the Central Manufacturing District Terminal building, but it was not seriously damaged. I serviced the instrument there in Vernon and put a new sheet on the record, started out for the Subway Terminal building and realized that I had forgotten the keys that I should have taken along with me. I went back, and as it happened there had been a strong aftershock while I was on the road and some of the fellows had been in an elevator in the building at that time. They got rolled around in that elevator until they were scared to death. Maybe they scared me a little bit. I went back down to the basement where the instrument was located. The basement had a big electrical switchboard with exposed copper buss bars and a 2,000 volt system. It also had a riser pipe that went to a 50,000 gallon water storage tank on the roof and you could visualize that riser pipe perhaps being fractured by the earthquake, and the only drain out of this area was a small floor drain in the small room where we had our accelerograph. It didn't look like a very healthy place to be. After again servicing the instruments, I went on to the Subway Terminal building and found a place where I could park the car in an open lot away from the buildings. I was a little amazed at the number of people that were standing around under big parapet walls that hadn't yet fallen with all these shocks that were continuing. I serviced the Subway Terminal building and went back through Vernon, checked that instrument again because that was on the way to Long Beach. On the way to Long Beach I got stopped twice by road blocks, one of them by an American Legion man assisting a Highway Patrol officer and another farther down was by some of the Navy boys - they were able to get a lot of men from the Navy to come and keep an eye on everything in town at that time. That was probably one reason that there was relatively little looting.

As you could see from the film, Long Beach was severely damaged with fallen masonry almost everywhere. The City Hall building itself was closed and the City Manager who was in charge under martial law was presiding on the City Hall steps. He assigned Herb Davies who was a structural engineer that I later worked for several different times to let me into the public utility building. This was a reinforced concrete building and suffered no damage. In fact the next day or several days it was in use as a center for first aid and medical activities. After Herb let me in, he wanted to know how I was able to get into town. I told him what I had done and he was silent for a while and I thought maybe they were going to take me out and shoot me. He said he probably would have done the same thing. Finally, near midnight, I headed home and on the way I was flagged down on E. 7th St. by a Highway Patrolman who was very much concerned because the roadway had dropped about 12 inches from the bridge abutments; it was supported on pilings across the channel there. He was afraid someone would break their neck. I got home about 1:15 a.m. and I needed to get home because I knew that probably somebody was going to want to get in touch with me. I didn't get any message that night, but I got one from Ludy the next morning. This letter from Captain Maher, which I got much later on, may be interesting because it shows how they felt about it in San Francisco. This was on March 12 that he wrote the letter, reproduced on the next page.

I didn't get this letter until after I had seen Captain Maher himself. Things were really slowed down and you couldn't telephone and the telegram that he sent never arrived. Ludy did come by the Lark overnight train and called me the next morning. I met him at the Subway Terminal building in Los Angeles and we checked the Subway Terminal instrument and the one in Vernon, then went down to Long Beach. We stayed in Long Beach all of Saturday and until Sunday morning sometime. We hoped that, perhaps, we could observe when an aftershock would start the accelerograph again. We stayed until morning and slept in the car in the parking lot a little bit during the night. It never operated again, so on Sunday morning at about 8:00 a.m. we left Long Beach and went to the Seismological Laboratory to use their facilities to develop the records that we had taken. In memory, it seems to me that everybody on their staff was there and saw those records, but when I looked at my notes of that date I find that the only ones that I mentioned were Martel and Gutenberg. Nevertheless, of course, it was a memorable event because for the first time instruments had made modern type recordings of destructive earthquake motion and it had been in such a short time from the start of the program. In fact, it was about 9 months from the time that the instruments were first installed. On the 19th of March Ludy, Captain Maher and a man from UC Berkeley and myself ran tilt tests on the instruments, decay curves and damping tests. So we had that information for the records. These were made on the three instruments at the Subway Terminal, Vernon and Long Beach. After that, well I should tell one other thing. Captain Maher did come down and meet us on Monday following the earthquake and he had brought with him a man from Berkeley and had a couple of accelerographs. Then we all went to Long Beach and there he was intent on getting some records of aftershocks taken in the basement and the top of one of the old hotel buildings, the old Breakers Hotel. He bullied the manager of the hotel into allowing us to do this. We stretched wires from top to bottom down through the elevator shaft and upset the hotel operations quite a little bit, got a room at the top and occupied it, and got the instruments out of the shipping boxes which were heavy wooden boxes. Unfortunately, the man from Berkeley had had no introduction to the instruments and didn't realize that accelerometers were packed in a separate box which he had missed. We had the recorders for two accelerographs, one on the roof and one in the basement and no accelerometers to do the actual recording. Of course, this was quite embarassing and what happened was that Captain Maher never did admit it to the hotel people, but he did detach me from that duty and told me to go back home and to catch the train and go to El Centro and San Diego and Colton and check those records. We didn't get any records from the other stations, only the three from Los Angeles and Long Beach.

Well, thereafter Ludy and I travelled California from one end to the other installing accelerographs, displacement meters and Weed seismometers. We did this in such places as Bishop, Sacramento, Eureka, Salinas, Santa Barbara and other places. In October, Franklin Ulrich came down and took charge of the work and in 1934 more money was made available for the program. Some of the people who joined then and who I'm real

DEPARTMENT OF COMMERCE
U. S. COAST AND GEODETIC SURVEY
FIELD STATION
510 CUSTOMHOUSE
SAN FRANCISCO, CALIF.

March 12,1933.

Mr.McLean:

Visited my office this morning expecting to find a communication from you or Mr.Ludy.

On March 10,1933,I wired to you as follows:"Ludy left for Los Angeles on train leaving San Francisco at eight thirty to-night.Stop.All instruments to be wxamined Stop Ludy has transportation requests."

I have not heard from you or from Mr.Ludy and it is necessary that I do hear from you.I have received orders to proceed to Los Angeles but before I comply with these orders I should know whether the instruments have operated properly,if they failed to operate or if through the collapse of buildings or rooms you have been unable to get to them and therefore can give no information as to whether they did or did not operate.

We have two instruments at U C and one in the storehouse.Information from you or Mr.Ludy will enable me to decide if I should take those instruments to Los Angeles so as to get at least records of the aftershocks.

Please advise me as to what has been done and if you see Mr.Ludy request him to do the same.Reply by wire.

Thos.J.Maher,
Inspector,Coast & Geodetic Survey.

Orders dated March 7,1933 from the Director are enclosed.

glad to see here were Bill Moore, John Blume, and then there was Dean Carder who was in the San Francisco area. As for me, I was made an assistant magnetic and seismological observer. The part that was impressive though was that there was better pay.

Don Hudson has questioned me about a discrepancy between two reports on this accelerogram for the Long Beach station, because in the Engineering News Record there were two different articles that reported on this. The first of them published on April 6, 1933 reported intensities of 3/10 to 1 g in the first few seconds. I think if you would look at the accelerogram in the display upstairs you will find it hard to interpret that record with the very best effort. The second article, published June 22, mentioned horizontal component values of only .23 g, one component 0.11 g and a vertical of .25 g. I thought it was interesting that in the first article there was a statement that after study in Washington, the records were to be sent to Byerly, Jacobson, Wood and Martel before the final interpretation was to be adopted. It occurs to me that one of those may have had something to do with this change in intensities. I also found among my papers a four page mimeographed article that was simply entitled, "Notes on Interpretation of Strong Motion Records." It was dated August 1933. It didn't say Coast and Geodetic Survey on it but that's where I got it. There were two statements that may be significant. One of them was "First Reports from the Washington Office of the Coast and Geodetic Survey" and tabulated only a few of the movements indicated on the grams. The second statement says, "The time is not ripe for too critical an analysis of the records because of certain instrumental limitations." Those last two words are underlined. Much work was still to be done in standardizing the new installations, and I have always had a personal feeling that perhaps one of the things about that Long Beach record was due to the quadrafiler suspensions. You might be interested in seeing those instruments, there is one in the exhibit and it has four stainless steel wires .003 inch in diameter that support the mass of the accelerometer. This quadrafiler suspension was used in order to, they hoped, eliminate violin string type vibrations in strong shaking, and a recent review of my 1933 notes shows me that on May 12, 1933 we received the first accelerometers with a pivoted suspension which soon became standard at that time in all of the instruments.

EARLY DAYS OF STRONG MOTION SEISMOMETRY IN THE UNITED STATES

by

William K. Cloud

Strong motion seismometry in the United States resulted from the efforts of engineers, scientists, and businessmen who in the late 1920's were impressed by the application of earthquake knowledge to the design of structures in Japan. They were convinced that the United States should focus attention on the engineering aspects of seismology, particularly on the development of suitable instruments for recording earthquake motions responsible for damage. Through talks, writings, and personal contacts federal aid was enlisted, and in 1931 Congress allocated additional funds to the Coast and Geodetic Survey for such a program.

Development of the necessary instruments for recording strong ground motion began immediately, and from the beginning this and all subsequent phases of the program were highly cooperative ventures. In writing of meetings held at the time, H.H. Heck stated, "The chief purpose of the work is for the benefit of engineers and architects. It has been felt that they should say what they want, and the general consensus of opinion obtained from them is that recording should start at the point where slight damage begins and that such records should have sufficient amplitude for interpretation. The upper limit should be the recording of acceleration for as wide a range as the design of the instrument permits, and the upper bound should exceed 0.2 the acceleration of gravity. The information desired includes the acceleration, the period, and the amplitude of ground motion."

Guided by these criteria personnel of the Coast and Geodetic Survey, National Bureau of Standards, Massachusetts Institute of Technology, and the University of Virginia developed the following strong motion seismograph prototypes.

(1) An accelerometer consisting of a loop-vane copper mass on a quadrifilar suspension attached to a frame, the mass free to rotate between pole pieces of a permanent magnet. This suspension was discarded in 1933 owing to difficulty in adjusting the four wires for equal tension. A pivot-and jewel spring-stabilized suspension system was substituted. This latter system was also discarded, the zero position having been found to shift during earthquakes. It was replaced by a simple unifilar suspension in 1947.

(2) An accelerograph that with a vertical and two horizontal accelerometers, included for operation a pendulum switch to start the instrument by means of earth motion, a mechanical commutator to switch the instrument back to a ready-but-holding state by means of energized circuitry, at about 70 second intervals, a mechanical circuit breaker to shut the instrument down after about five operations, a clock operated flag to provide time by interrupting a light beam at 1/2 second intervals, a recorder using focused light beams reflected from mirrors on timer and accelerometer components to record data on moving photographic paper, and storage battery to provide energy.

(3) A displacement meter. A rather large instrument containing two mast-and-boom, ten second period pendulums. Other components were similar to those in the accelerograph.

(4) A simple, but not too accurate, strong motion seismograph consisting of a mass of about 6 pounds resting on 3 vertical wires, two slotted levers coupled to a rod on top of the mass and attached to styli that recorded two directions of motion on the bottom of a smoked glass plate, and a clock device that when triggered by a earthquake pulled the glass plate providing a crude idea of time.

Concurrent with instrument development a series of meetings was held with engineers and seismologists to work out an economically feasible program. As a result of these meetings California was selected as a laboratory in which to begin strong motion investigations. The consensus was that conditions in California, both as to type and frequency of earthquakes, were optimum for obtaining results in a shorter time span than would be possible in other areas.

Responsibility for implementing the program was assigned to Commander T.J. Maher, inspector in charge of the San Francisco field station of the Coast and Geodetic Survey. With advice from California engineers on sites, installation of the new strong motion seismographs began in July 1932. By a stroke of luck three of the stations installed were in buildings at Long Beach, Vernon, and Los Angeles. Less than eight months later on March 10, 1933 the disastrous Long Beach earthquake occurred, and was recorded at the three stations. These first useful records of damaging earthquake motion justified the program and gave impetus for additional effort.

Following the earthquake, plans for further investigations were developed by engineers, architects, seismologists, and others interested for business reasons at a series of conferences in the San Francisco Bay Region and in Southern California. The plans called for a crash program starting in 1934 under the supervision of Franklin P. Ulrich. Accomplishments during the first two years were impressive.

The network of strong motion seismographs was enlarged to 51 instruments.

The periods of 292 structures were measured with portable vibration meters developed by H.E. McComb, Frank Neumann, Ralph McLean, and Hugo Benioff.

The first ground and building vibrator was developed by John A. Blume and L.S. Jacobsen of Stanford University.

The damage to type III masonry buildings during the Long Beach earthquake was studied under the supervision of R.R. Martel of the California Institute of Technology.

The ground periods recorded in routine operation of teleseismic instruments were studied by Beno Gutenberg of the Seismological Laboratory at Pasadena.

The existing questionnaire program was expanded in cooperation with Perry Byerly of the University of California.

The double integration of strong motion acceleration records was a subject of research by Frank Neumann of the C & GS.

Upon completion of the crash program, the Coast and Geodetic Survey was assigned responsibility for continuing earthquake investigations in the western United States through a special field party, the Seismological Field Survey, with headquarters in San Francisco, and with Franklin P. Ulrich in charge. After Mr. Ulrich's death in 1952 William K. Cloud became Chief of the Party, and remained Chief until his retirement in 1971.

The years that followed the crash program in 1934-1935 were ones of consolidation, routine operation, and gradual improvement of instruments and methods. By 1964 the network of strong motion seismographs had expanded to 71 stations, and extended to regions in the western United States outside California.

A small displacement meter developed by D.S. Carder has been incorporated into many of the strong motion instruments. A low cost instrument, the seismoscope, had been designed and produced jointly by the Coast and Geodetic Survey and the California Institute of Technology to supplement strong motion seismographs. A network of somewhat more than 100 seismoscopes had been installed in California. Several hundred strong motion earthquake records were available for study. Response spectra has become an acceptable method of analysis for engineering purposes.

Questionnaire coverage of both small and large earthquakes and the field investigation of damaging earthquakes had become routine. The use of strong motion and teleseismic equipment to record ground effects from large nuclear and chemical explosions continued.

The slow growth of the strong motion seismograph network from 1932 to 1964 at an averaged rate of slightly over 2 stations a year was due mainly to the fact that the standard Coast and Geodetic Survey accelerograph was not a mass-produced, on the shelf item. Each instrument was custom built and thus expensive, up to $8,000 each.

From 1964 on several things led to explosive growth of the network. Modern, less expensive, strong motion accelerographs were developed and mass produced by instrument companies. The Alaskan Earthquake of March 27, 1964 generated widespread interest in earthquake investigation and loosened funding, and ordinances passed in 1965 by Los Angeles and Beverly Hills required owners of new buildings higher than 6 stories to buy three accelerographs for each building.

The Coast and Geodetic Survey ceased to exist in the late 1960's when it became part of NOAA. However, the Seismological Field Survey continued to exist as a unit of NOAA until the early 1970's. It went out highlighted by the damaging San Fernando earthquake of February 9, 1971 which produced 241 strong motion accelerograph records and 144 seismoscope records, the largest number of strong motion records ever obtained during a single earthquake and aftershocks, and on one record the highest acceleration ever recorded during an earthquake, above 1 g.

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HISTORY OF ACCELEROGRAPH DEVELOPMENT

by

D.E. Hudson
University of Southern California

Most scientific and technical apparatus has slowly evolved over a long period of time and its early history is lost in the dim past. In addition, such developments are often anonymous or involve small contributions from innumerable people whose individual ideas cannot be identified. Such is not the case with strong motion accelerographs. Early publications of the U.S. Department of Commerce identify exactly who did what, and many of the pioneers of the field are still active and can fill in the details. This is thus a good time to collect and preserve the information for posterity.

The story begins with Dr. K. Suyehiro, Director of the Earthquake Research Institute of the University of Tokyo. He was initially a mechanical engineer and naval architect, a specialist in vibrations, who was converted to earthquakes by the 1923 Tokyo earthquake.

Dr. Suyehiro was induced to come to the U.S. in 1931 by John Freeman, a former president of both ASME and ASCE, to give a series of lectures on "Engineering Seismology" based on his research investigations in Japan. These lectures were sponsored by the ASCE and given at four schools -- U.C. Berkeley, Stanford, Caltech, and M.I.T. These were very successful and launched each school on a career in earthquake engineering. The lectures were published in the Transactions of the ASCE and can still be read with profit. In these lectures, Dr. Suyehiro emphasized the importance of the direct measurement of destructive ground motion. He expressed his surprise that this had never been done, and recommended development and deployment of special instruments for this purpose. He suggested that the Wood-Anderson seismometer, recently designed in the U.S., could be modified for this purpose.

H.O. Wood and John Anderson designed their seismometer in 1921 at the Carnegie Seismological Laboratory in Pasadena, which evolved into the Caltech Seismological Laboratory. This is a classic of scientific instrument design.

It completely reversed a tendency at the time to produce very large instruments. A current seismological problem in those days was the measurement of long period waves in the earth, requiring a long pendulum in the seismograph. Thinking in terms of a simple pendulum, the longer the pendulum, the longer the period. Wood and Anderson realized that a compound pendulum could be given a long period by making the distance from the center of mass to the support point very small. So they produced a torsion pendulum with an arm of 1 mm. in length. This was simple, inexpensive, and easy to adjust. The relatively low cost made it feasible to install the instrument at a number of sites, and it was the availability of simultaneous measurements at a number of sites that made it possible for Richter to develop his magnitude scale. Built into the Local Richter Magnitude definition is the magnification of the standard Wood-Anderson seismometer, which was 2800 times. Figure 1 is reproduced from the 1925 paper in the Bulletin of the Seismological Society of America in which Wood and Anderson described their seismometer. This is an accurate sketch of the model which you will see in the exhibit, which was built in the shops of the Fred Henson Co. in Pasadena.

In the early 1930's, mainly as the result of an energetic campaign by John Freeman, the U.S. Coast and Geodetic Survey was given an assignment and a small amount of funding to design and deploy instruments for earthquake engineering. Frank Wenner of the Bureau of Standards was brought in to help, and he, acting on the suggestion of Dr. Suyehiro, designed a transducer based on the Wood-Anderson type with a sufficiently high natural frequency of 10 cps to act as an accelerometer in the frequency range of structural interest. A recording drum for the instrument consisting of a 6-inch wide photographic paper on a rotating drum which translated along a screw to separate the traces was designed by D.L. Parkhurst, H.E. McComb, and E.C. Robison. The accelerometer went through several design stages with various suspensions -- first, a "quadrifilar" suspension of four fine wires (Fig.2); second, a pivot suspension (Fig. 3); and last, a solid torsion wire suspension (Fig. 4).

The recording drum was ultimately replaced by a 12-inch wide paper magazine and take-up roll mechanism. Examples of all three suspension systems and the various recording systems will be found in the exhibit. General views of several versions of the complete accelerographs are shown in Figs. 5, 6 and 7.

It was recognized from the beginning that at the relatively high recording speeds required (1 cm/sec) continuous recording would be impracticable and that an inertia starting device triggered by the earthquake itself would be needed. The first starters were uni-directional spring mass pre-loaded systems arranged to make an electrical contact when ground acceleration exceeded a pre-set value. These proved to be much subject to extraneous vibrations and malfunctions, and were replaced by a horizontal pendulum starter designed by H.E. McComb. Figure 8 shows a photograph of one of the original starters. A number of versions of these starters will be seen in the accelerographs in the exhibit. The success of the pendulum starter depended on (1) platinum contact surfaces, and (2) a break-circuit relay system. The starter will of course operate on a non-unique set of initial ground motion-time functions, but in practice its characteristics have been justified by its success in the field. Very few malfunctions have occurred, and there has been little loss of significant information at the beginning of the record.

At the same time that the above USCGS accelerograph was being developed, the group was also working on several related instruments which will also be found in the historical exhibit. It was early realized that it would be difficult to get accurate information from the accelerograph about long period waves of period around 10 seconds. For that purpose, special long period displacement meters were constructed. The original model shown in Figs. 9 and 10 contains two unity magnification horizontal pendulums of 10 second period. This is a large, cumbersome device, four feet on a side, built in the days before miniaturization. Later on, smaller 5 sec. inverted pendulum devices were designed by D.S. Carder and were installed during the 1950's in the standard USCGS accelerographs along with the accelerometers (Fig. 11).

Another line of development started in the 1930's was that of simpler lower cost devices suitable for deployment in large numbers in dense networks. The strong motion accelerograph shown in Fig. 12 was designed by A.J. Weed of the University of Virginia. It has a 6-lb. mass supported as an inverted pendulum by three stiff vertical wires operating with a natural frequency of 5 cps. A mechanical lever system scribes two perpendicular components of horizontal motion on the underside of a smoked glass plate which is translated through a total distance of 7 inches by a clockwork system to give a rough time axis. Several dozen of these devices were deployed in the field, but later advances in accelerograph instrument technology made them obsolete and the exhibit contains one of the last survivors.

The USCGS instruments which we have been discussing above were hand made devices, custom built in small instrument shops on special order. They were consequently relatively expensive and often unavailable or in very uncertain supply. It was recognized during the 1940's and 1950's that until there was commercial development and marketing with something like off-the-shelf availability at a fixed price, there could be no large scale deployment of the equipment. It then appeared that a commercial version of the Wood-Anderson seismometer was being marketed by the Lehner-Griffith Co. in Pasadena. In fact, seismologists had been moving in the direction of lower magnification devices for strong motion earthquake measurements, and the Caltech Seismological Laboratory had been operating a number of Wood-Anderson type seismometers at a magnification 8 instead of 2800. In the 1950's, Lehner-Griffith offered a 4-channel 35 mm. film recording seismograph with two components of 2800 magnification and two of magnification 4.

In 1959, discussions were initiated with Robert Griffith, who is attending our present meeting, about the modification of his standard Wood-Anderson seismometer to give it a natural frequency of 10 cps and of his recording system to give it speed of 1cm/sec, thus reproducing the essential characteristics of the USCGS accelerograph. Before this could be carried out, the Lehner-Griffith Co. was acquired by United Electrodynamics Co., which incidentally was at the time occupying a building owned by Hugo Benioff, the famous Caltech seismologist, geophysicist and seismological instrument designer. In the United Geomeasurements Division of UED, the idea of the strong motion accelerograph was picked up by Robert Swain, also at our meeting today, who induced the company to support a small development program. Under project directors Robert Bradspies and William Rihn, who is also with us at our present meeting, the AR 240 accelerograph was produced, and was marketed in 1963 under the direction of another of our workshop participants, Harry Halverson (Fig. 13). This first commercial accelerograph recorded on 12-inch wide photographic paper, with 18 cps natural frequency accelerometers and a horizontal starting pendulum, and was a highly successful instrument of which approximately 200 were built. Some famous accelerograms were obtained on AR 240's -- the 1966 Parkfield records, the 1967 Koyna Dam record in India, and the 1971 Pacoima Dam record.

At this same time, the USCGS group at the Albuquerque Instrument Laboratory developed a new design of the old standard accelerograph under the direction of Charles Langer. This was known as the USCGS Mark II accelerograph, and six of these were produced by United Geomeasurements at about the time the AR 240 appeared (Fig. 14). No more Mark II's were manufactured and it was never widely deployed because by that time the AR 240 was satisfactorily fulfilling the basic instrumental needs of the field.

The commercial availability of the AR 240 made it feasible to evolve the Los Angeles Building Code requiring three accelerographs in high-rise buildings, and this code in turn helped create the kind of market which stimulated further commercial development.

At this point the MO 2 accelerograph appeared from New Zealand (Fig. 15). Designed by R.I. Skinner and P. Duflou of the Department of Scientific and Industrial Research, it recorded a 30 cps accelerometer on 35 mm. film, and pioneered an electrodynamic starter. The MO 2 satisfied the Los Angeles code at about one-third the price of the AR 240. This stimulated the development in 1966 of the RFT 250 at about one-half the price of the AR 240 (Fig. 16). The RFT 250, designed under the direction of William Rihn, used a simplified transducer, a compact inverted pendulum as a starter, and recorded on 70 mm. film. By this time United Electrodynamics had become Teledyne-Earth Sciences. Their next development was the RMT 280, the first of the analog tape recording accelerographs, which recorded on an instrumentation type tape cartridge (Fig. 17). Only a few of these devices were built before being overtaken by newer developments. In 1969 Teledyne-Earth Sciences was incorporated into Teledyne-Geotech, which in 1975 redesigned the RFT 250 in a somewhat simplified form as the RFT 350. Soon after, the product line was sold, first to Terrametrics, and then to Terra Technology Corporation, the company which at about the same time pioneered the digital accelerograph (Fig. 18).

In 1969 the team of Swain, Griffith, Rihn, and Halverson organized a new company, Kinemetrics, Inc., which designed and marketed the SMA-1 accelerograph in 1970 (Fig. 19). This was a 70 mm. film recording compact accelerograph with a double reflecting optical system, and a vertical electrodynamic starter. It had early been recognized that for most stations and most earthquakes vertically arriving P-waves would be the earliest arrivals and hence could advantageously be used to start the accelerograph ahead of the stronger S-waves. This vertical starter became the standard in the field and has been used widely since for a variety of seismic trigger devices. The SMA-1 accelerograph has become the current standard workhorse in the field. Instrument No. 5,000 was produced some time ago, and the number installed in the world must now be approaching 6,000. In 1972 the SMA-1 was modified to produce an electric output, and appeared as the SMA-2 recording on analog tape cassettes (Fig. 20), and as the SMA-3 (Fig. 21), a multi-channel central recording tape cassette instrument widely used in nuclear power plants. The final development of this particular line of accelerographs was the CRA-1, a central recording system of 1974, which uses electro-optical galvanometers recording 14 channels on a 7-inch wide film, widely used for the instrumentation of buildings, bridges, dams, etc. (Fig. 22).

We will now backtrack a little in time to indicate some of the parallel developments going on in Japan. You will recall that much of the impetus for the initial U.S. work on accelerographs was provide by Dr. Suyehiro. He was, in fact, more successful in launching the U.S. program than he was in his own country. Not until 1951 was the Strong Motion Acceleration Committee formed in Japan, which designed the first accelerographs installed in that country. The first SMAC accelerograph, reported on at the First World Conference on Earthquake Engineering, Berkeley, in 1956, used mechanical levers as a magnifying device, and recorded with a sapphire stylus on waxed paper (Fig. 23). It was built and marketed by the Akashi Instrument Co. and was a relatively expensive device. With a natural frequency of 10 cps and an unusually large damping of 100% critical, the SMAC accelerograph attenuated the higher frequency waves somewhat more rapidly than the original USCGS accelerographs, and considerably more so than later generation U.S. devices. This gives the uncorrected Japanese accelerograms a somewhat different appearance than typical U.S. records, and at first caused some speculation about possible differences between Japanese and U.S. earthquakes. It is only recently that Japanese literature has begun to include information on corrected accelerograms and it is now apparent that U.S. and Japanese earthquakes are not as different as had once been imagined.

Earthquake engineering is now truly an international activity, but as far as accelerograph development is concerned, there is little to report from the rest of the world except for the work in Japan and New Zealand mentioned above. A number of ingenious instrument types have been experimented with in the U.S.S.R., but none of them have been produced or deployed in sufficient numbers to have produced many significant accelerograms. Adaptations of U.S. designs have been constructed in various South American countries, India, China, and elsewhere, but again such devices have not progressed past the experimental phase. Accelerograph design has thus been primarily a California, or West Coast activity, and this partially accounts for the local flavor of the present workshop.

We will leave our story of accelerograph development with the appearance around the middle 1970's of the digital magnetic tape recording accelerograph. These developments belong more to the current state-of-the-art reviews which will occupy us in later sessions than to our present historical background.

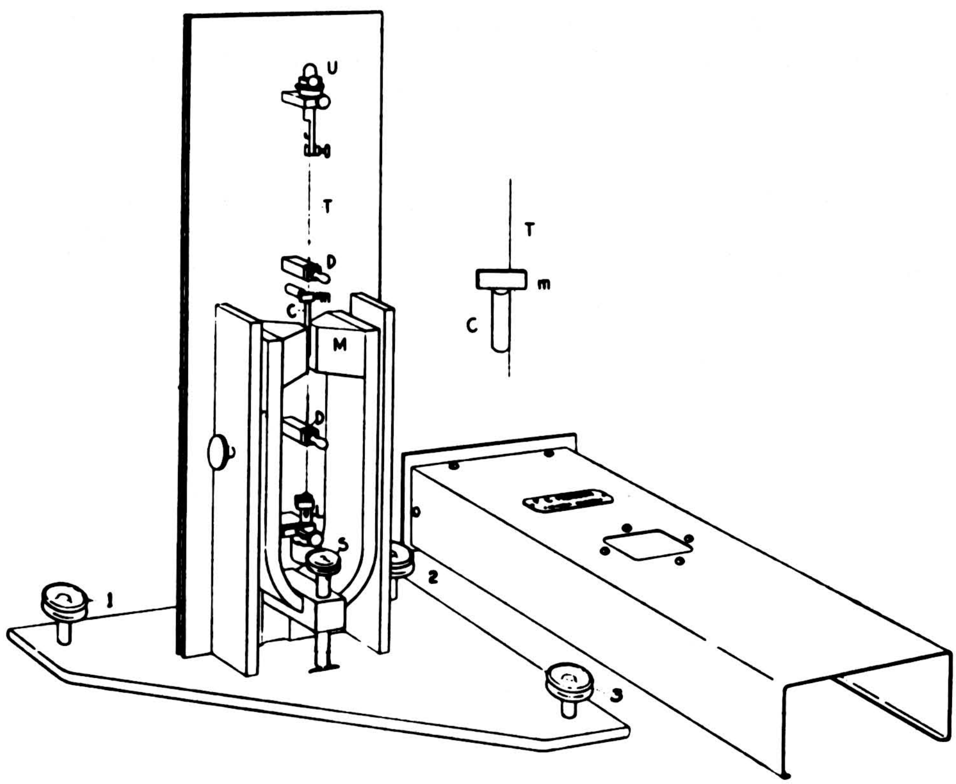

Figure 1: The Original Wood-Anderson Seismometer.

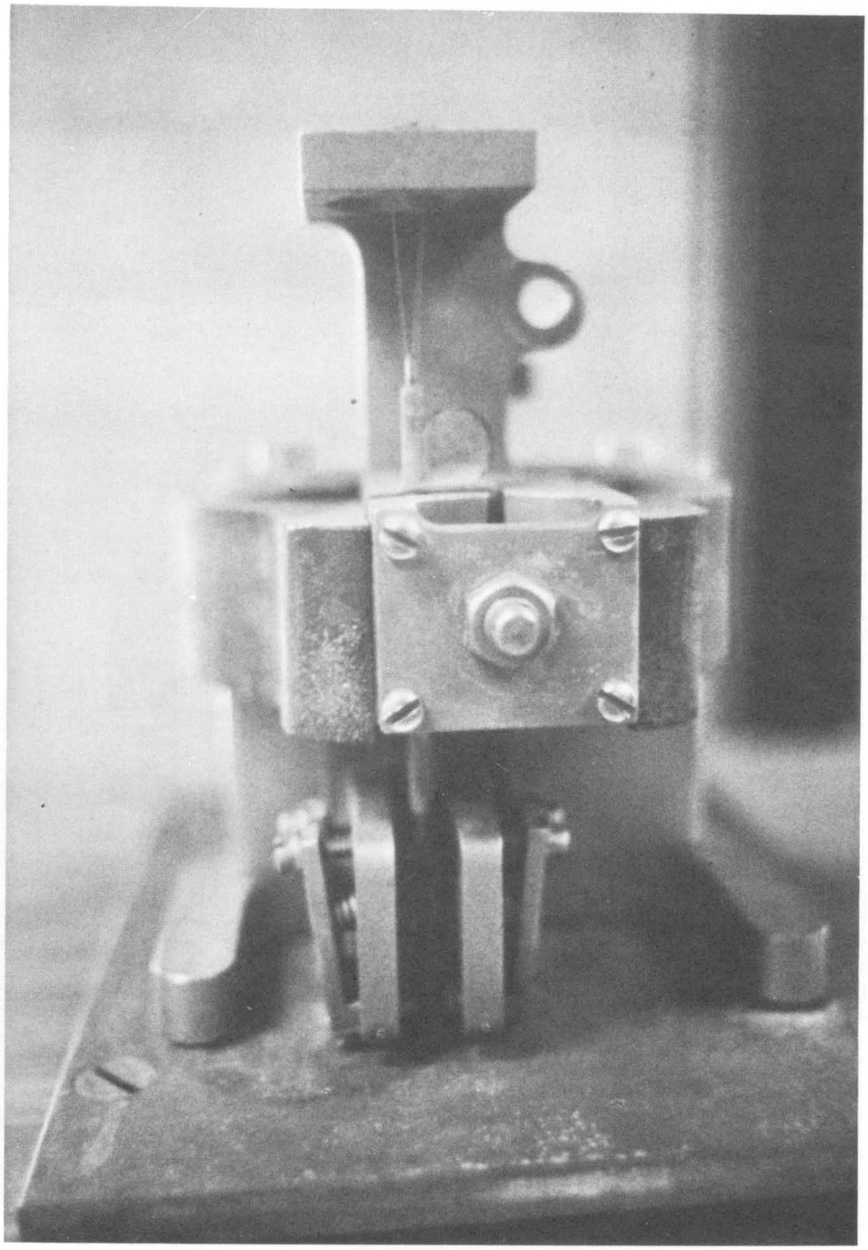

Figure 2: Accelerometer Transducer with Quadrifilar Suspension.

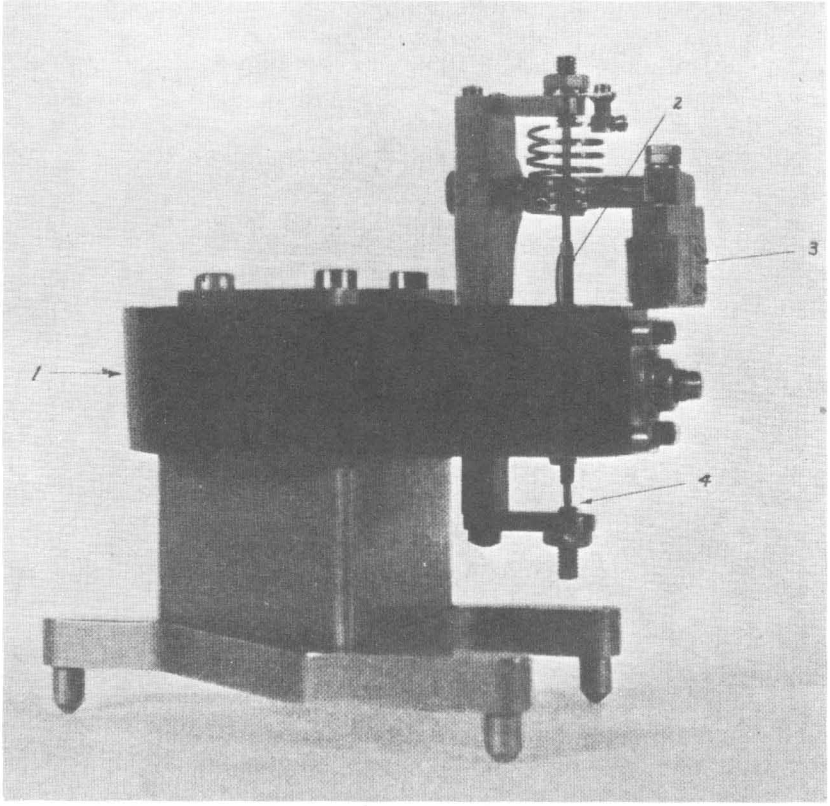

Figure 3: Accelerometer Transducer with Pivot Suspension.

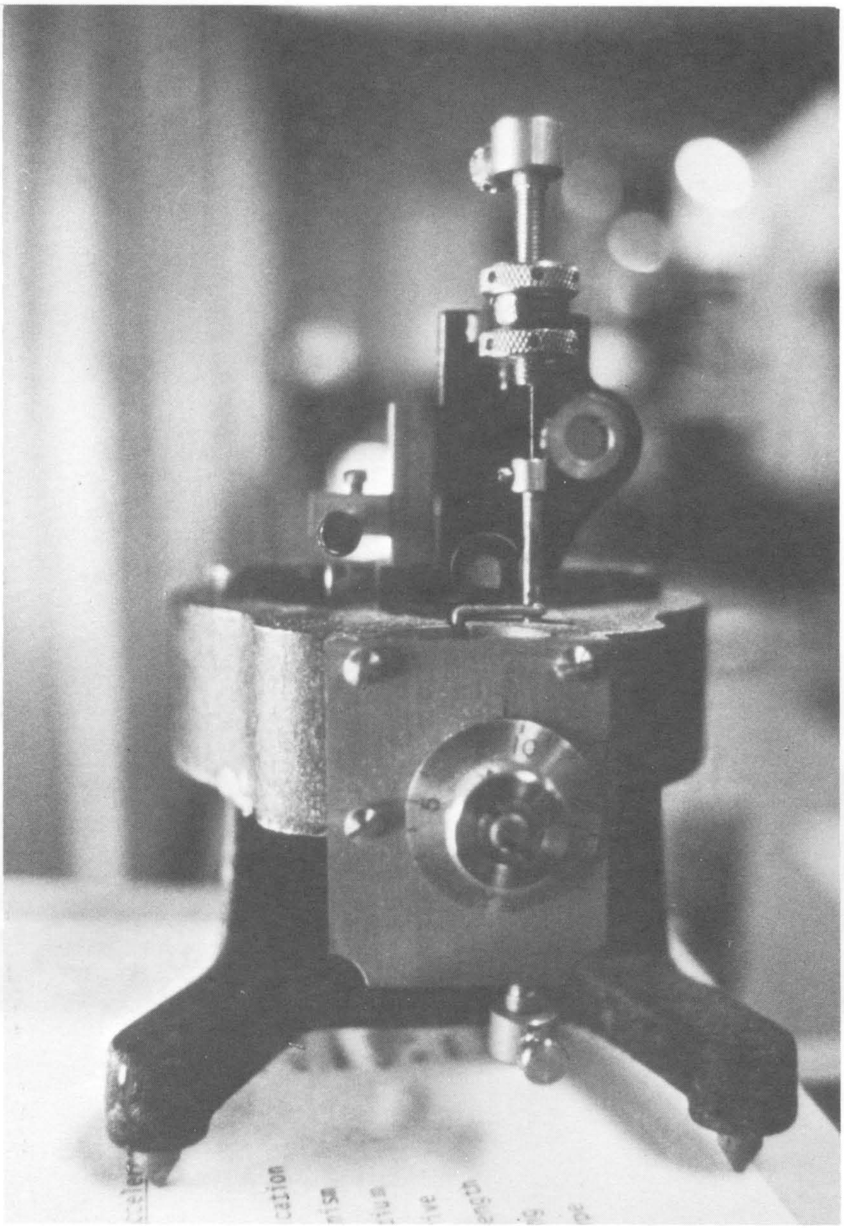

Figure 4: Accelerometer Transducer with Torsion-Wire Suspension.

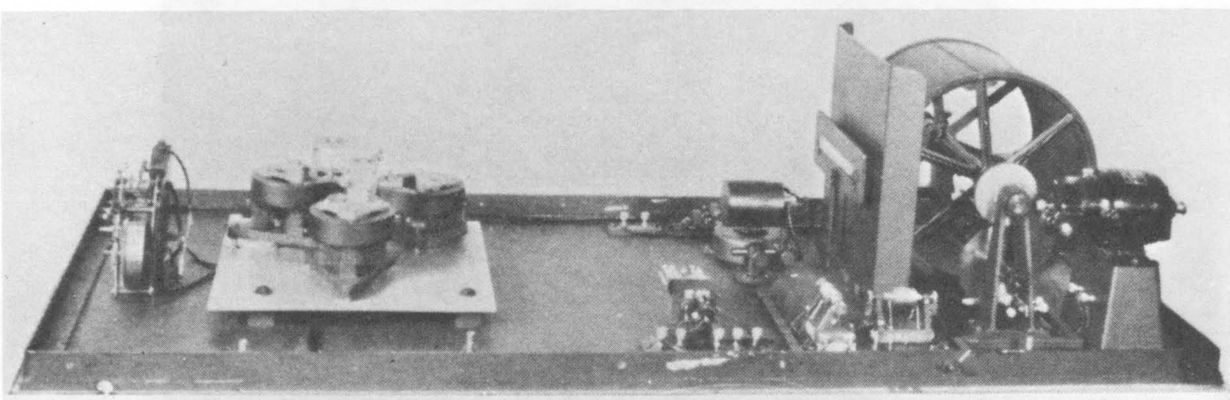

Figure 5: Original Version of the U.S.C.G.S. Strong Motion Accelerograph with Quadrifilar Suspensions and Translating Drum Film Recorder. This is the model producing the 1933 Long Beach Accelerogram.

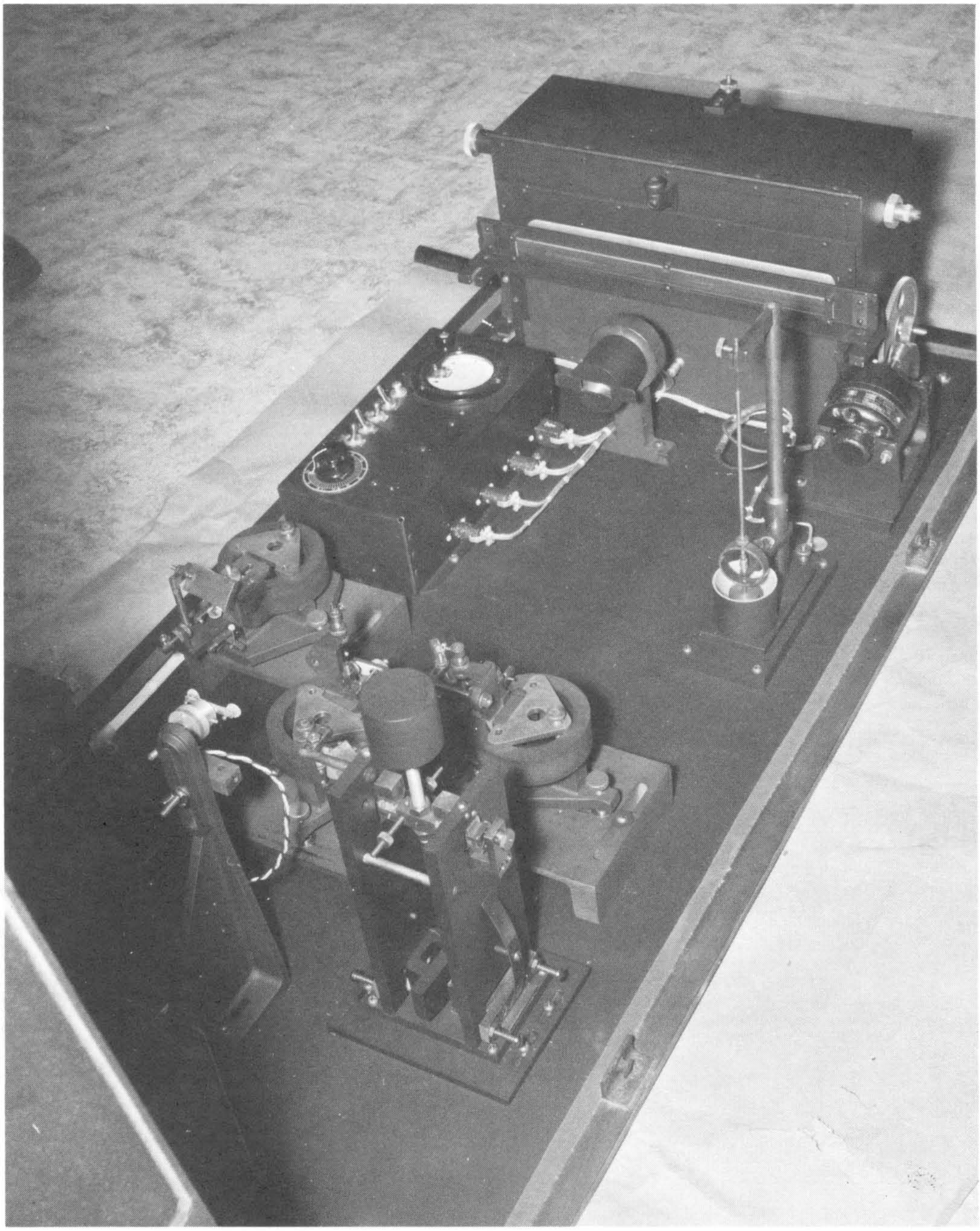

Figure 6: Later Version of the Standard U.S.C.G.S. Strong Motion Accelerograph with Continuous Take-Up Film Magazine, Horizontal Starting Pendulum, and Carder Displacement Transducers.

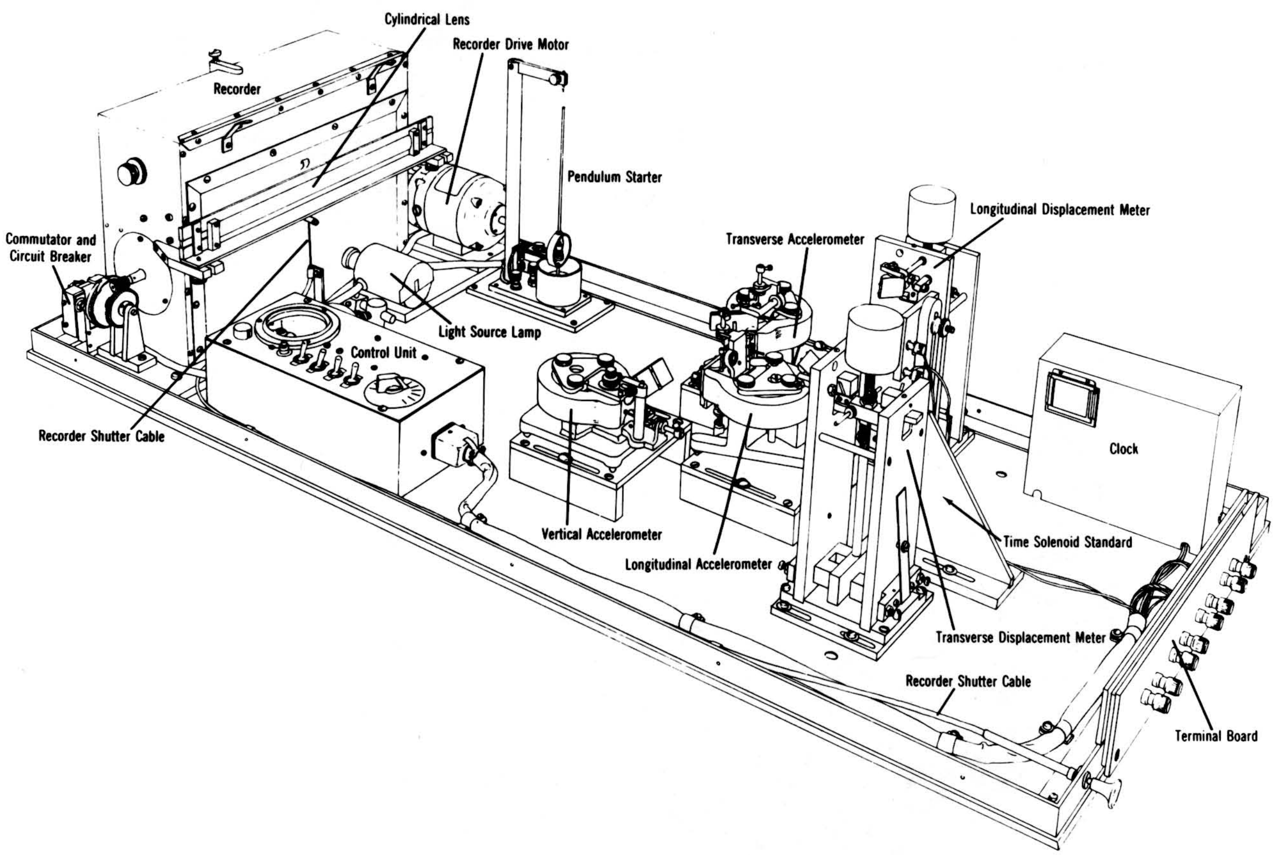

Figure 7: Schematic Diagram of Standard U.S.C.G.S. Strong Motion Accelerograph.

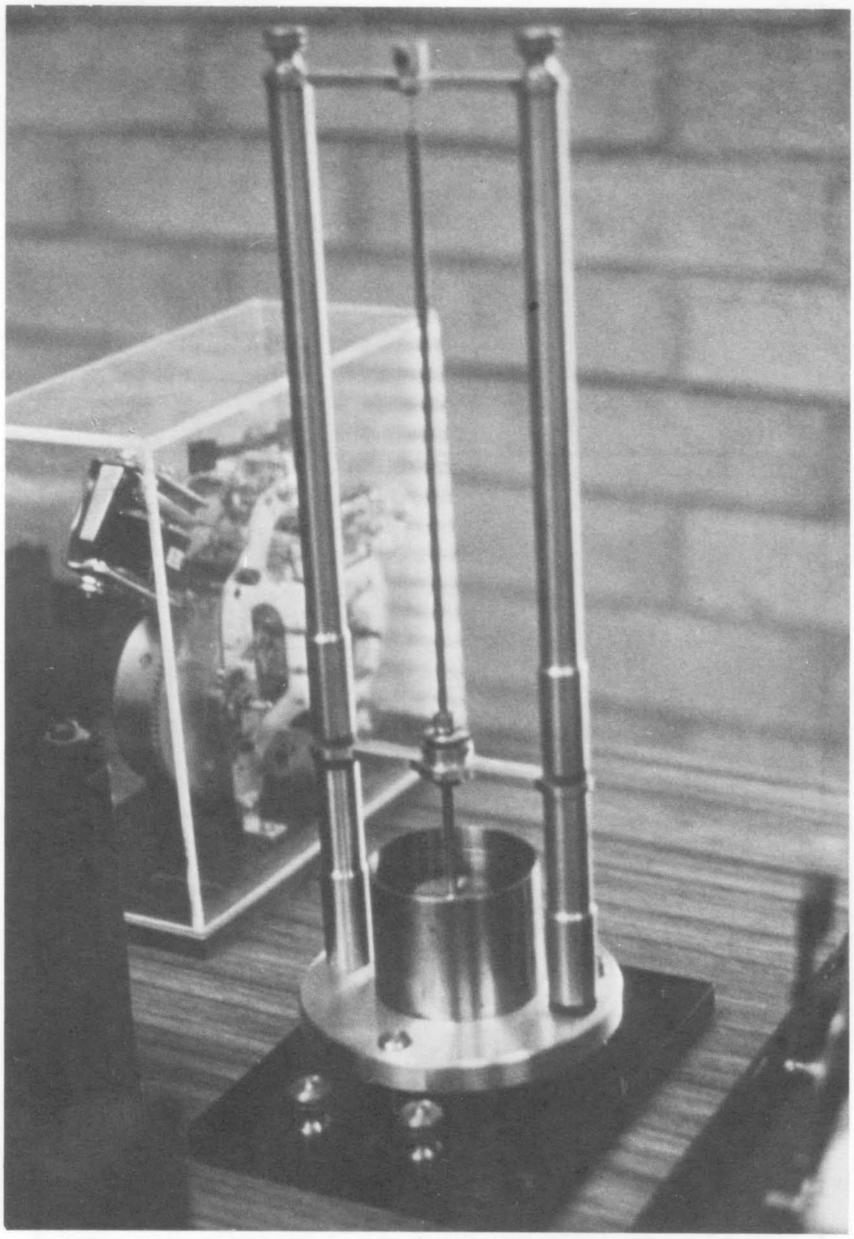

Figure 8: Horizontal Pendulum Starter for U.S.C.G.S. Accelerographs.

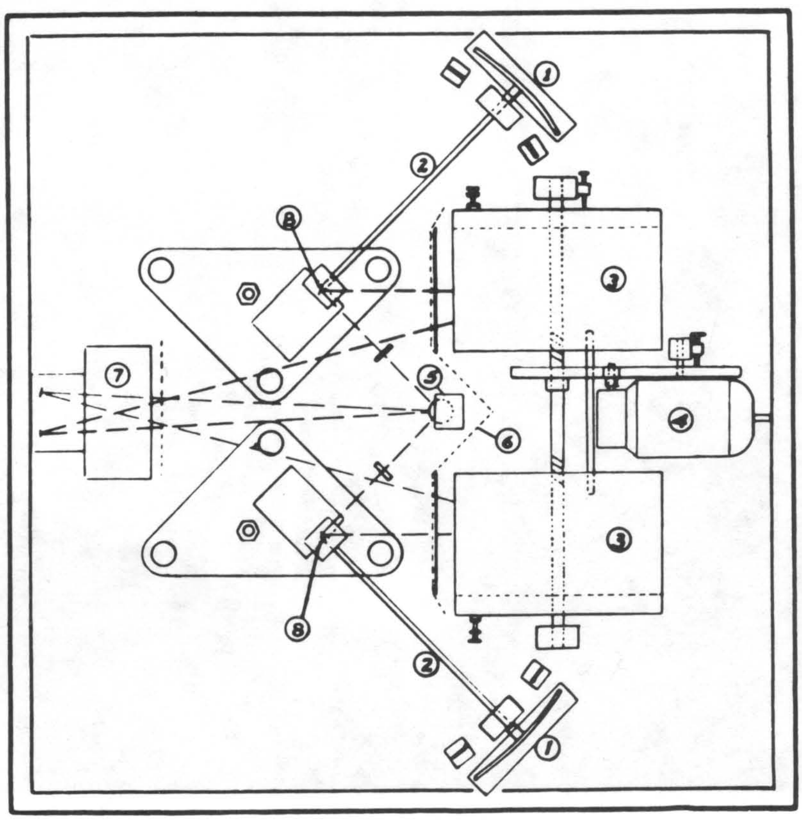

Figure 9: Schematic Diagram of U.S.C.G.S. Displacement Meter.

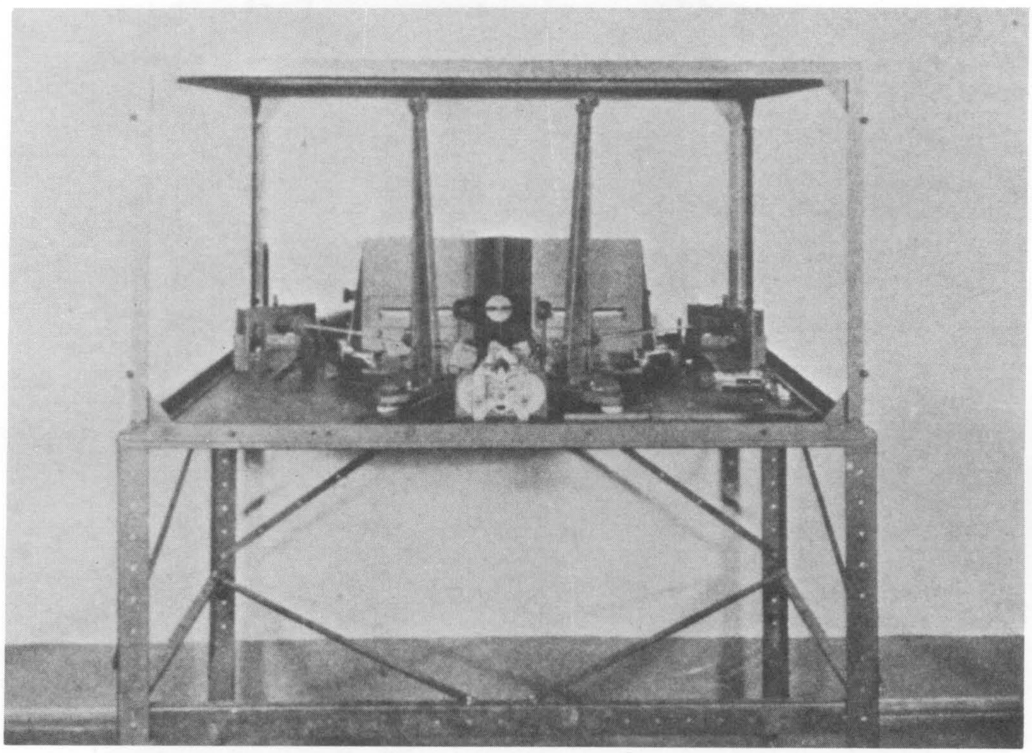

Figure 10: Displacement Meter.

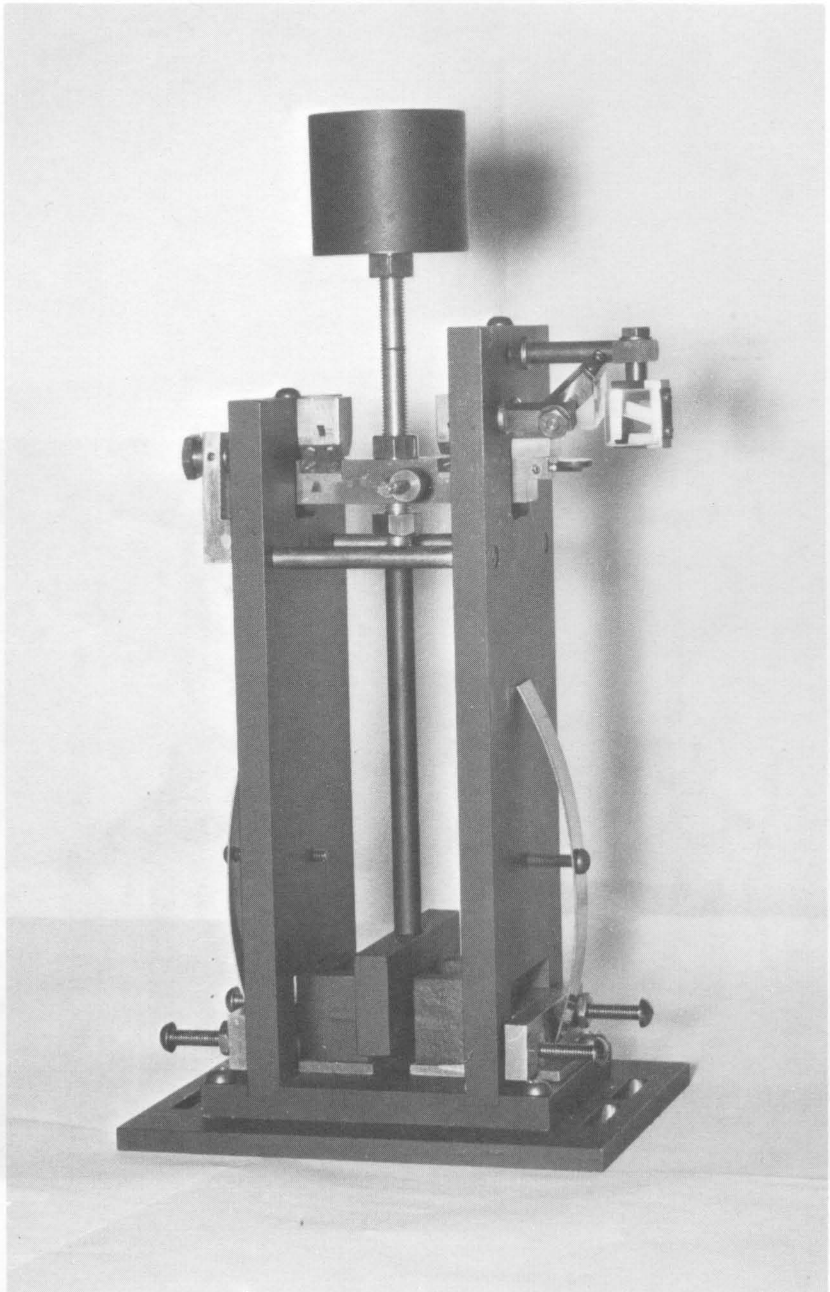

Figure 11: Carder Displacement Meter for Standard U.S.C.G.S. Accelerographs.

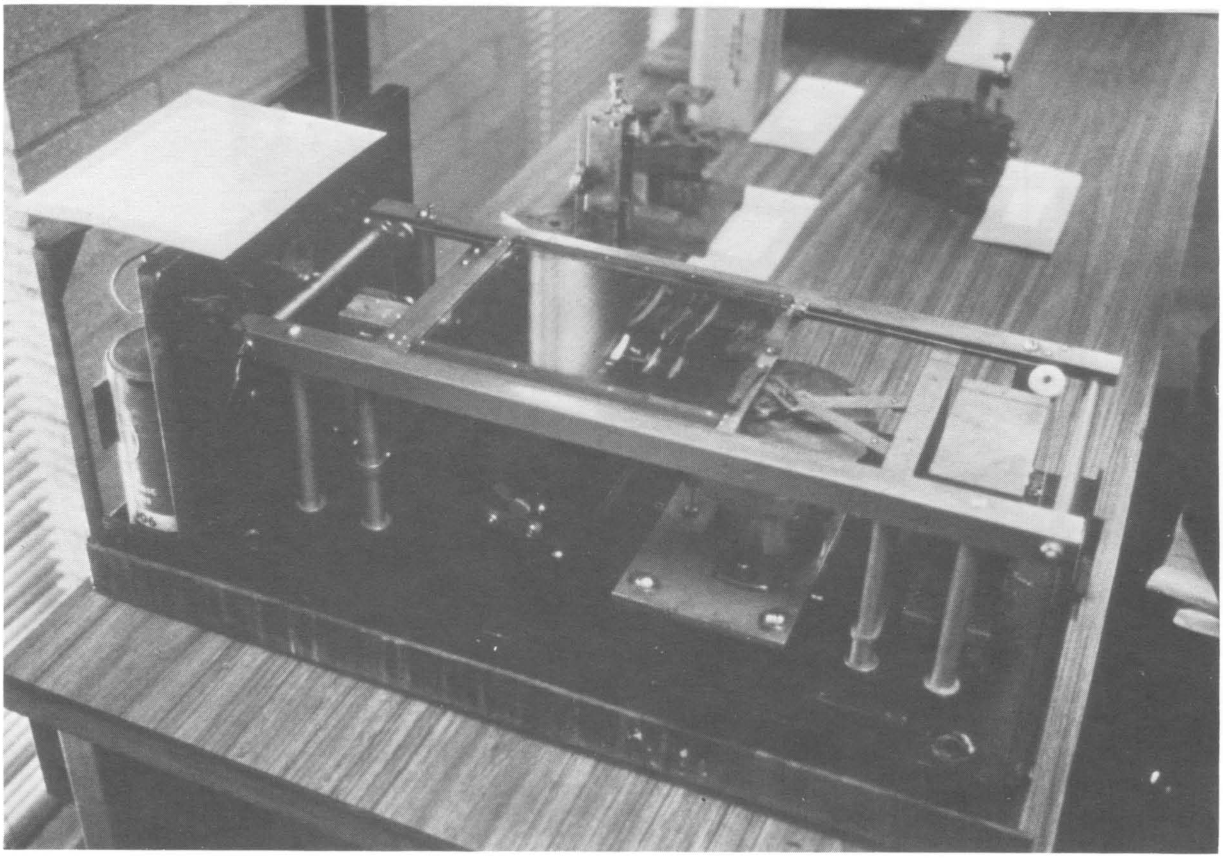

Figure 12: Weed Strong Motion Accelerograph.

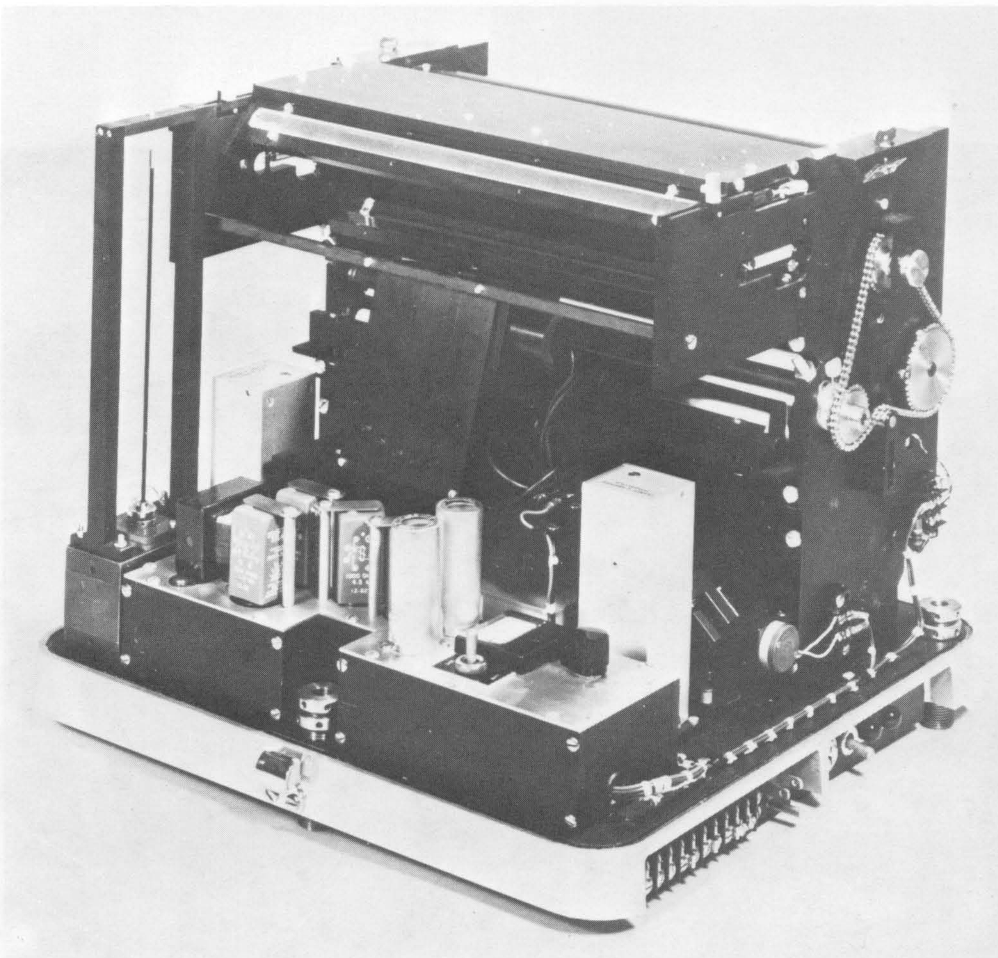

Figure 13: AR 240 Strong Motion Accelerograph.

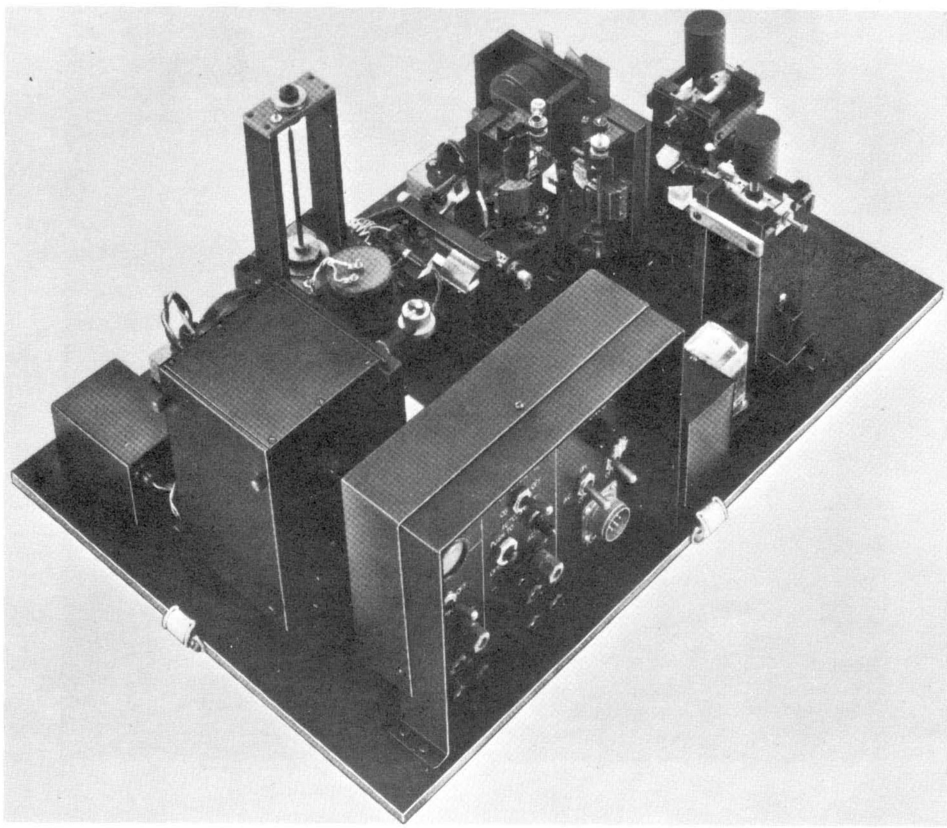

Figure 14: USCGS Mark II Accelerograph.

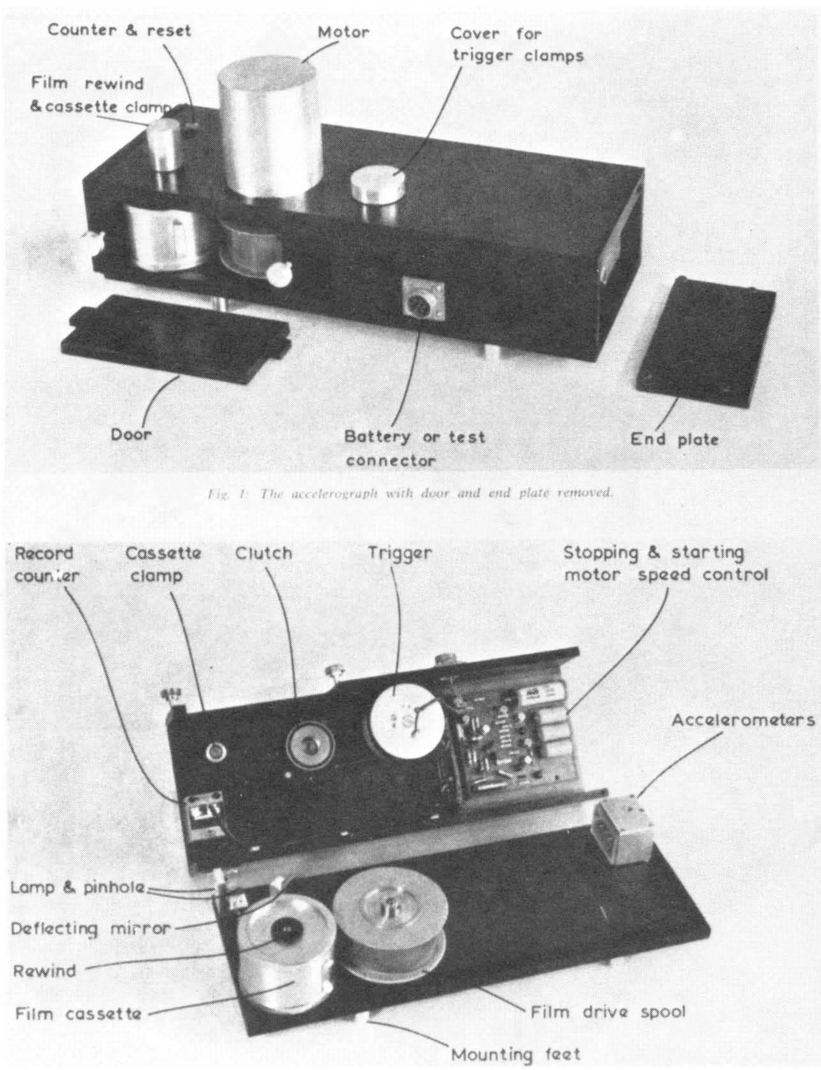

Figure 15: New Zealand MO2 Strong Motion Accelerograph.

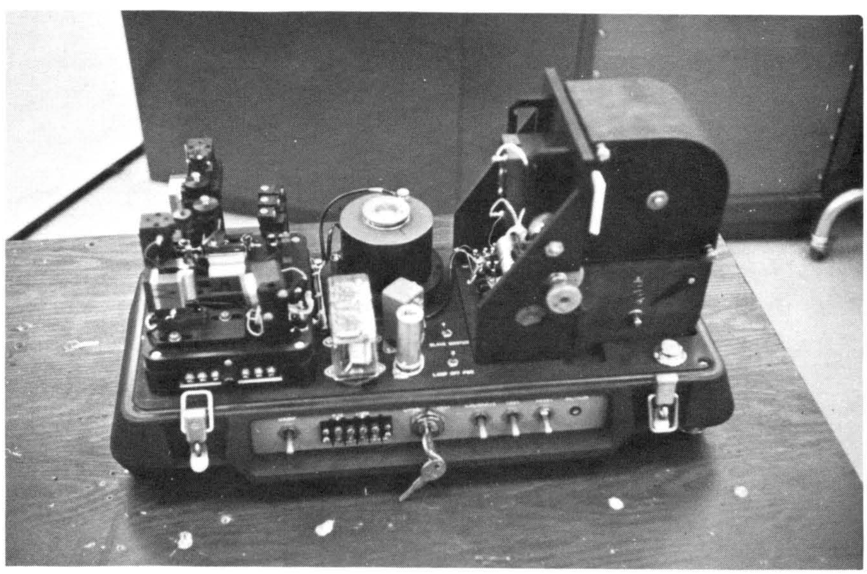

Figure 16: RFT 250 Accelerograph.

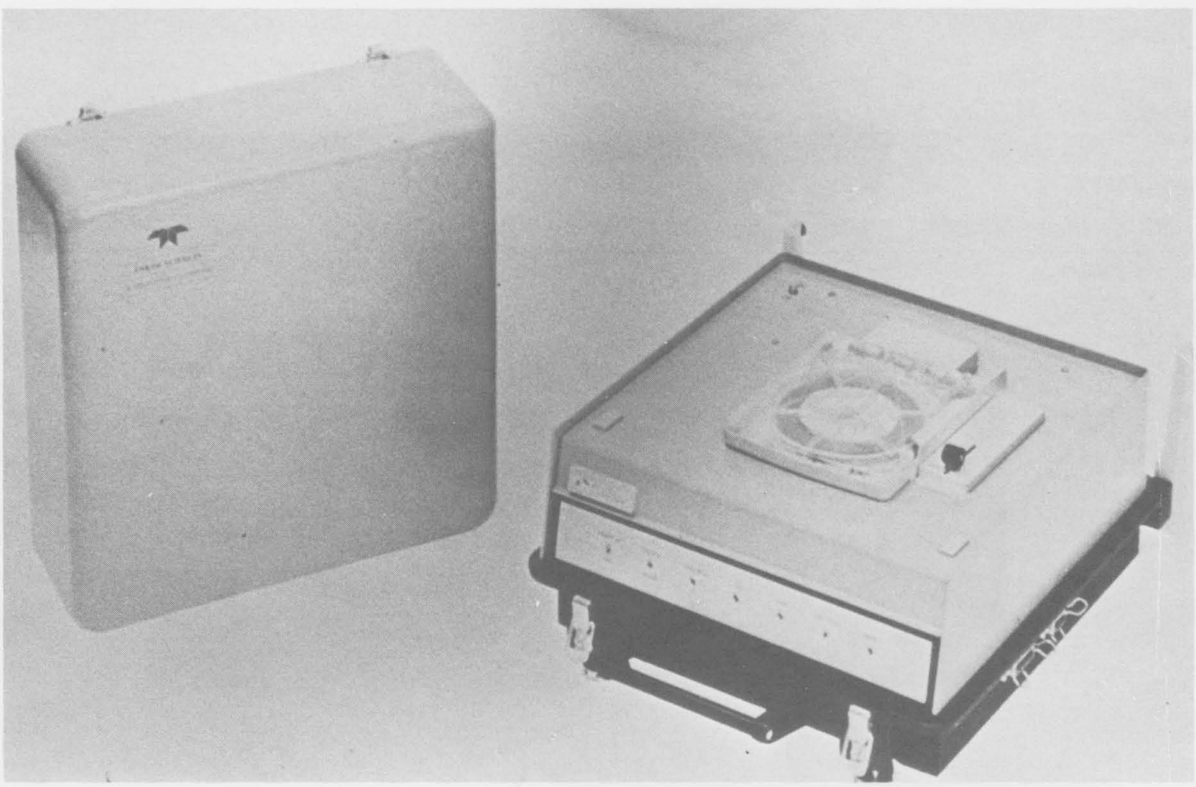

Figure 17: RMT 280 Accelerograph.

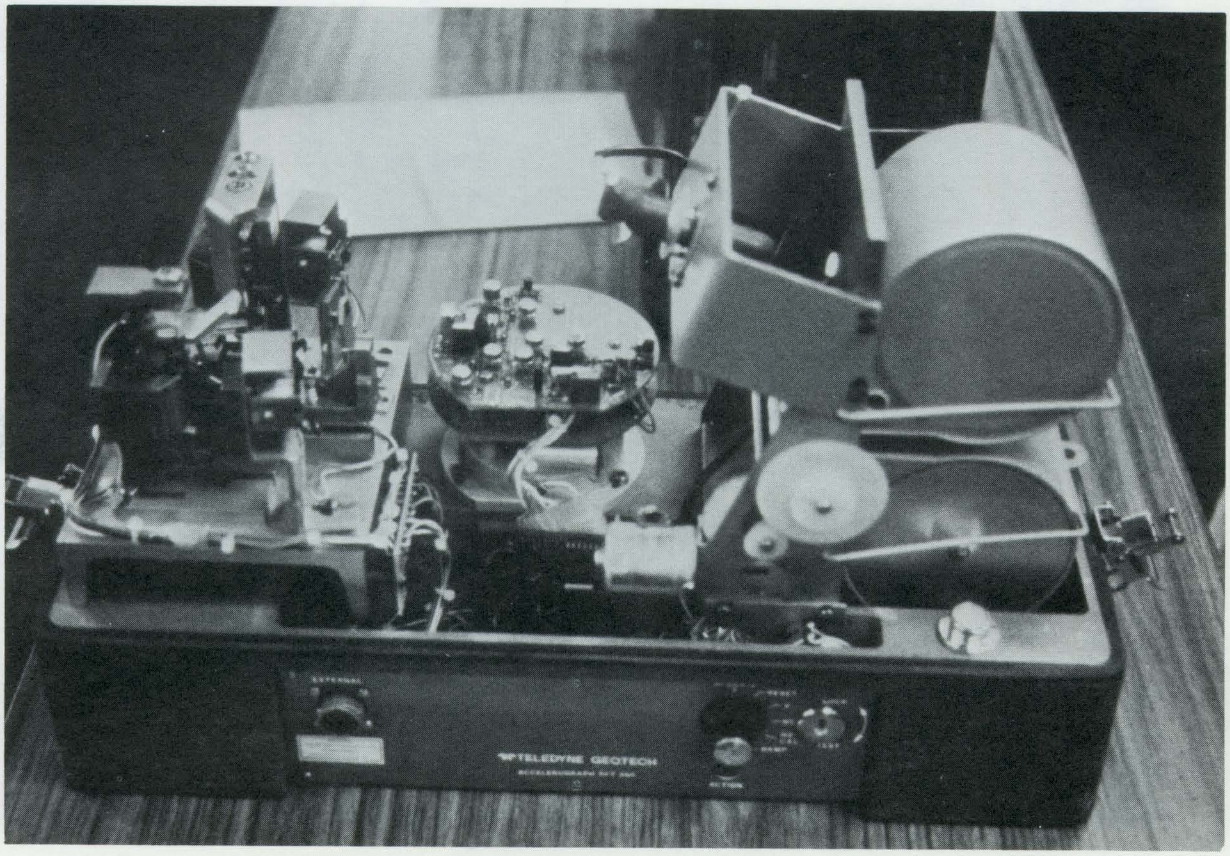

Figure 18: RFT 350 Accelerograph.

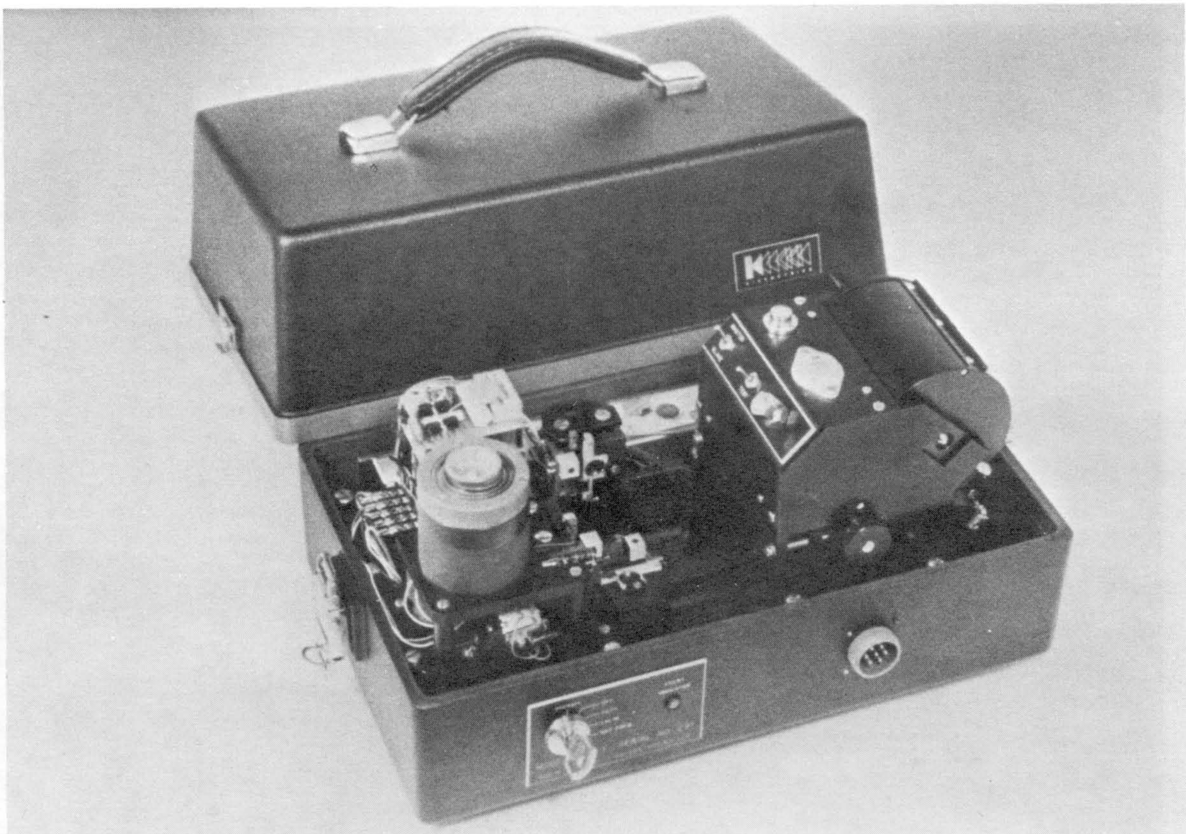

Figure 19: SMA-1 Accelerograph.

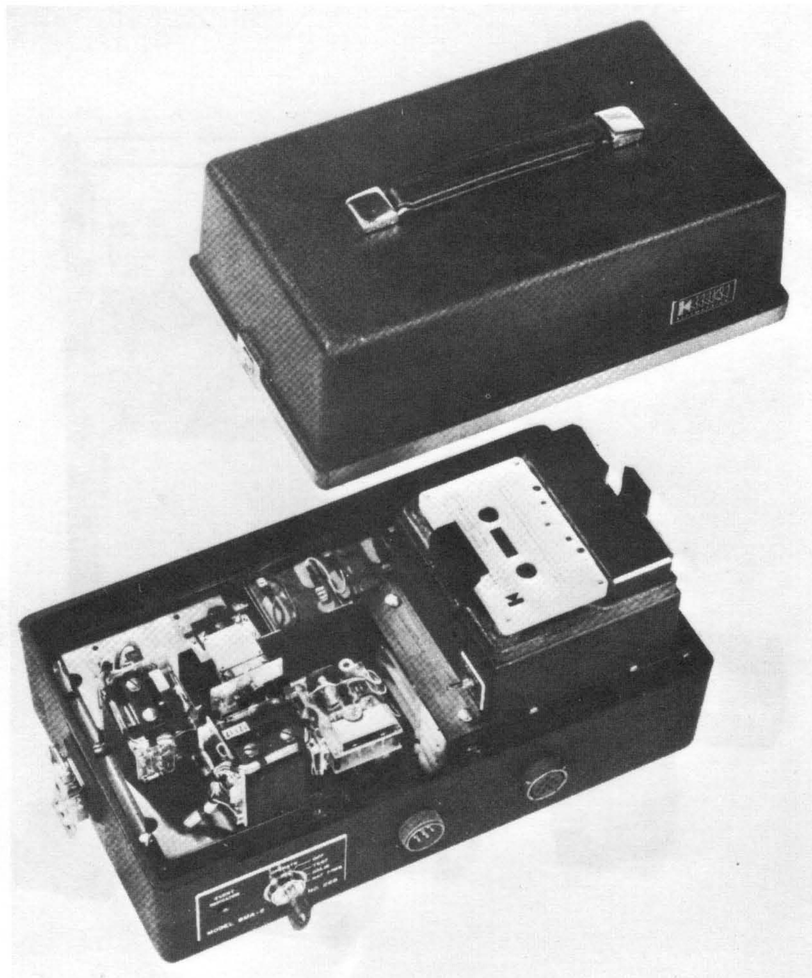

Figure 20: SMA-2 Analog Tape Recording Accelerograph.

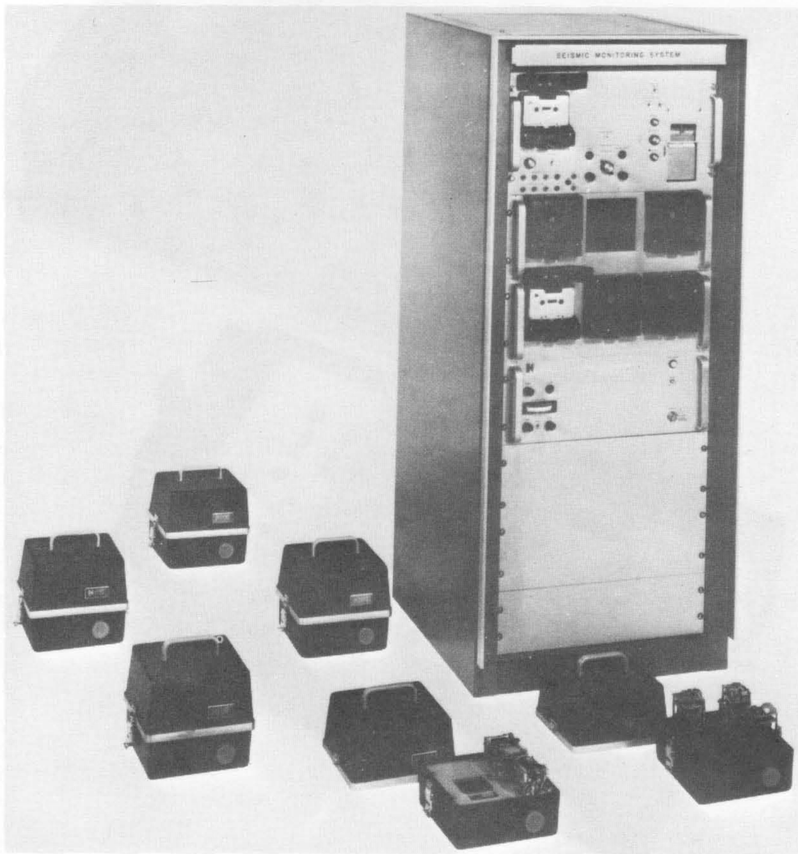

Figure 21: SMA-3 Analog Tape Recording Multi-Channel Accelerograph System.

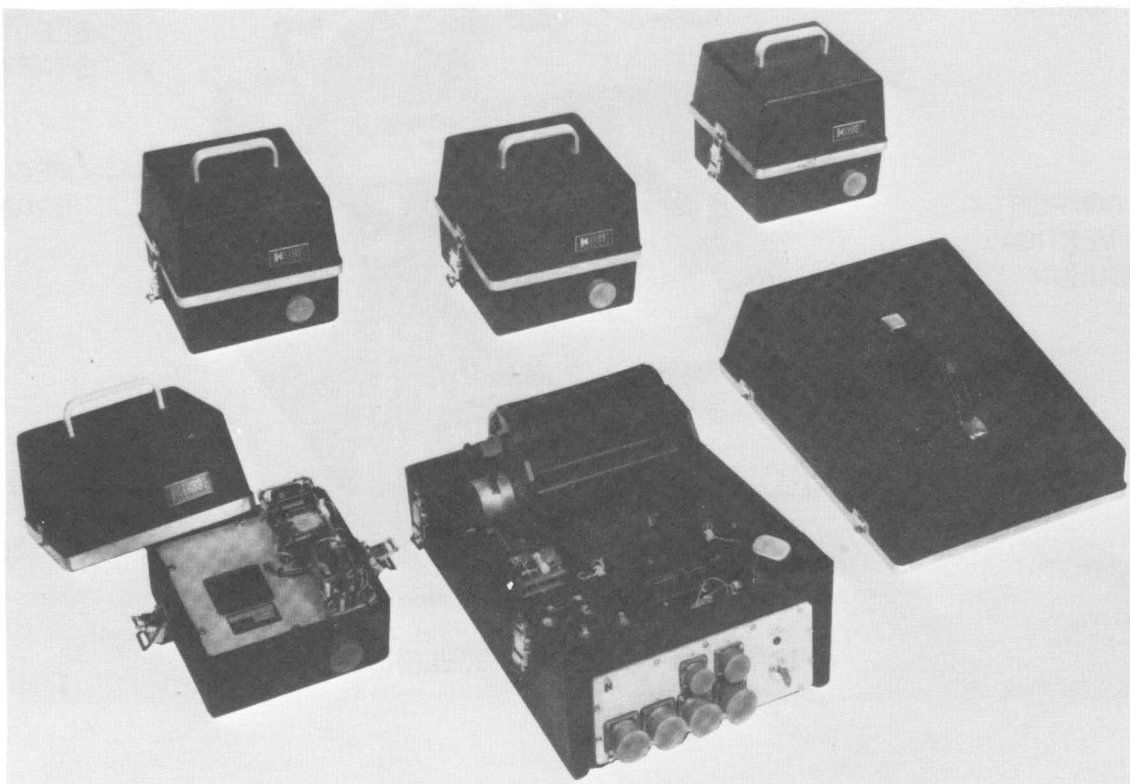

Figure 22: CRA-1 Central Recording Multi-Channel Accelerograph System.

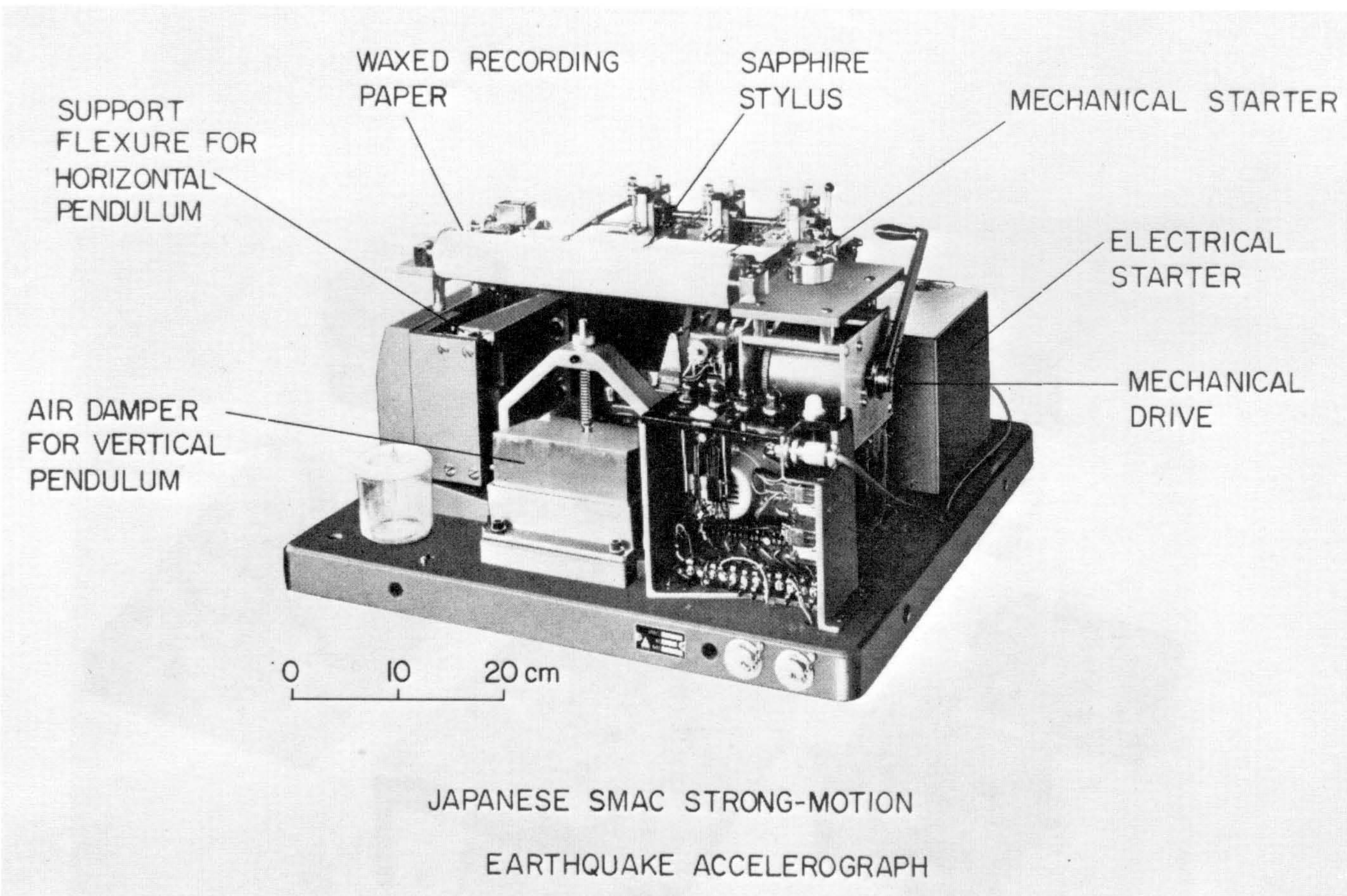

Figure 23: Japanese SMAC Accelerograph.

HISTORY OF ACCELEROGRAM DATA PROCESSING

by

A. Gerald Brady
U.S. Geological Survey, Menlo Park

In looking back over the literature on early analysis and early interpreting of earthquake records, I was impressed by the feeling that everyone was expressing then -- that these records contain high quality data, but that much more could be done with them if we had some means of analyzing them more thoroughly. The particular concerns were: (1) the cost and inconvenience of integrating the records for ground displacements, (2) the instruments were mechanical devices, whose characteristics of behavior could be corrected for, it if were economic, and (3) the desire for understanding how the ground motion would actually affect structures on the ground where records had been obtained. It is on those three points that I will focus my attention -- integrating for ground displacement, some instrument corrections, and calculation of response spectra. Figure 1 shows a schematic representation of a transducer, from an SMA-1. The notation for the various parameters is that used by F. Neumann in 1936.[1] He used a constant k for the electromagnetic damping constant and he used p for the natural frequency of the device. He wrote down an equation connecting the motion x of the base of his accelerograph with that of the amplitudes read off of the record which he called y:

$$\ddot{x} = \ddot{y} + 2k\dot{y} + p^2 y$$

Neumann also wrote this equation in an integrated form:

$$\dot{x} = y + 2k\int_o^t y\,dt + p^2\int_o^t\int_o^t y\,dt\,dt + C_1 + C_2 t$$

and concluded that if the single and double integrations could be carried out with sufficient accuracy the ground displacement could be determined. He used a commercially available integrator to carry out these integrations for a number of records, one sample of which is shown in Figure 2. This is the L.A. Subway Terminal accelerograph recording for the historic March 10, 1933 event. The velocities have low-amplitude, long-period waves in them that nowadays we would regard with some concern and the displacement after the second integration had large displacement pulses with periods of some 50 to 60 seconds at amplitudes reaching 40 cm. In the back of Neumann's mind is the feeling that we have to be very confident of the accuracy of these records that are to be integrated, in view of the time and effort it takes to integrate them, and he was very cautious in the conclusions he reached. George Housner, in 1947, was the next investigator to closely examine the problem of double integration. At the L.A. Subway Terminal Building there were two displacement meters as well as an

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[1]Neumann, F. "Analysis of Records" in Earthquake Investigations in California, 1945-35, Special Publication No. 201, U.S. Dept. of Commerce.

accelerograph, and efforts were being made at this time to compare the ground displacement meters with the computed displacement. At first it did not appear that there was much agreement between the two determinations. Figure 3 shows the computed velocity and displacement of one of the components at the Subway Terminal Building for the October 2, 1933 event. The two components were not aligned in the same directions as the displacement meter components. After a 45° rotation of the components it was possible to compute the displacement in the correct direction, and it was then quite clear that if a sine wave component were removed from the computed displacement, the two displacements would then look much alike. In this way it was realized that ground displacements calculated from accelerograms contain displacements that the researchers in those days did not feel were true, and that the displacements needed to be adjusted or corrected by removing spurious long-period sine waves. An effort to develop a standard correction technique was made in 1961, by Berg and Housner, under the assumption that the distortion that might occur during the recording on an accelerograph could be approximated by a parabolic distortion in the original accelerogram trace. This corresponds to a cubic distortion in the velocity and it seemed reasonable that a cubic removed from a velocity is about as far in the long-period direction as one should go, because to remove shorter periods than that from the record would likely distort the true wave motion in the frequency range of interest. The parabolic correction, which worked reasonably satisfactorily, was least-squares-fitted to the acceleration. It was still possible, however, to get a recorded displacement that did not correspond well at all with a parabolically adjusted acceleration. At about this same time, efforts were made to check on whether the errors that were appearing in displacements were due to the original reading of the records. Figure 4 is a comparison of separate digitizations of the same records at four universities: Illinois, Michigan, Berkeley and Caltech. In an effort to compare computational methods, the calculation of the parabolic baseline was removed from the acceleration and the integrations were also independently done at each of the four universities. Figure 4 is an indication of the spread in the ground displacements from such independent determinations.

In order to get a better knowledge of the errors that were affecting the long periods visible in the displacements, we did some repeated digitizing of a straight line. Figure 5 shows straight line digitizations that we did at Caltech in 1971 in an effort to identify the causes for the errors that were appearing in semi-automatic digitization of strong-motion records. The five individual digitizings, on averaging, resulted in less high-frequency amplitudes and there were certainly some long-period components that might well be due to errors in the digitizing machine itself. It could be shown that on two integrations of this digitization of a straight line, which might be called an acceleration of a "zero" earthquake, the resulting "displacements" were full of long-period noise, as indicated in Figure 6. The scales here are actually the scales of the units of the digitizer (y-axis) and centimeters on the digitizer table (x-axis). It is quite clear that there was a long-period error problem in the digitizing machine itself. Figure 7 shows the results of some tests which involved moving an accelerograph to and fro on a smooth table and recording directly the accelerations (on the recording film) and displacements (by external measurement) of the instrument. By moving the accelerograph in an appropriate sine wave with varying periods, first with short periods of 2 or 3 seconds, passing through a period of some 10 seconds, and eventually reaching periods longer than 20 seconds, an accurate estimate of the longest period that the recorded and the subsequent digitizing was capable of reproducing accurately could be obtained. This led eventually to the choice at Caltech of a long-period limit of around 14 to 16 seconds, below which we were confident of the Fourier content. This result was used for the Caltech data processing project that ran from 1968 through 1975, producing standard data which was reasonably accurate between the high-frequency limit of 25 Hz and a long period of 14 seconds.

Turning next to the question of instrument correction, that is to say, methods of correcting for the fact that at higher frequencies the response of the instrument falls off, we note that Neumann back in 1936 was also well aware of this problem, although he was mainly concerned with the influence of such factors on the integrated ground displacements. The Caltech project was concerned with an instrument correction that would provide a corrected acceleration-time record, and this involved the calculation of derivatives of the record. It was found that the first derivative and second derivative of the accelerogram could be determined with acceptable accuracy as long as the high-frequency noise was removed first. The correction was then performed with a "filter" whose transfer function effectively left everything untouched for frequencies out to 10 Hz, the natural frequency of the instrument for many of those early recordings. The calculation of the instrument corrections by the relatively simple differentiation scheme used in the early days of data processing is no longer satisfactory for the extended high-frequency corrections now desired in modern measurements.

The third subject of concern from the very beginning of data processing was the determination of structural response to earthquake ground motions and this quickly resulted in the formulation of response spectrum theory. One of the early attempts to calculate response spectra involved applying the acceleration record to a mechanical device that would mechanically swing a torsion pendulum to and fro to record the peak response. This mechanical torsion analog system was followed by an electrical analog which was used in the early days by Housner, Martel and Alford. This electric analog work resulted in a 1951 report which collected for the first time response spectrum curves for a number of notable earthquake records. It was from such collections of response spectra and related studies that George Housner was able to develop the basic concepts of design spectra which have been used so extensively by structural engineers since then.

At about this same time digital computations began to become more and more attractive, and considerable thought was given to controlling errors and building up confidence in these new computational techniques. It soon became evident that digital computations were preferable to analog techniques.

It might also be mentioned that the development of the seismoscope at about this time was an effort to find one point on the response spectrum curve which could be obtained at a considerably lower price than from installing strong-motion recorders which would record continuously once triggered, followed by digitization and by some relatively elaborate calculations. The seismoscope came into its own while strong motion recording instruments were still expensive. The analysis required for a seismoscope record was almost trivial. By 1968, however, methods for standard computer calculations of response spectra were published and were being readily used in various organizations. In fact, these mid-1960 calculations for response spectra are those which are still being used.

Some final figures will highlight the latest stages in the data processing story. Figure 8 is a general indication of the effects of filtering of accelerograms on the frequency content, and sums up the progress that has been made during 50 years of work on the integrated ground displacement problem. Figure 8 also relates to the selection of the long period beyond which to remove components that may be spurious. There are some automatic procedures that one can go through based on a considerable amount of analysis of all the records recovered to date, which is another state-of-the-art operation.

It is possible nowadays to digitize accelerograms at sampling rates that are much higher than was considered possible some years ago. With a careful instrument correction we can be confident of frequencies not only as high as the natural frequency of the transducers, but maybe up to twice that frequency. Current U.S. Geological Survey practice uses a filter that includes an instrument correction out to 50 Hz, a cosine taper reducing to zero at 100 Hz, and an anti-aliasing correction removing all content higher than 100 Hz. Finally in Figure 9 we see results of simultaneously recorded records from seven instruments across the Imperial Valley for an aftershock of the 1979 event. Such records, which show displacements from which all signal content longer than 2 seconds has been removed from the acceleration data, give displacements that appear seismologically correct, and give us the feeling that during 50 years of effort at integrating, instrument correcting, and calculating response spectra, we have indeed come a long way.

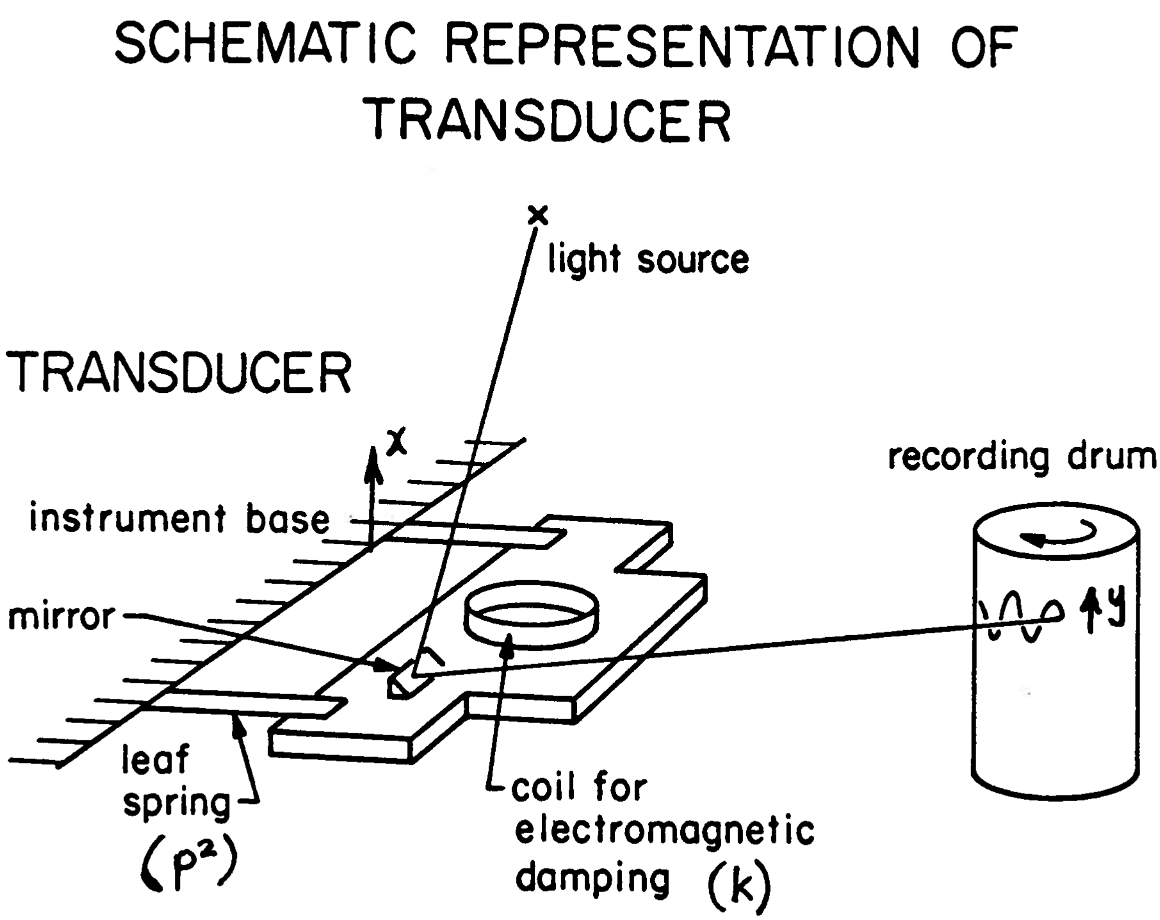

SCHEMATIC REPRESENTATION OF
TRANSDUCER
light source
TRANSDUCER
x
recording drum
instrument base
mirror
y
leaf
spring
(p^2)
coil for
electromagnetic
damping (k)

Figure 1.

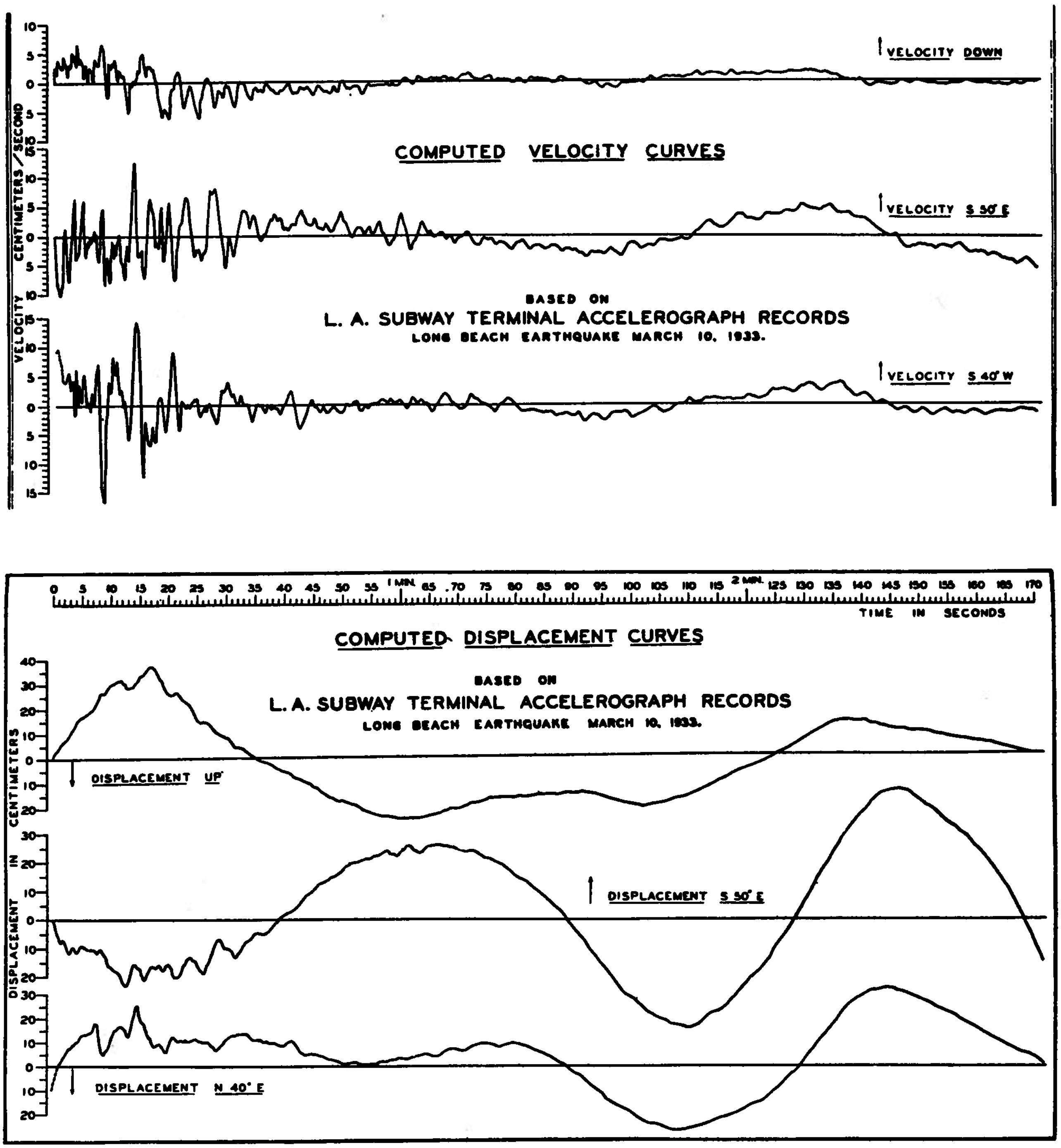


Figure 2. (adapted from F. Neumann)

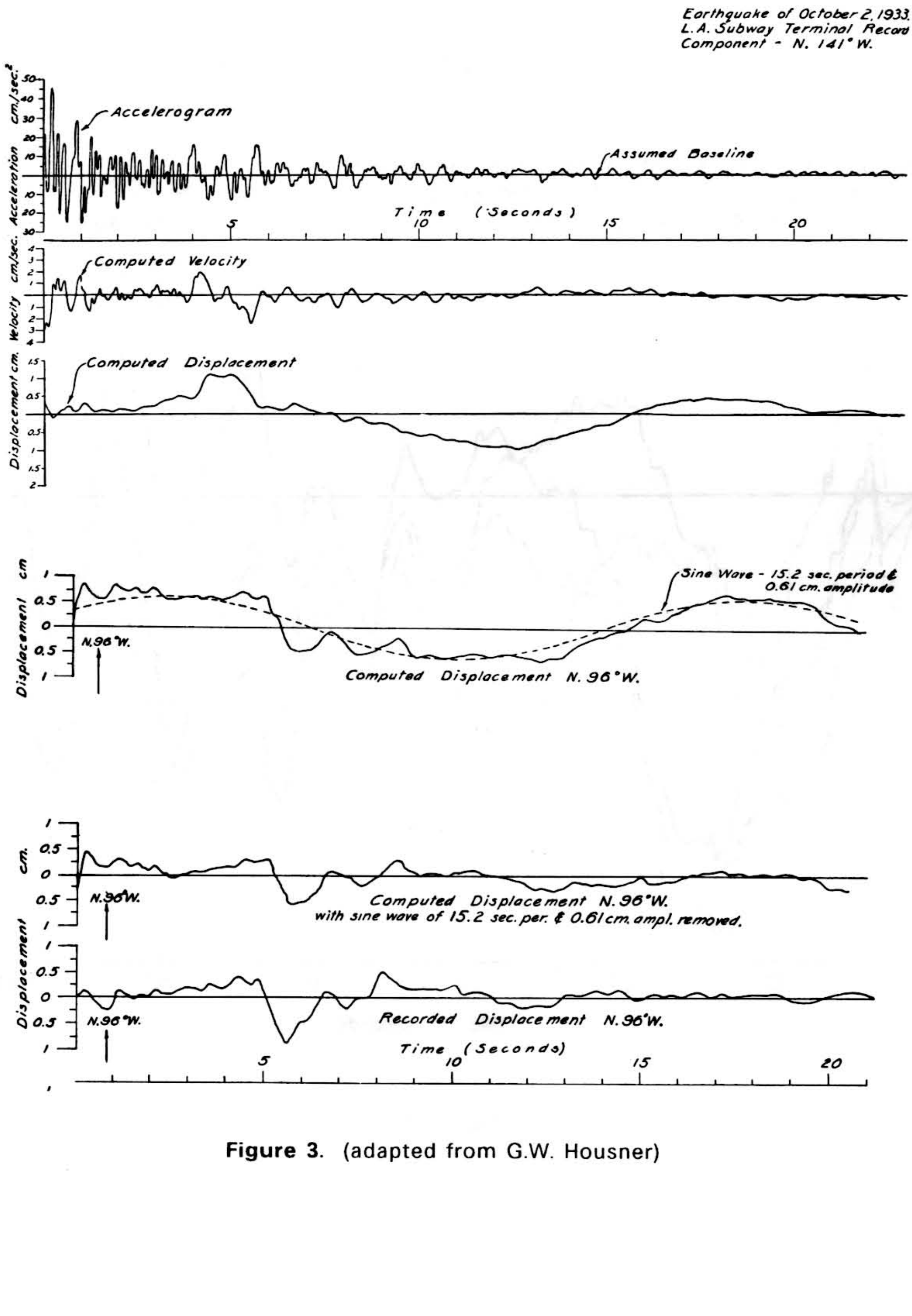


Figure 3. (adapted from G.W. Housner)

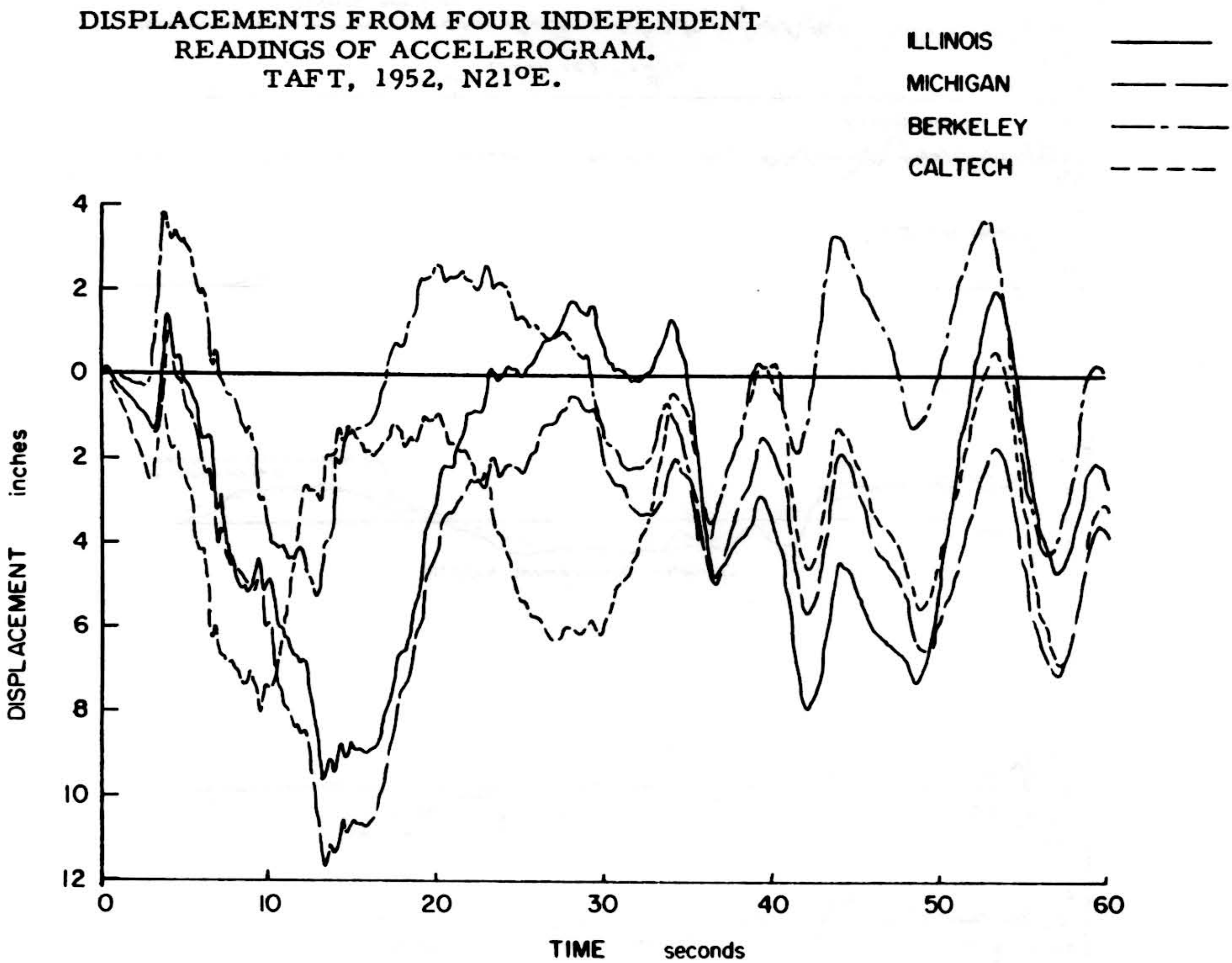

DISPLACEMENTS FROM FOUR INDEPENDENT READINGS OF ACCELEROGRAM.
TAFT, 1952, N21°E.
ILLINOIS
MICHIGAN
BERKELEY
CALTECH
DISPLACEMENT inches
4
2
0
2
4
6
8
10
12
0
10
20
30
40
50
60
TIME seconds

Figure 4.

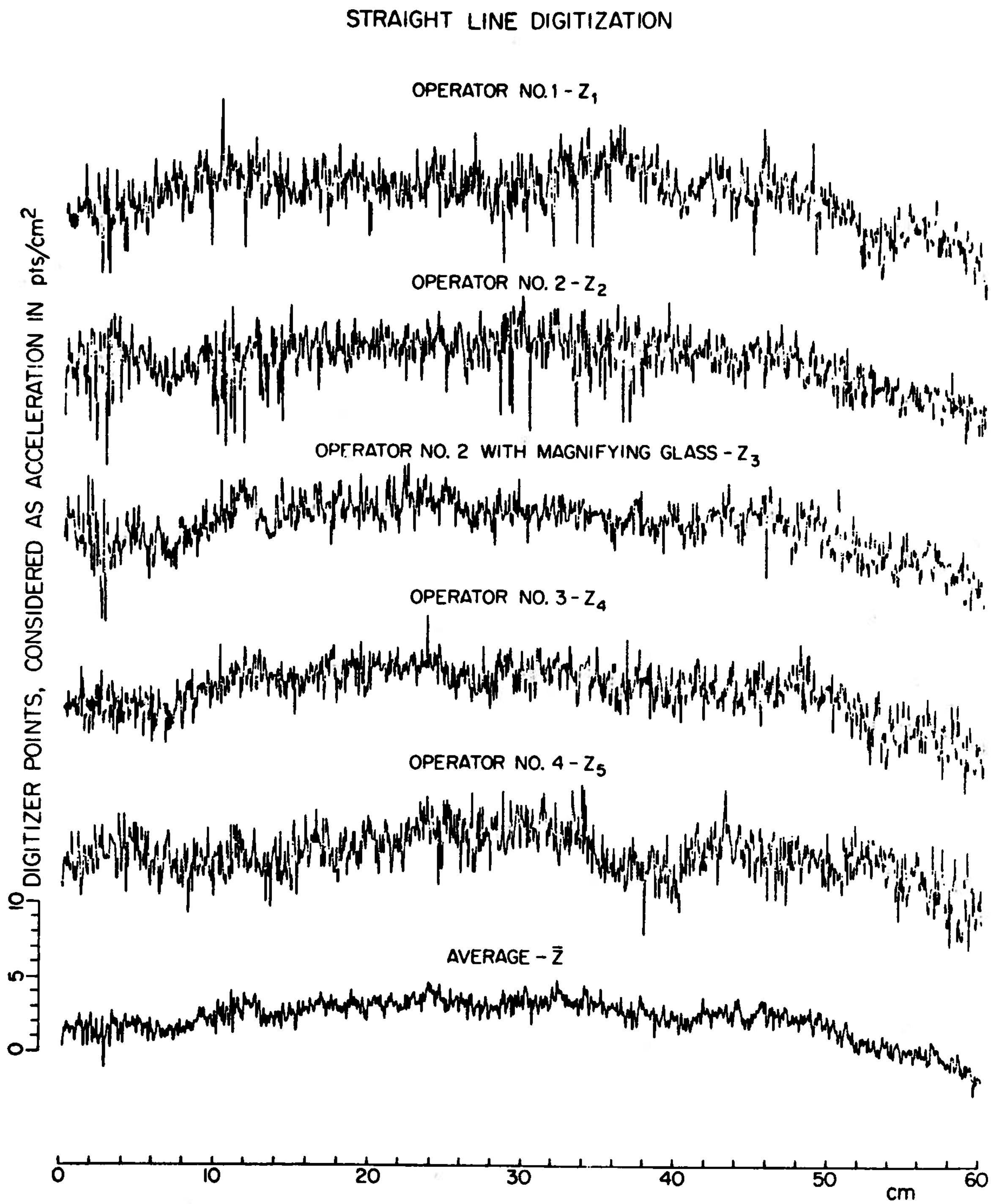


Figure 5. (adapted from M.D. Trifunac)

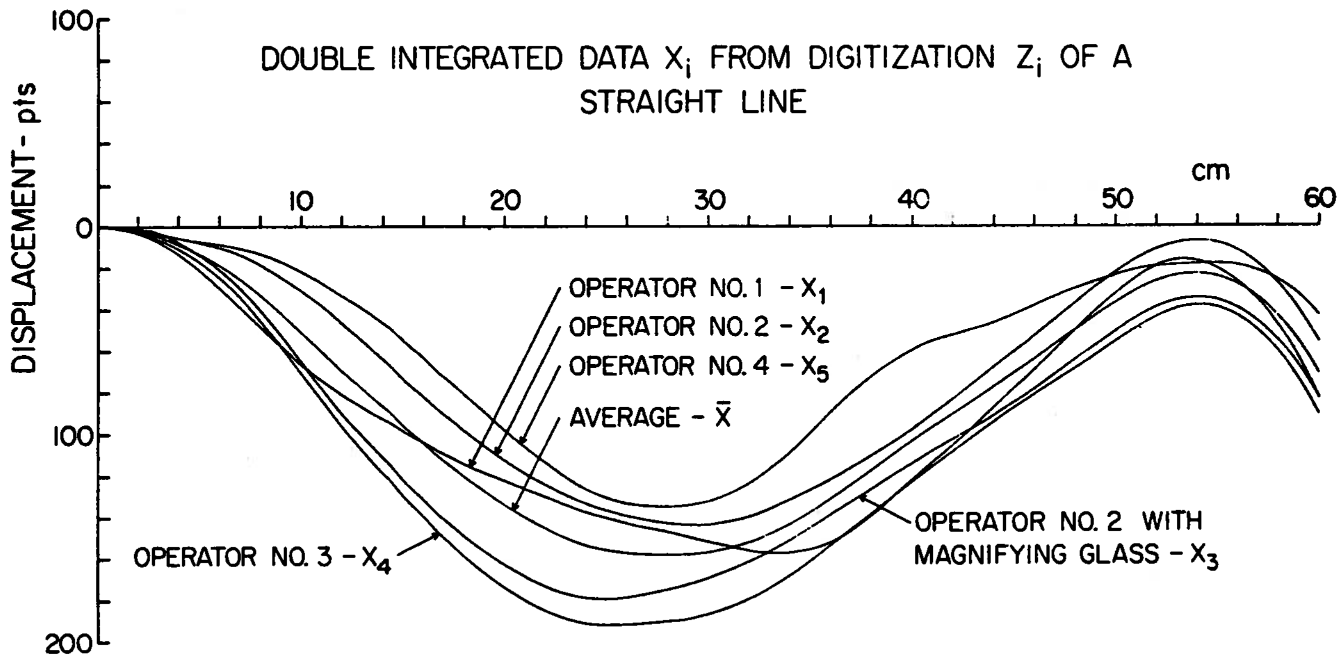
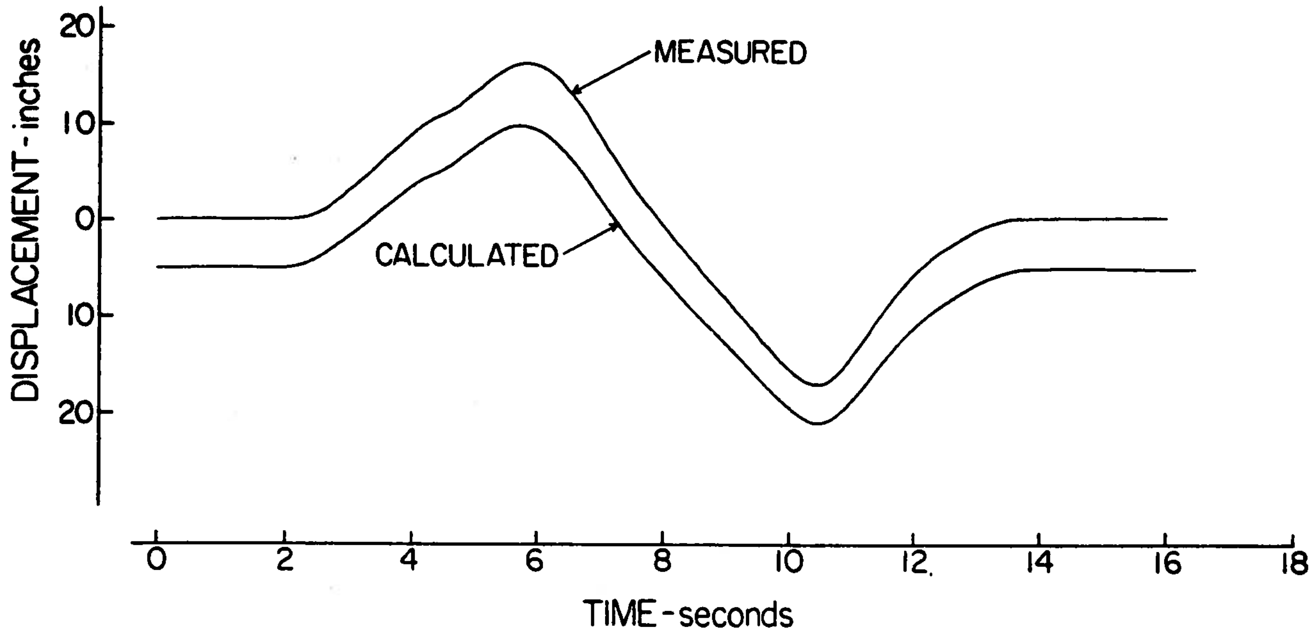


Figure 6. (adapted from M.D. Trifunac)



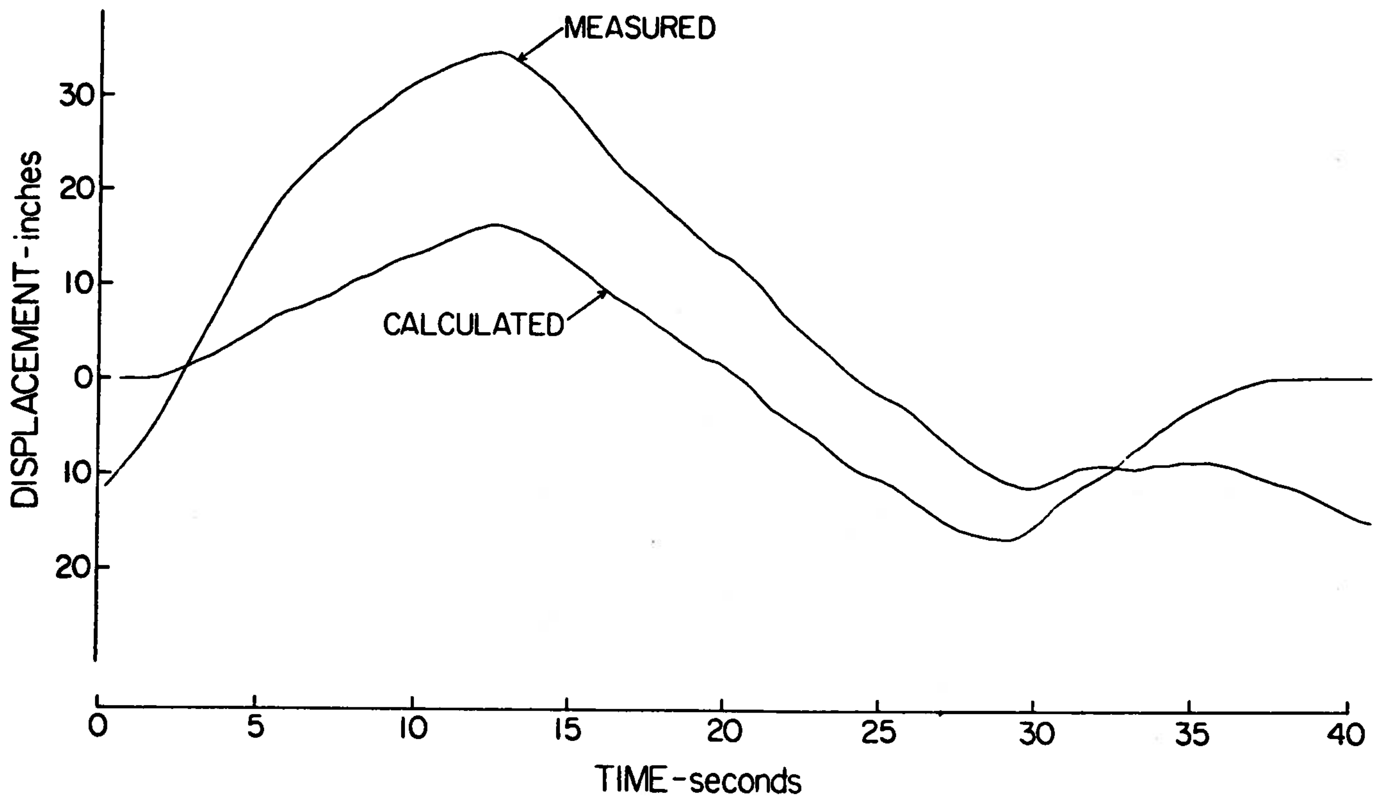


Figure 7. (adapted from M.D. Trifunac)

Displacements from filtered accelerogram

El Centro Array 5 , James Road , 140°

Imperial Valley aftershock 2319 , October 15 , 1979

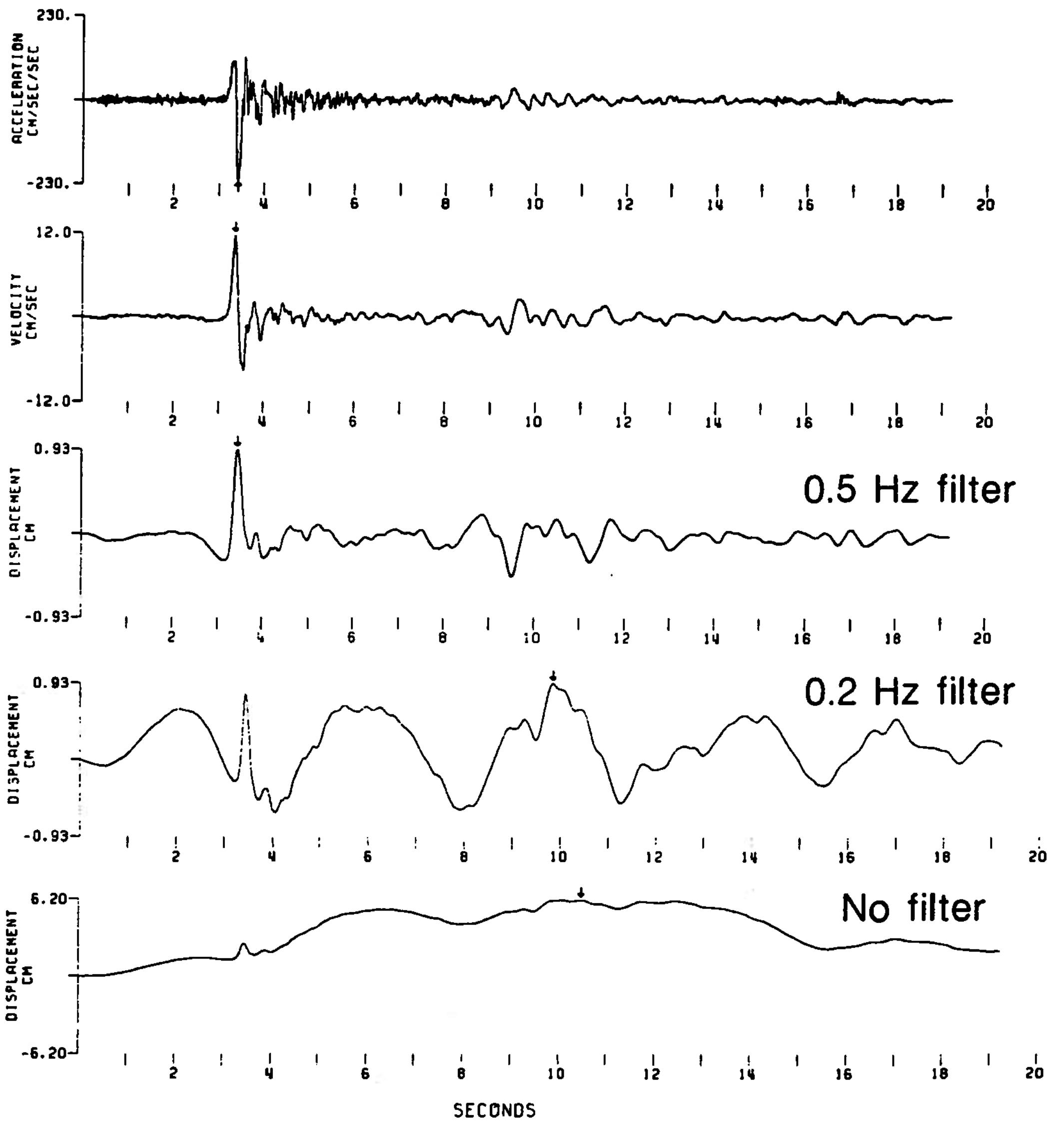


Figure 8.

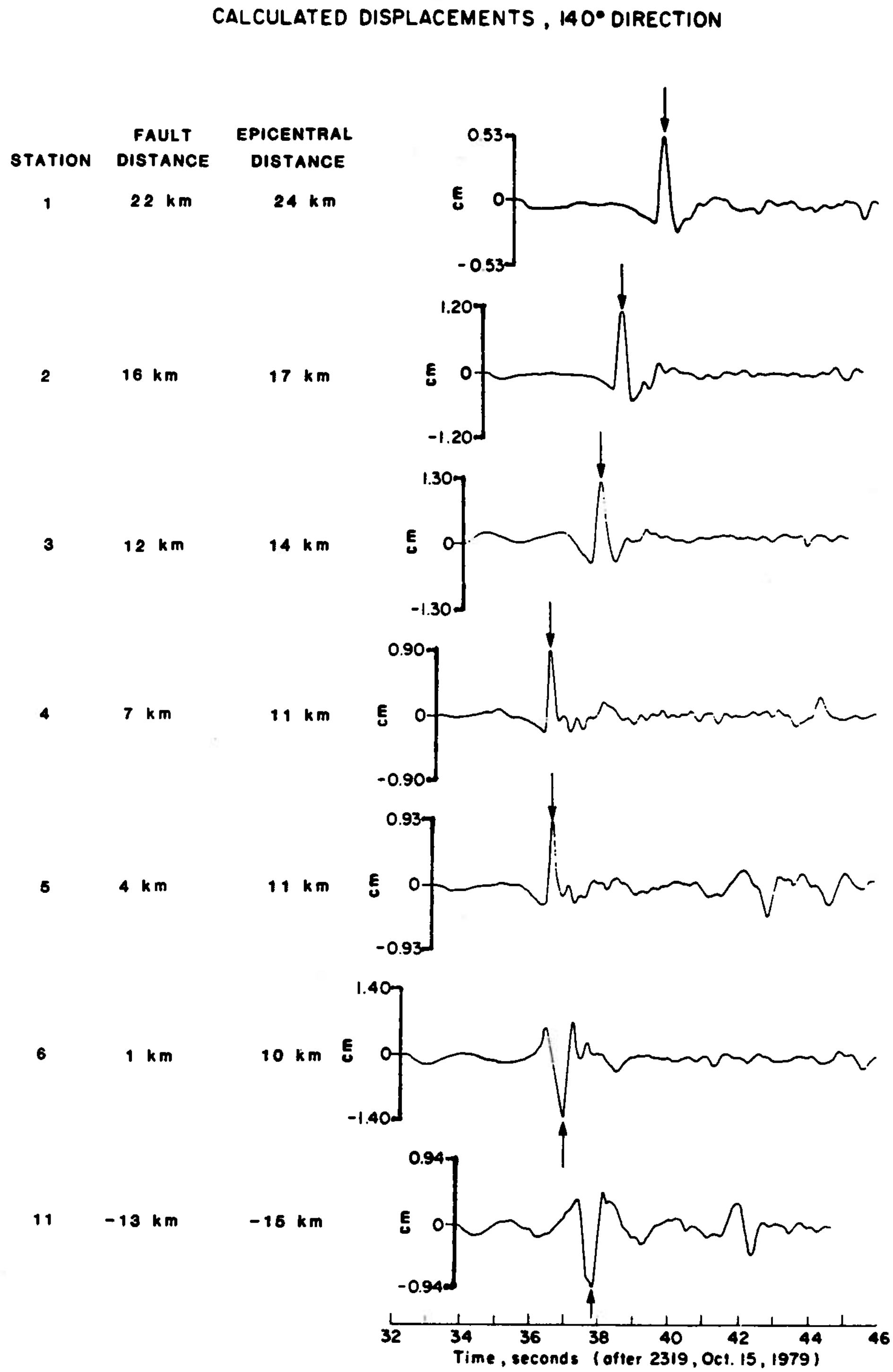


Figure 9: Simultaneously recorded records, Imperial Valley, 1979

BACKGROUND PAPERS FOR PANEL SESSIONS

STRONG MOTION INSTRUMENTATION SYSTEMS

by

D. E. Hudson
University of Southern California

INTRODUCTION

I should like to accomplish three things during my presentation - first to outline the basic objectives of our measurement of strong earthquake ground motion; second, to summarize the essential characteristics of currently available instruments and systems; and, finally, to indicate some of the newer problems and opportunities appearing in our subject - as a basis for more detailed discussions during our forthcoming panel session.

For many reasons the acquisition, installation, and operation of strong motion instrumentation is entering a new phase. The number of strong motion accelerographs now installed ($\approx$ 6,000) presents constant and formidable problems of field maintenance, data collection, and data processing. The relatively high cost of proposed new instrument types and the increasing complexity of field checking and maintenance adds significant economic problems for any major expansion of the world network. Ambitious new plans for strong motion array systems represent an order of magnitude jump in cost and management problems. It will in the future be necessary to seek more diligently for optimum solutions to instrument and array design. It is clear that in many respects existing systems are far from optimal designs, and that major improvements in equipment and operation are still to be realized. It also seems unlikely that we have at present the most effective organizational structure to initiate, carry out, and correlate research and development in the field. These are matters which I hope we can fruitfully discuss during our workshop.

STRONG MOTION MEASUREMENTS

The objective of strong motion instrument design is to produce a transducer-signal conditioner-recorder system from which the maximum amount of information on the characteristics of earthquake ground motion or structural response can be obtained. From the instrument record, subsequent data processing should produce the most accurate values of ground motion over the widest dynamic range and frequency range compatible with feasible costs of instrument deployment, maintenance and data processing. It has long been recognized that such systems could take many different forms. It is not essential, for example, that the instrument produce a record directly proportional to ground displacements, velocities, or accelerations. For many technical reasons, it has developed that the system which most nearly meets all the requirements of field simplicity and ruggedness, ease of installation, calibration, and maintenance and overall accuracy of data processing produces outputs closely proportional to acceleration over the frequency range most often involved in earthquake engineering applications. It is in this sense that the basic instruments used for such measurements of strong ground motion and of structural response are called "strong motion accelerographs." It should be realized, however, that even for such instruments a considerable amount of data processing and instrument correction is needed to produce accurate ground motion information over the maximum possible frequency range. It is also not to be implied that ground acceleration has a special significance. For earthquake engineering applications the ground displacements, velocities, accelerations, and their spectral content are all of importance.

These basic ground motion and structural response measurements are of major importance to earthquake engineers because they make it possible to (1) compare various earthquakes in different parts of the world according to their overall characteristics and potential for structural damage; (2) interpret the behavior of particular structures and decide whether damage resulted mainly from strong ground motion or weakness in the structure; (3) quantify the basic parameters of the processes of earthquake generation and transmission so that seismological investigations can be interpreted and applied to engineering problems, and (4) provide the extensive data bank necessary to deal with the large number of variables involved in the generation and propagation of earthquake waves and their interactions with structures. These basic objectives should always be kept in mind by instrumentation system designers. It is easy to become so interested in the fascinating technical problems and challenges of the instrument itself that the overall objective of the program becomes dim. This is even more important for some of our ambitious array projects, which are becoming so expensive that economic costs can be justified only if the major objectives of the array have been very clearly defined and evaluated. A useful exercise in the planning of any large instrumentation system is to imagine that the ideal earthquake has occurred, that all of the equipment has operated perfectly, and then to picture in detail just what data analysis would be conducted and what research studies could be carried out.

STRONG MOTION INSTRUMENTATION SYSTEMS

All instrumentation systems now in use or in the design stage are combined analog-digital systems. They are analog in the sense that the basic transducer is an analog device, and digital in the sense that data processing is carried out in digital form. The basic differences between competing systems lie in the point at which analog/digital conversions take place and the way in which they are carried out.

Figure 1 illustrates in diagrammatic form a number of strong motion instrumentation systems currently in use. The top diagram is perhaps the simplest possible in principle. The transducer is a mechanical single-degree-of-freedom system, the magnification is by mechanical levers, and the recording is by stylus on wax paper. Digitization is carried out by hand or by a semi-automatic digitizing machine, usually on a photographically enlarged record. The standard Japanese SMAC is typical of this type of device, and it now numbers some 1,000 accelerographs, mostly in Japan.

The second diagram illustrates what is the most popular device now deployed throughout the world. We traced the historical development of these instruments at an earlier session - suffice it to say for our present purpose that there are at least 6,000 of these devices now in active operation. Digitization is performed either with semi-automatic digitizers hand-set on the recorded trace, or now increasingly commonly by completely automatic scanning type digitizers which are available in several different types.

An important point to make is that no matter what the future brings in instrument development, we will have for many years to come thousands of photographic analog trace devices operating in the field producing important earthquake records. An important aspect of data processing is a constant improvement in the way that such analog records can be treated, with a consequent increase in the amount of information which can be retrieved from old records. Many of the existing accelerograms contain more information than has ever been abstracted, and this will remain for many years as an important objective for our investigations.

The analog tape systems shown in the next two diagrams are an intermediate stage in the technology which is rapidly being bypassed by digital recording. Analog tape has suffered from a relatively high equipment cost and a high noise level which reduces the effective dynamic range of the system. Such analog tape systems exist mainly as multi-channel central recording systems, of which there are enough presently existing to pose some data processing problems which have not been much investigated.

The bottom diagram illustrates an analog photographic type multichannel central recording system which has been widely used for structural response installations. Again special data processing techniques are called for, with the number of existing instruments justifying more thorough studies of optimal information retrieval, system noise spectra, etc.

The diagram second from the bottom illustrates what we may call a first generation digital recording system. Several commercial configurations of this type have been deployed in the field, mainly on an experimental basis, but rapid developments in the digital field have already moved on to more complex devices.

Figure 2 illustrates a "second generation" digital accelerograph, which uses more effectively some of the special possibilities inherent in digital systems. The use of pre-event memory plus more sophisticated types of triggering, along with increased dynamic range, are attractive features of such systems, obtained of course at the price of increased cost and power consumption.

Figure 3 shows a "third generation" digital system which can fairly be said to represent the present state-of-the-art. The use of the microprocessor makes it possible to greatly increase the configuration flexibility of the system, and enables one to in effect continually tailor the system to the particular signal being measured. By the use of multiple transducers, or by systems of continually altering transducer characteristics, such systems may soon approach a long-term goal of simultaneously satisfying seismologists and earthquake engineers.

ANALOG AND DIGITAL RECORDING

This is perhaps a good place to summarize briefly the present advantages and disadvantages of digital recording versus older analog recording. Among the potential advantages of direct digital recording are: (1) a pre-event memory can easily be incorporated, to recover first ground motions and to permit intermittant recording techniques; (2) a wide dynamic range, extended by gain-ranging, may improve overall measurement accuracy and make it possible to combine certain seismological and earthquake engineering investigations; (3) data processing is simplified and speeded up; (4) complicated trigger algorithms may be used; and (5) parameter changes of all kinds can be continuously introduced. In presently commercially available forms, digital systems have certain inherent disadvantages, some of which natural design evolutions will no doubt overcome: (1) High power requirements reduce stand-by time after external power loss. The standby time is typically several days rather than the several months common for analog accelerographs. (2) The increased overall complexity requires more frequent field service and a higher level of training for field technicians. (3) Instrumentation costs are significantly higher, perhaps reducing network density. (4) Relatively elaborate data processing systems may be necessary to prepare digital tape from the field for computer processing, or for a quick monitor and inspection or test of earthquake data. The balance of the pros and cons will of course tilt one way or the other depending on the overall purpose of the instrumentation system. It might be mentioned that at present all available digital systems use a mechanically driven tape drive which is probably the most complicated part of the device. In view of the great simplification which would result from the use of a solid state memory for recording, it is to be hoped that this technology will evolve in the near future to where it would be economically feasible.

STATIONS AND ARRAYS

The design of strong motion systems has depended very much on whether the devices were to be primarily individual stations, or were to be part of a network or an array. The first strong motion accelerographs were independent stations placed far from other stations, at points at which it was believed that there was a high probability of strong earthquake ground motion in the near future. It was recognized that many of the instruments would need to be maintained for many years without producing a single record. As the number of accelerographs multiplied, the assemblage of instruments began to be seen as a network, whose primary function was to ensure that no damaging earthquake would occur anywhere near the network without being recorded by at least one accelerograph. This modest goal has now been achieved for many important seismic regions in the world, but there remain many other highly seismic regions for which even this minimal objective has not been attained. A network may be defined as any group of instruments having some common feature, such as management, maintenance, or data processing. Each station of the network can independently produce information of value, but the total information from the network is greater than the sum of the parts, since relationships can be established between measurements at various sites.

Very early in the development of strong motion earthquake instrumentation the idea emerged of deploying a number of interconnected instruments to study in detail particular features of ground motion or structural response. Such an interrelated group of instruments, which may or may not also be part of a broader network, is called an array. The first arrays were structural arrays in tall buildings, usually consisting of three accelerographs hard-wired for common timing, at the ground level and at upper floor locations. At present there are hundreds of high-rise buildings instrumented in this way, and many arrays involving multiple transducers recording at central points have been installed in dams, bridges, and power plants.

Such structural arrays afford an excellent example of the interrelationships between the purpose of the array and the design of the instruments. In earlier days, the structural dynamic characteristics of a building could be determined with a reasonable accuracy from simple measurements of input ground motion and structural response. Today much more elaborate methods of system identification have been developed, which if properly implemented can produce more complete and accurate information about structural characteristics, including non-linear behavior. Such methods require, however, a timing accuracy between various channels which was not usually attained by earlier systems, and it is now necessary to develop much more complicated data processing techniques in an attempt to compensate for such instrumental shortcomings.

The development from individual stations to arrays, and the improvements in dynamic range, much increases the amount of data to be processed, and this also influences the overall design of the instrumentation system. A low density network will produce so few accelerograms that it matters little whether digitization and data processing is time consuming or not. A high density array on the other hand may produce a constant flow of records which if not produced directly in digital form may swamp the data processing facilities.

STRONG MOTION TRANSDUCERS

Although we have so far been emphasizing instrumentation systems, the individual components of the system may also present interesting problems and possibilities for significant improvements. As an example, let us conclude by a brief consideration of some aspects of transducer design. Most of the currently installed analog type strong motion accelerographs employ a basic transducer of the single-degree-of-freedom oscillator type, with velocity proportional electrodynamic damping and direct mechanical or optical amplification. Such a transducer is described by two basic parameters, the undamped natural frequency and the fraction of critical damping. These are relatively stable parameters requiring little adjustment, being little influenced by changes in environmental conditions and being easy to check and calibrate.

All of the newer digital accelerographs and some of the central recording analog film recording systems now use a so-called force-balance type transducer. Since transducers of this type pose some problems not present in older devices, and offer some interesting possibilities for future development, I should like to comment on them here.

Figure 4 shows a very schematic diagram of the elements of a force-balance transducer, also commonly referred to as a servo-accelerometer or as a feedback accelerometer. The essence of the device is that the displacement of the transducer mass is sensed, and signals proportional to the displacement and to the relative velocity are applied through a force generaator to the seismic mass in a direction such as to balance out the inertia force associated with the base acceleration. In addition to the velocity, or derivative feedback signal, an integrated feedback signal can also be used.

If the measured output of the system is taken to be proportional to the relative displacement of the mass, the characteristics of the force-balance system are exactly the same as for the direct single-degree-of-freedom non-feedback system. In this case, the whole function of the feedback circuits is to establish the natural frequency and damping of the system. Most force balance transducers are designed so that the electrical quantities in the feedback system are entirely responsible for the characteristics of the system, which then can be easily altered over a wide range. If instead the output of the transducer is made proportional to the balance force required to maintain the relative displacement of the seismic mass to a small value, the frequency characteristics of the device are much altered. Figure 5 compares the two frequency response curves, and shows that a much wider range of possibilities exist. In either case the phase-shift characteristics can be made reasonably linear to preserve wave-shape of complicated waves forms.

The advantage of the force balance transducer thus lies in the ease with which the basic transducer characteristic can be altered by electrical means, which in turn could easily be controlled by the microprocessor in a digital accelerograph system. Although no presently existing system exploits these possibilities, they should be investigated. A disadvantage of the force balance transducer is the large number of elements involved in setting the instrument characteristics, changes in which might significantly alter instrument response. Since electrical differentiating circuits are not exact, for example, the mathematical models used to describe force balance systems may not be as accurate as those used for the older systems. This could influence both the problem of instrument evaluation and checking, as well as the transducer corrections used for extending frequency range in the data processing procedures.

SIMPLIFIED SYSTEMS

It is perhaps worthwhile to make some comments on so-called simplified instruments. In the early days it was widely believed that if a low-cost device costing a few dollars could be very widely distributed, much information might be quickly obtained, and many such devices were proposed and even constructed. Peak reading devices, or systems without accurate time recording, were often suggested. A common fate for such systems was to discover that once realistic manufacturing and marketing costs were included, the price was not after all so low. There was also a growing realization that the costs of installation, maintenance, data collection, processing and dissemination were often of such a magnitude that the actual first cost of the particular device installed at the site was not a large factor. In addition, technical developments and lowered costs resulting from quantity production have much lowered the costs of time recording systems. In most applications, the consensus is that the more complete information obtained from time-recording systems justified their choice over simpler devices.

SYSTEM EVALUATION

The greatly increased complexity of modern strong motion instrumentation systems would seem to justify a more comprehensive program of instrument and system evaluation than is commonly carried out. At present there does not seem to be within the earthquake engineering community any group or organization with a special mission to conduct investigations of this kind. Even such fundamental studies as the establishment of the overall noise spectra for a proposed system are seldom carried out. Figure 6 is an example of one of the few studies that have been made of typical noise spectra for a transducer - film recording-semi-automatic digitized accelerograph system. More investigations of this kind for the newer types of accelerograph systems are urgently needed.

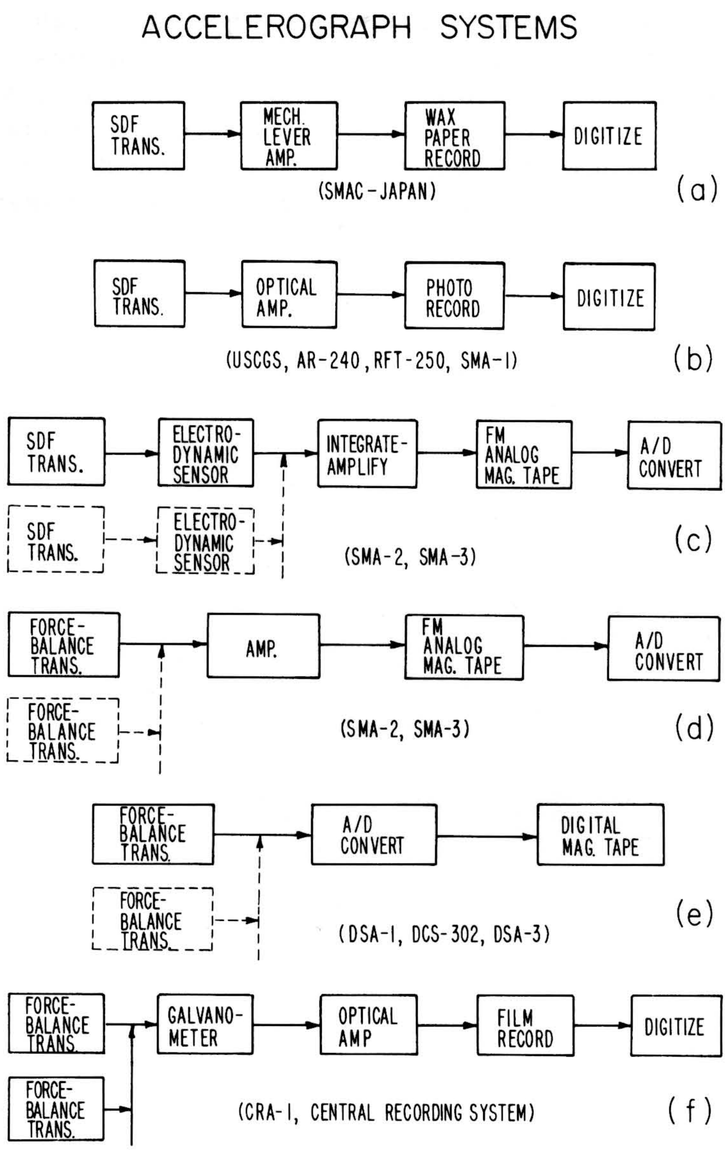


Figure 1: Accelerograph Systems.

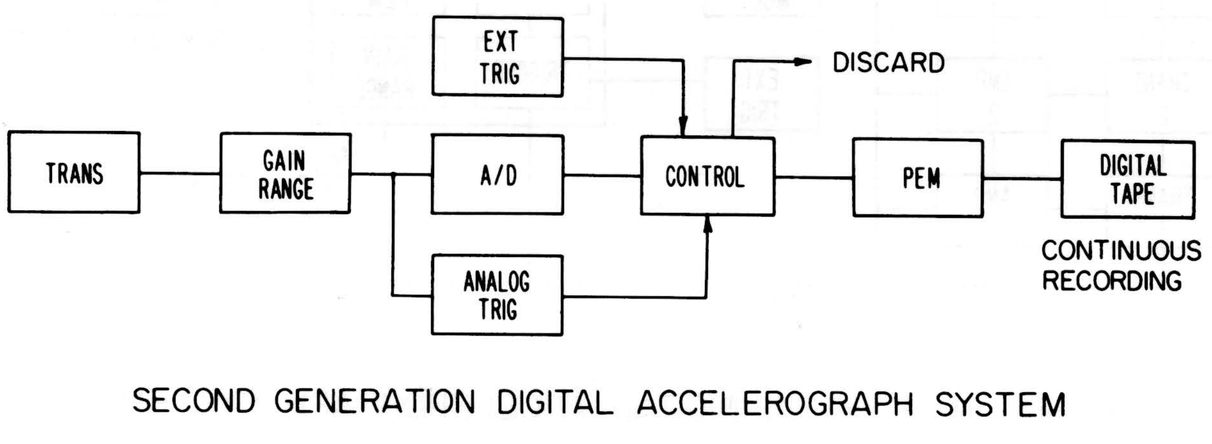


Figure 2: Second Generation Digital Accelerograph System.

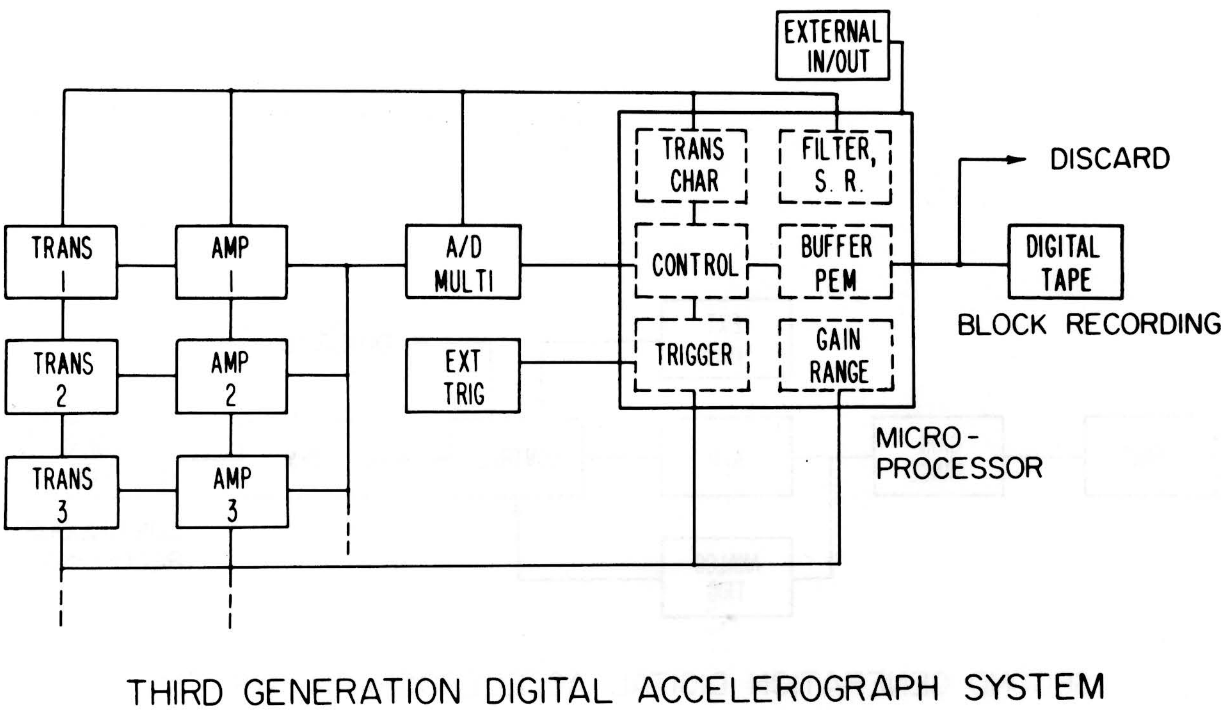


Figure 3: Third Generation Digital Accelerograph System.

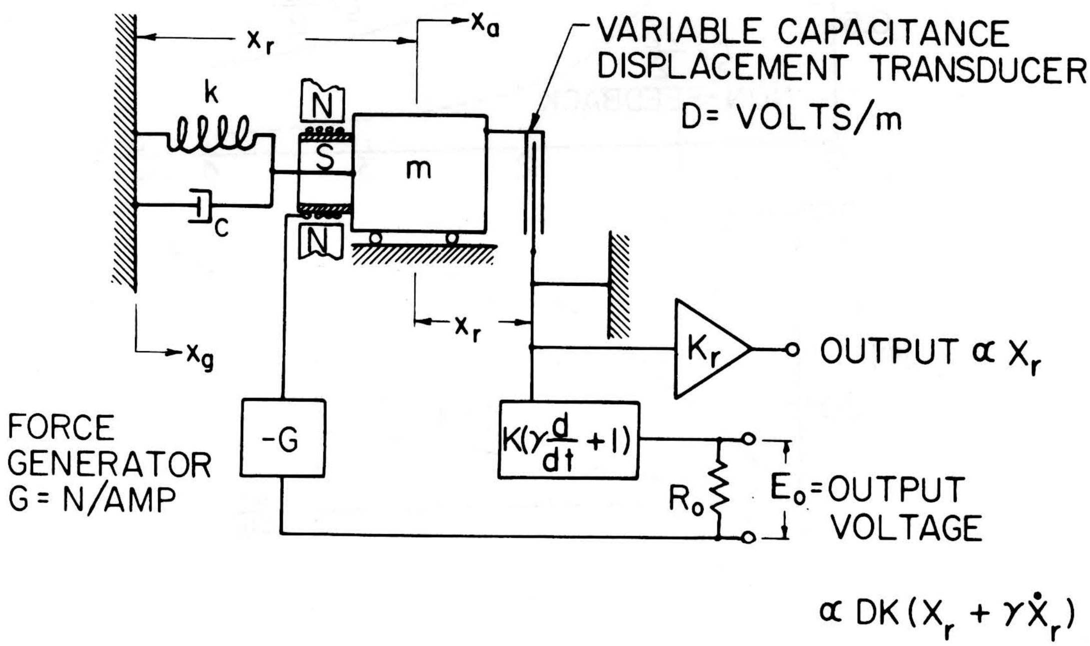


Figure 4: Elements of a Force-Balance Type Transducer.

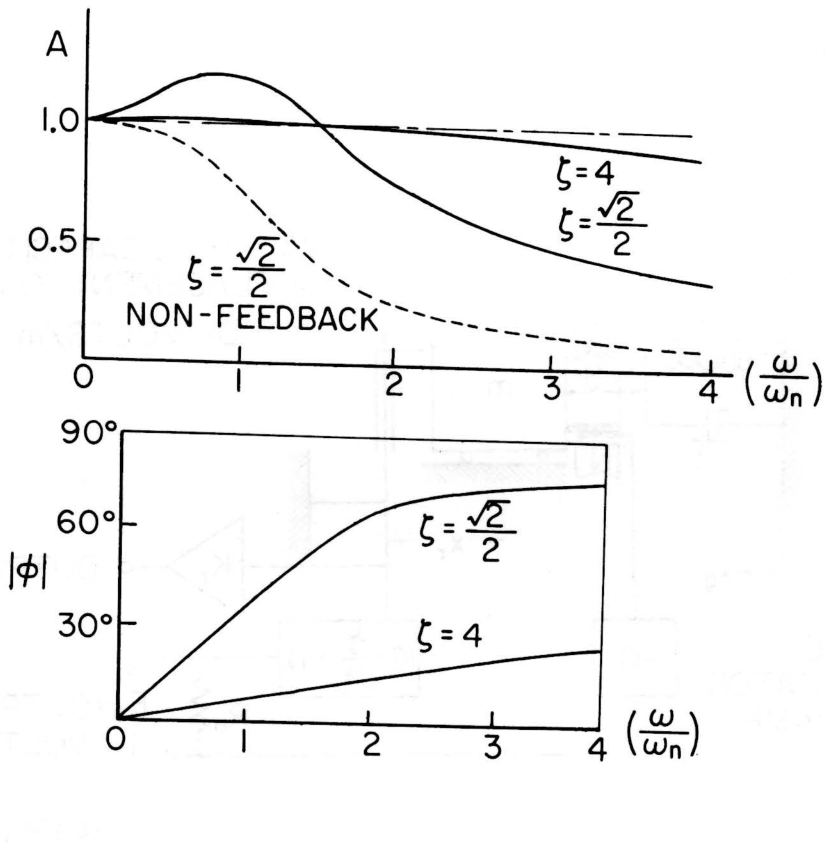


Figure 5: Characteristics of Feedback and Non-Feedback Transducers

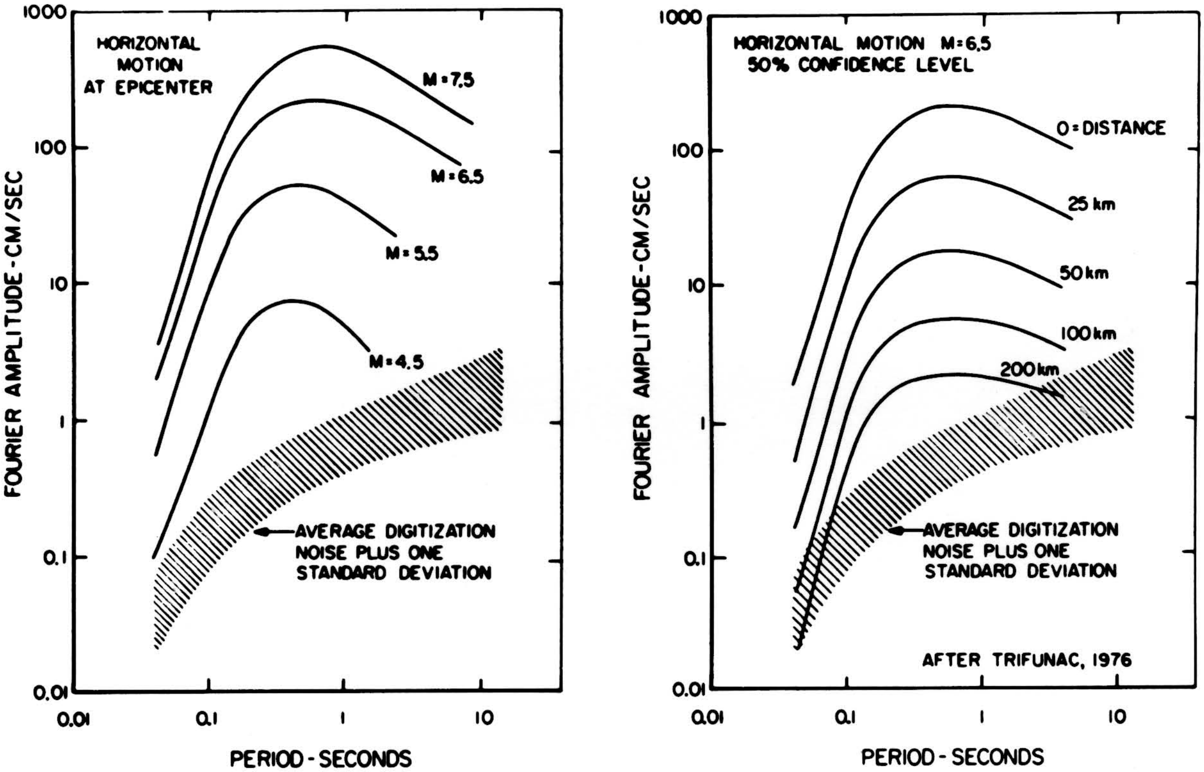


Figure 6: Noise Spectra for a Standard Accelerograph System

STRONG-MOTION NETWORKS IN THE UNITED STATES; A REVIEW

by

Roger D. Borcherdt[2]

Abstract

Strong motion data from large earthquakes provide the basis for the design of buildings, bridges, dams and other critical structures as well as the basis for research on fundamental problems related to earthquake hazard evaluation, earthquake processes, and internal structure of the earth. Review of existing strong-motion data acquisition programs in the United States shows significant progress in instrument deployment since 1933, but that significant improvements in data acquisition capabilities are needed for scientific and engineering research studies. The need for installation of several additional well-designed strong-motion arrays (free field and structural) in areas of the United States likely to experience major earthquakes is readily apparent.

Introduction

Safeguarding life and property from the destructive effects of earthquakes is a major national as well as world-wide problem. Since the most widespread destructive effects of earthquakes are due to strong shaking, either directly through shaking-induced structural damage, or indirectly through shaking-induced ground failures, effective programs to measure, analyze, and predict strong earthquake-generated ground motions and structural response to such motions are vital to national and international earthquake hazard reduction efforts. Earthquake strong-motion data provide the basis for the design of engineered buildings, bridges, dams and other critical structures as well as the basis for research on fundamental problems related to earthquake processes, and internal structure of the earth.

Even though there has been a substantial increase in the strong-motion data base in recent years and in spite of the fact that several large (greater than magnitude 7) damaging earthquakes occur each year in different parts of the world, there is still a scarcity of ground-motion data for large earthquakes at distances less than 40 kilometers. The lack of data on the responses of instrumented structures, particularly damaged structures, to strong earthquake motions is even more critical. The scarcity of data is due to inadequate amounts of instrumentation and defines an urgent need for expanding both the U.S. and international programs to collect and disseminate near-fault strong motion and structural response data.

Existing instrumentation networks in the United States are summarized and results presented for an expansion of the strong ground-motion network in California. Evaluation of the present networks by Borcherdt and others (1984) shows that should another major

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earthquake such as that of 1857 or 1906 occur, the present network is not sufficient to provide a minimally adequate record of near source strong ground motions.

Strong-Motion Networks and Arrays in the United States

Strong-motion instrumentation programs in the United States are operated by a number of federal, state, and local agencies and several universities with varying degrees of coordination provided by a national program operated by the United States Geological Survey (USGS). Currently there are over 2,000 accelerograph installations located in 38 states (Figure 1). Most of these accelerographs are located in or near buldings or other structures, and a majority of the instrumentation is located in California (Figure 2). The two largest networks are operated by the California Division of Mines and Geology (CDMG), which manages the California Strong Motion Instrumentation Program, and the USGS, which operates a national strong-motion program. In addition to its own instruments, the USGS also operates on a reimbursable basis the instruments owned by the California Department of Water Resources (CDWR), the Federal Highway Administration (FHWA), the Metropolitan Water District (MWD) of Los Angeles, the Veterans Administration (VA), and several other agencies. Other large networks are operated by the Army Corp of Engineers and the University of Southern California (USC), and smaller networks are operated by the California Institute of Technology, the University of California at Los Angeles (UCLA), Lamont-Doherty Geophysical Observatory, and others. The existing strong-motion networks are designed to obtain data for a variety of purposes, including: (1) ground-motion studies; (2) structural response studies; and/or (3) facility-evaluation studies. Following is a brief summary of the networks operated for these various purposes.

Ground-Motion Arrays

Currently there are approximately 629 installations designed for the express purpose of obtaining ground-motion data (Table 1); 188 of these are operated by the USGS, 244 by the CDMG, 74 by the USC, 51 by the VA, and 72 by other institutes (Switzer and others, 1980). In addition, there are numerous instruments nationwide located at instrumented structure sites that may provide additional ground-motion data (see sections following on Structural-Response Arrays and Facility-Evaluation Arrays). Seventy-two percent of the existing ground-motion sites are located in California, 19% in other parts of the West, 4% in the Central U.S., and 5% in the East (Table 1). Approximately 25% of the instruments are installed in instrument shelters, and the remainder are installed in buildings at ground level or in the basement. Sites in the latter category are not considered to be ideal "free-field" sites and may yield strong-motion recordings that include structure-induced motions.

The national program operated by the USGS includes ground-motion instruments installed in regional arrays in California. The regional arrays are located in Alaska (51 instruments, including those of cooperating agencies, Figure 3), along the San Jacinto and San Andreas faults in southern California (37 instruments), Hawaii (19 instruments, Figure 4), the New Madrid region of the Mississippi Valley (16 instruments, plus those of cooperating agencies, Figure 5), and the Pacific Northwest (16 instruments). The isolated

Table 1. Summary of Ground Motion Stations in the U.S.

Location	Agency	Number of Station Types*: Instrument Shelters	Buildings	Unidentified
		WESTERN U.S.		
Alaska	USGS	12	24	–
	Other	2	3	10
California	CDMG	104	140	–
	USC	–	74	–
	USGS	14	73	–
	VA	–	6	–
	Other	13	16	16
Hawaii	USGS	–	19	–
Nevada	USGS	1	5	–
	VA	–	1	–
Northwest	USGS	2	14	–
	VA	–	6	–
	Other	3	3	–
Rocky Mountain	USGS	1	3	–
Region	VA	–	2	–
Southwest	VA	–	4	–
	Other	2	–	–
Utah	USGS	–	1	–
		CENTRAL U.S.		
North Central	VA	–	2	–
Mississippi	USGS	–	16	–
Valley	VA	–	5	–
South Central	VA	–	2	–
		EASTERN U.S.		
Northwest	VA	–	13	–
	Other	–	2	–
Mid-Atlantic	VA	–	6	–
Southeast	USGS	–	3	–
	VA	–	4	–
	Other	–	1	–

*Source: Switzer and others, 1980.

sites nationwide are located at VA Hospital facilities in Seismic Zones 2 and 3, as defined in the Uniform Building Code (ICBO, 1973), and at a few facilities located in Seismic Zone 1. The closely-spaced-instrument arrays are located in Bear Valley (1 array, 9 stations) and the Imperial Valley (2 arrays, 19 instruments). The largest of the arrays in the Imperial Valley is the El Centro Array, which was designed to obtain data on ground-motion attenuation and consists of 13 stations in a 45km-long array that crosses the Imperial fault near El Centro (Figure 6). The El Centro Differential Array, also located in the Imperial Valley, is a 6-instrument 300m-long array in El Centro (Special array, Figure 6) that is designed specifically to record differential ground motions at closely spaced intervals (Bycroft, 1980).

The California strong-motion program, established in 1982 and operated by the CDMG, is funded by a tax on building permits and has as its objective the instrumentation of representative geologic sites and structures statewide. The CDMG ground motion stations are located at numerous isolated sites statewide and in several closely-spaced-instrument arrays including: the APEEL Array operated cooperatively with the USGS in the San Francisco Bay Region (9 stations in a linear array crossing the San Andreas and Hayward faults), the Chalome-Shandon Array (40 stations in a two-dimensional array near Chalome), and the Gilroy Array (5 stations in a linear array crossing the Calaveras fault established in conjunction with the USGS near Gilroy). The CDMG also operates a 3-instrument down-hole station in San Benito.

The other extensive U.S. ground motion network is that of the University of Southern California. This network is located in the Los Angeles region and is intended to provide data for the study of the influence of subsurface geology and local site conditions. Smaller ground-motion networks and isolated stations are also operated by other universities and agencies; these include Lamont-Doherty Geological Observatory, the California Institute of Technology, and the University of California at Berkeley, which operates a 3-instrument down-hole array in Richmond, California.

Structural-Response Arrays

Currently there are approximately 109 structures nationwide instrumented to obtain data for structural response studies (Table 2): 76 buildings, 14 bridges, and 19 dams. Many of these structures have been extensively instrumented to obtain information on the important aspects of structural response. In the cases of buildings, for example, the instrumentation is located so as to provide information on the overall deflected shape of the structure and to differentiate torsional and translational response. Other structures contain less instrumentation but are of interest because of the importance and location of the structure. In either case, the general intent is to obtain data that can be used to improve engineering design practice.

The structures instrumentation program of the USGS consists of 9 buildings and 9 bridges (Table 2), 11 of which are maintained with funds provided by other agencies that own the instruments. Most of the structures in this program have been extensively instrumented in accordance with instrumentation techniques developed at the USGS (Rojahn and Matthiesen, 1977; Rojahn and Ragget, 1981); approximately one-half of the structures are located in California, several in Alaska and Washington, and 1 each in New

Table 2. Summary of Structures Instrumented to Provide Data for Structural-Response Studies

Location	Agency*	Number of Structures With Extensive Instrumentation	Number of Structures With Minimal Instrumentation
		BUILDINGS	
California	CDMG	51	–
	CIT	–	2
	UCLA	3	11
	USGS	1	2
	VA/USGS	4	–
Alaska	USGS	1	–
		BRIDGES	
Alaska	USGS/FHWA	1	–
California	CMDG	3	–
	CDMG/FHWA/USGS	1	–
	CDOT/USGS	–	3
Missouri	USGS/FHWA	1	–
Nevada	UNV	–	1
New York	FHWA/USGS	1	–
Washington	WHD/USGS	3	–
		DAMS	
California	CDMG	5	14

*CDMG – California Division of Mines and Geology, Sacramento.
CDOT – California Department of Transportation, Sacramento.
CIT – California Institute of Technology, Pasadena.
FHWA – Federal Highway Administration.
UCLA – University of California, Los Angeles.
USGS – U.S. Geological Survey, Menlo Park, California.
UNV – University of Nevada, Reno.
VA – Veterans Administration, Washington, D.C.
WHD – Washington (State) Highway Department.

York and Missouri. During the late 1960's and early 1970's, instruments in numerous code-instrumented buildings in California were also maintained under this program, then operated by the Seismological Field Survey of the Coast and Geodetic Survey (later known as the Environmental Science Services Administration and still later as the National Oceanic and Atmospheric Administration). Since 1973, however, the maintenance of code-instrumented buildings in California has been phased out of the national program due to changes in funding and objectives of the program.

The structures instrumentation program of the CDMG, which currently contains 51 buildings, 4 bridges, and 19 dams, may eventually contain more than 400 instrumented structures, if projections made several years ago prove to be accurate. The objective of this program is to instrument representative buildings, bridges, dams, and other structures statewide to obtain data to improve engineering design practice. Because the program is funded through a tax on new building construction in California, the CDMG program naturally emphasizes the instrumentation of buildings. Most of the structures instrumented under the program have been instrumented in accordance with techniques developed at the USGS (Rojahn and Matthiesen, 1977; Rojahn and Ragget, 1981), and the vast majority are located at sites where damaging levels of ground motion can be expected to occur within the expected useable life of the instrumentation (20 to 40 years). The structures are selected on the basis of advice provided by an advisory panel (the Strong Motion Instrumentation Committee of the California Seismic Safety Commission), which acts on recommendations provided by organizations such as the Structural Engineers Association of California, the California Department of Transportation, and other state and local agencies that operate structures that would be adversely affected by earthquakes.

The remaining instrumented structures (Table 2) have been instrumented by the faculty of several universities interested in the solution of earthquake engineering problems. The California Institute of Technology has instrumented 2 buildings, UCLA operates instruments in 14 buildings (11 of which were originally LA code-instrumented buildings), and the University of Nevada operates instruments on 1 bridge. Most, if not all, of these programs have been funded by the National Science Foundation.

Facility-Evaluation Arrays

Currently there are more than 460 structures instrumented nationwide to obtain data to evaluate the safety of the instrumented structure following earthquake-induced strong-ground shaking (Tables 3a, 3b, and 3c): 133 dams, 12 pumping, power, and filter plants, and more than 315 buildings. What differentiates these arrays from those designed to obtain structural response information are the amount and location of strong-motion instrumentation. Structures instrumented to provide safety-evaluation data generally contain less instrumentation than would be required to provide data adequate for rigorous 3-dimensional structural response studies. More specifically, structures instrumented for facility evaluation normally contain only that instrumentation required to provide information on ground motion input, peak structural response, and changes in model properties, particularly natural period changes.

Most of the instrumented buildings that fall under the category Table 3b are 10

Table 3a. Summary of Dams Instrumented to Provide Data for Facility-Evaluation Studies

Location	Number of Structures by Agency*				
	ACOE	CDWR	MWD	WPRS	Other
		WESTERN U.S.			
Alaska	2	-	-	-	-
California	17	8	7	6	3
Nevada/Utah	-	-	-	4	-
Northwest	13	-	-	2	1
Southwest	3	-	-	-	-
Rocky Mountain Region	5	-	-	3	-
		CENTRAL U.S.			
North Central	16	-	-	-	-
Mississippi Valley	1	-	-	-	-
South Central	17	-	-	-	-
		EASTERN U.S.			
Northeast	11	-	-	-	-
Mid-Atlantic	6	-	-	-	-
Southeast	7	-	-	-	-

*ACOE – Army Corps of Engineers, Vicksburg, Mississippi.
CDWR – California Department of Water Resources, Sacramento.
MWD – Metropolitan Water District, Los Angeles, California.
WPRS – U.S. Water & Power Research Service, Denver, Colorado.

stories or higher and most are located in California, primarily in Los Angeles. Those buildings instrumented because of building code requirements contain 3 accelerographs: 1 in the basement, 1 near midheight, and 1 near the top. The other buildings normally contain 2 or 3 accelerographs; 1 in the basement, 1 near the top, and 1 near midheight if there is a third. In the near future the City of Los Angeles may reduce the number of instruments required per building to one near the top because it is believed that data from such instrumentation will provide data sufficient for safety evaluation. At present most of the instruments installed for safety evaluation in buildings are not regularly maintained.

Dams instrumented for facility-evaluation purposes are located nationwide (Table 3a) and most are instrumented by the Army Corps of Engineers (ACOE). In most cases the accelerographs are located on the abutment, toe, and/or crest of the dam. ACOE maintains its network in coordination with the USGS maintenance program, whereas

Table 3b. Summary of Buildings Instrumented to Provide Data for Facility-Evaluation Studies

Location		Number of Structures Code-Instrumented	VA Hospitals	Other
		BUILDINGS		
California				
	Los Angeles	200+	0	0
	San Francisco	0	1	6
	Other Cities	100+	4	2
Utah				
	Salt Lake City	0	1	0
Washington				
	Seattle	0	0	1

Table 3c. Summary of Pumping, Power and Filter Plants Instrumented to Provide Data for Facility-Evaluation Studies

Location	Number of Structures by Agency* CDWR	MWD	Other
California	9	2	1

*CDWR - California Department of Water Resources, Sacramento.
MWD - Metropolitan Water District, Los Angeles.

instruments on the other dams are maintained on a reimbursement basis by the USGS.

All 12 pumping, power, and filter plants are located in California and all are maintained on a reimbursable basis by the USGS. Most plants contain 2 instruments at different levels, one of which is normally the basement or lowest level.

Adequacy of Strong Ground-Motion Instrumentation in California

Studies by the Federal Emergency Management Agency at the request of the National Security Council (Press, 1980) indicate that the damaging effects of strong-ground shaking generated by a major earthquake could exceed those of any natural disaster thus far experienced by the nation. Earth scientists in general agree that the state of California can expect to experience at least one major earthquake in the next 50 years with a probability exceeding 50 percent and several small but damaging events in the same time interval. Yet, to date no strong-motion recordings of a major earthquake have been obtained in the United States.

A comprehensive examination of existing strong ground motion instrumentation in California was conducted by Borcherdt and others (in press). The locations of existing instrumentation were examined in relation to probable locations for major earthquakes as determined by Lindh (1983) and Sykes (1983). Results of this examination indicate that present instrumentation will not provide the data needed to describe the nature of near-source strong-ground motions likely to be generated by the next major earthquake.

Conclusions of the study by Borcherdt and others (1984), suggest that a minimum of 200 free-field sites and 16 dense arrays are needed in addition to existing locations to assure that the next major earthquake is recorded adequately. Based on an evaluation of earthquake potential by Lindh (1983), 86 of the free field sites and 8 of the dense array sites are considered to be in the highest priority categories for installation. Considering that available strong-motion program resources must be utilized to instrument other areas of the United States and to instrument buildings, bridges, and dams, the recommendations by Borcherdt and others (1984) indicate that a significant expansion in present total program resources is required to assure that the next major earthquake is recorded adequately.

Acknowledgments

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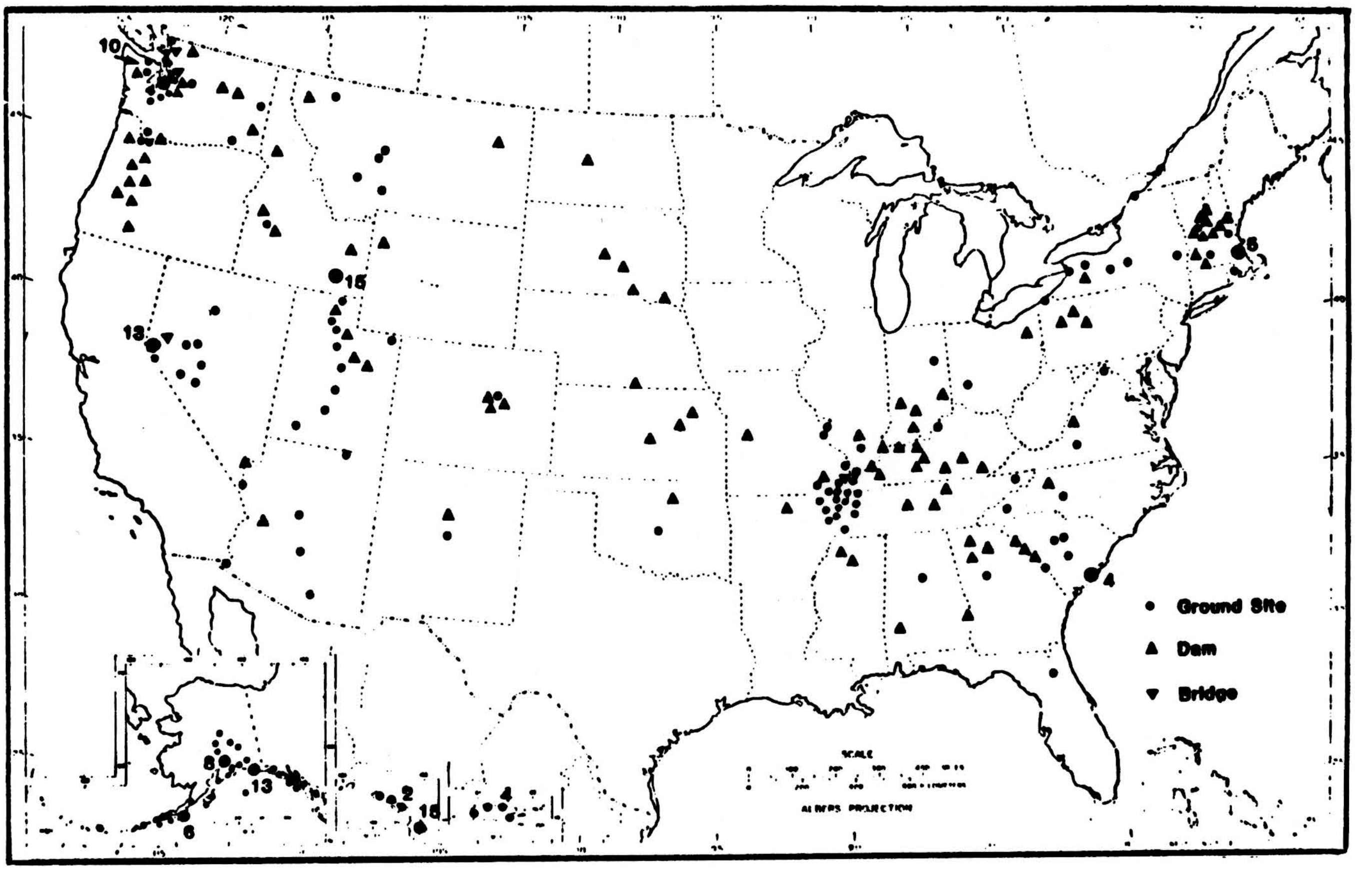

Figure 1: Known accelerographs in the United States outside of California. Excludes commercial nuclear-powered electrical generating plants. April 30, 1981.

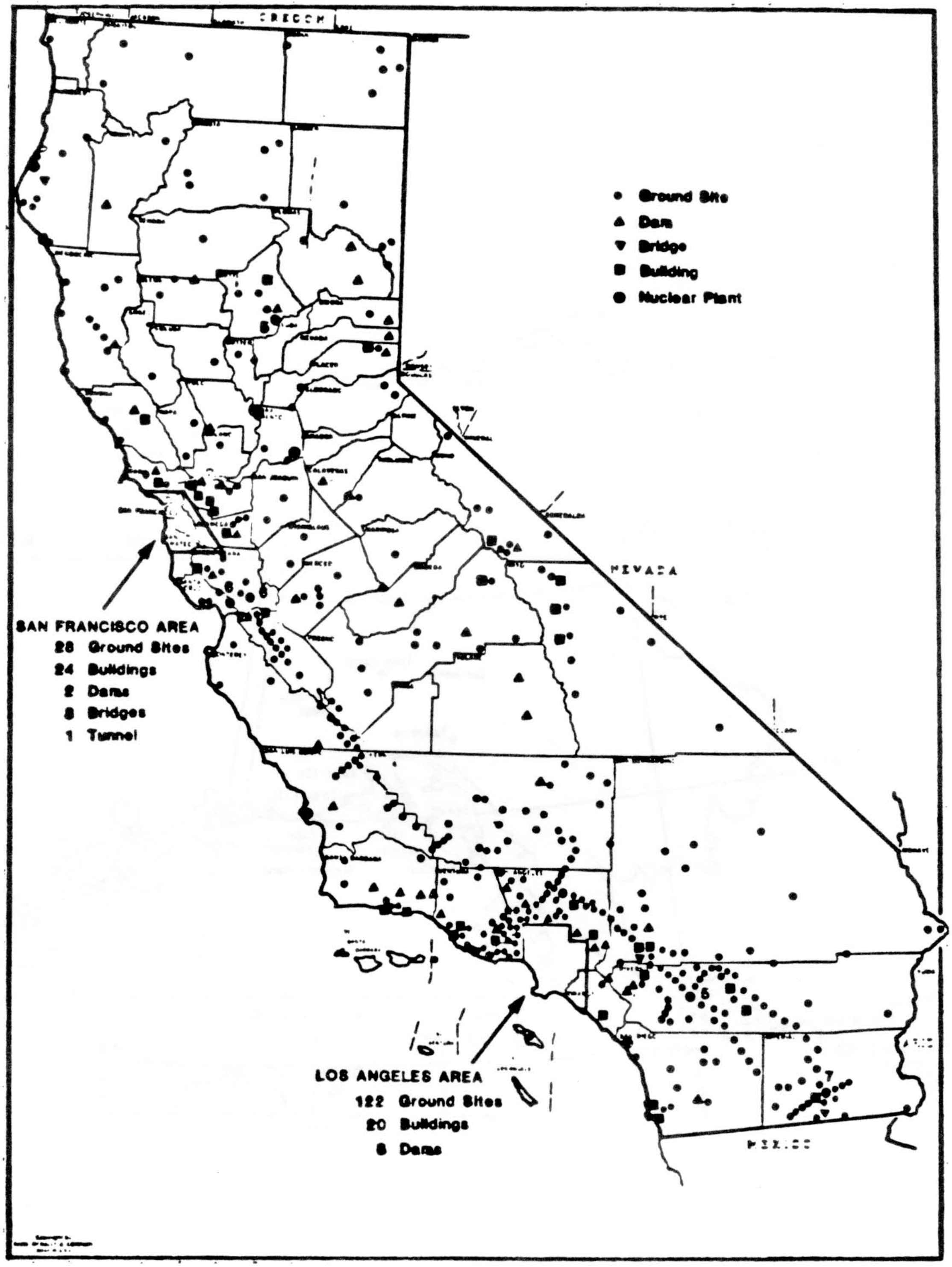

Figure 2: Known accelerographs in California. Excludes instruments required by building codes. April 30, 1981.

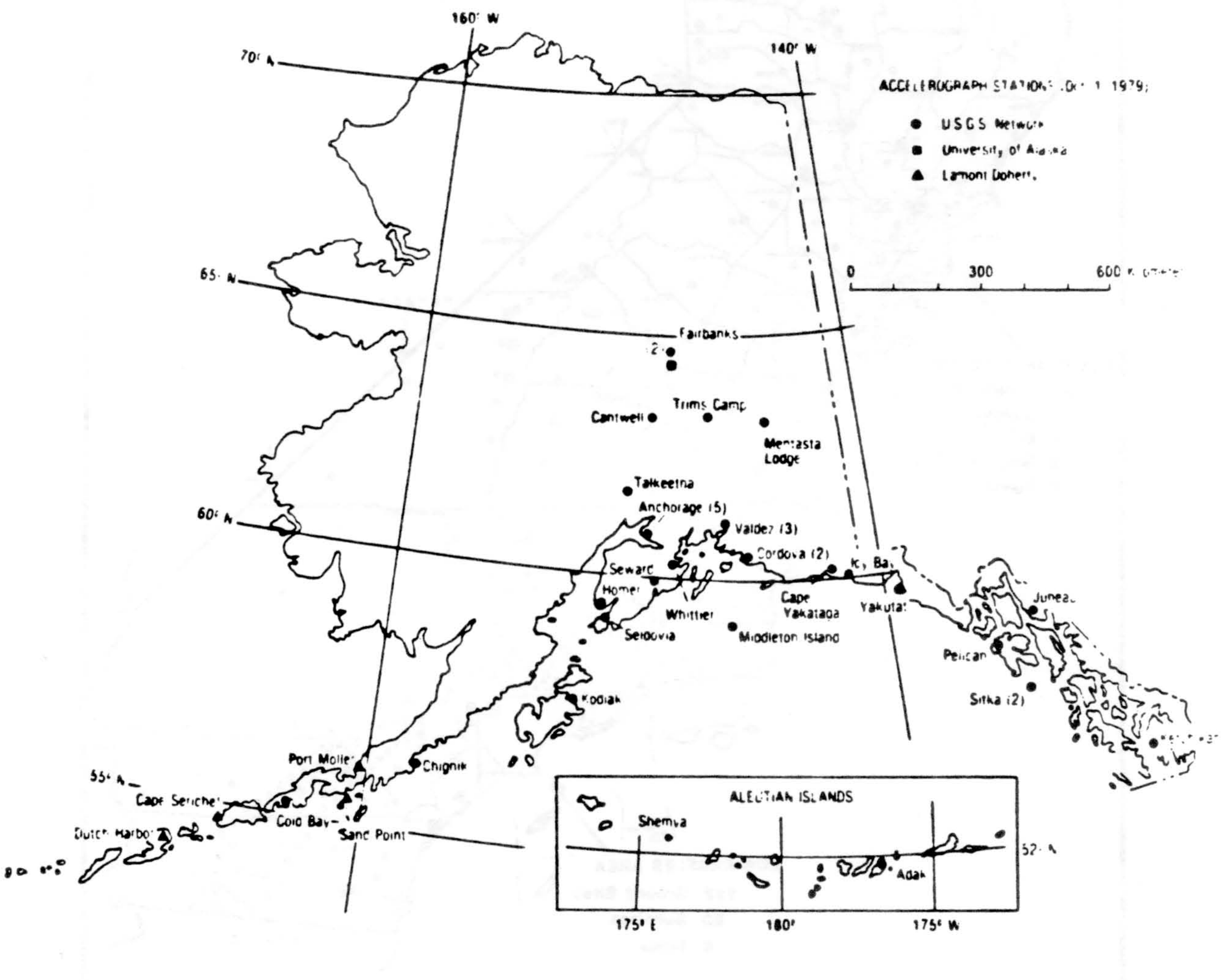

Figure 3: Accelerograph stations in Alaska. Numbers in parentheses are the total accelerograph stations at the indicated locality (from Porcella, 1979).

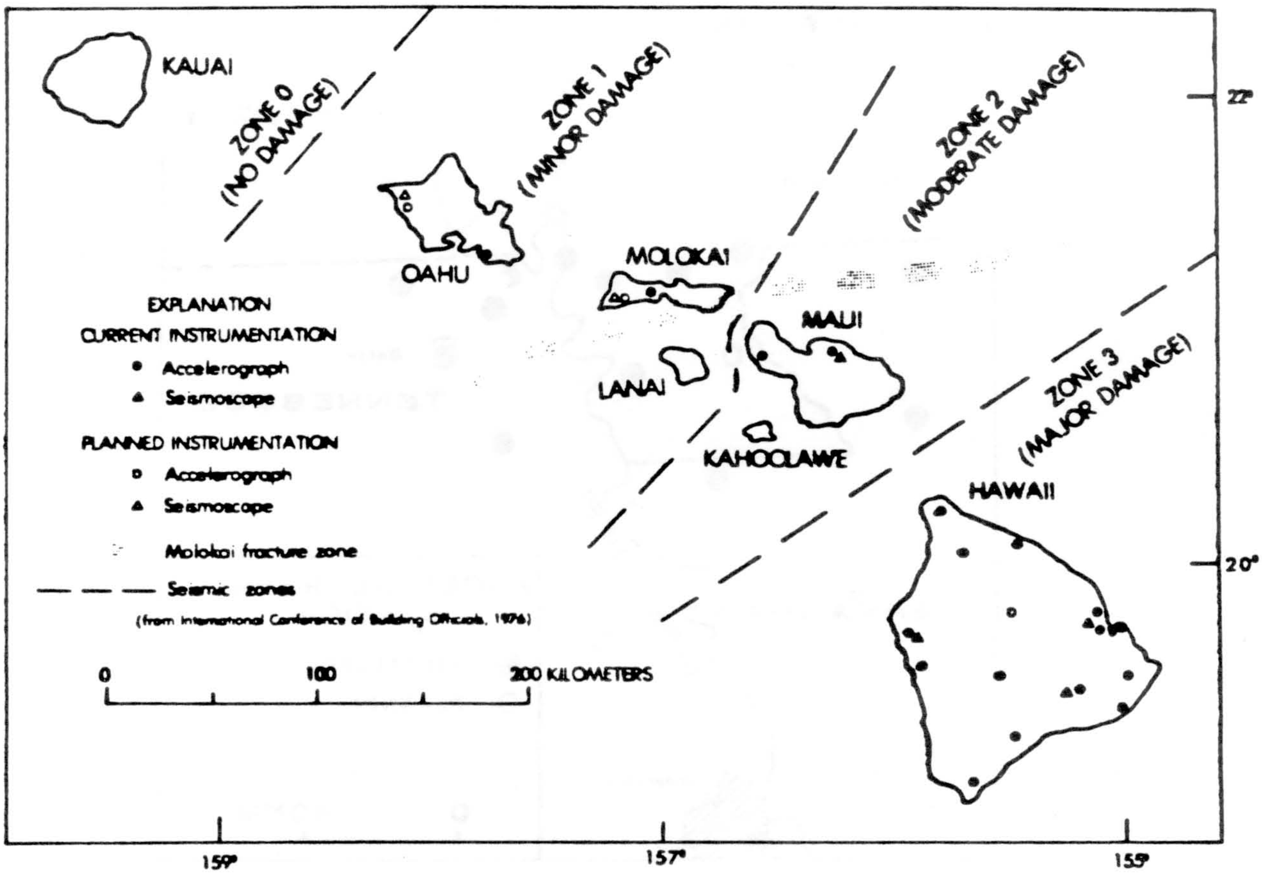

Figure 4: U.S. Geological Survey strong-motion network in Hawaii (from Porcella, 1980).

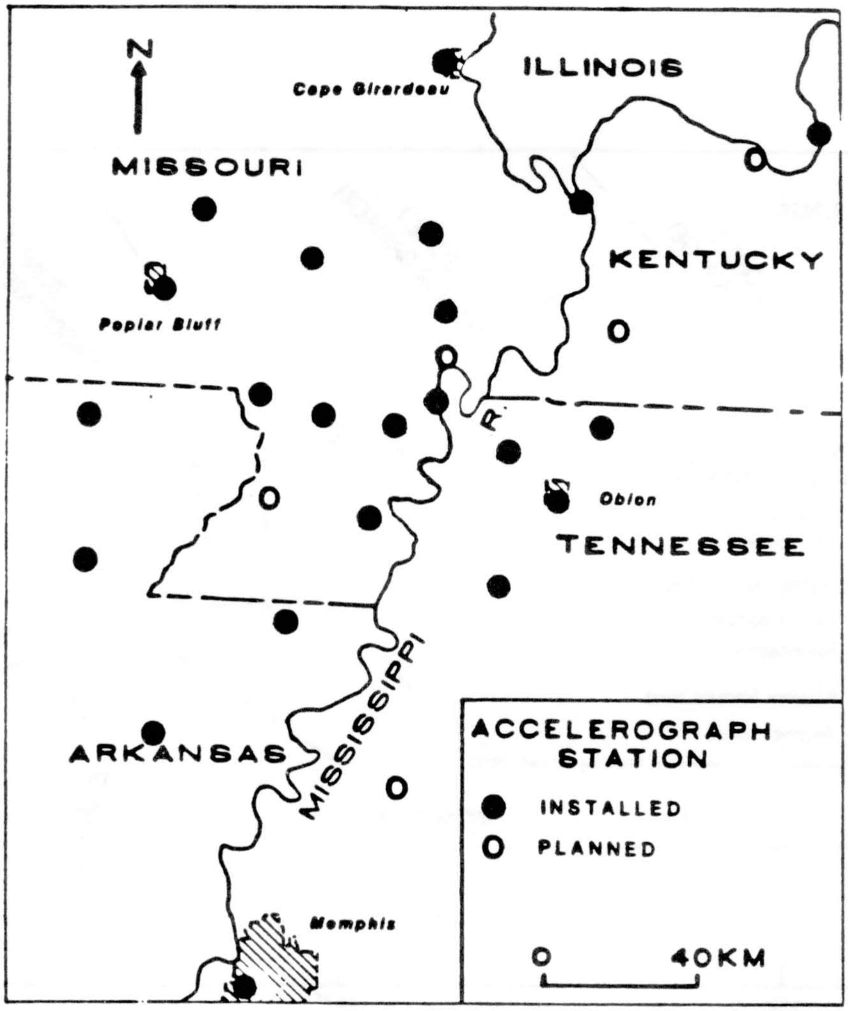

Figure 5: Strong-motion network for the New Madrid seismic zone (after Porcella, 1978).

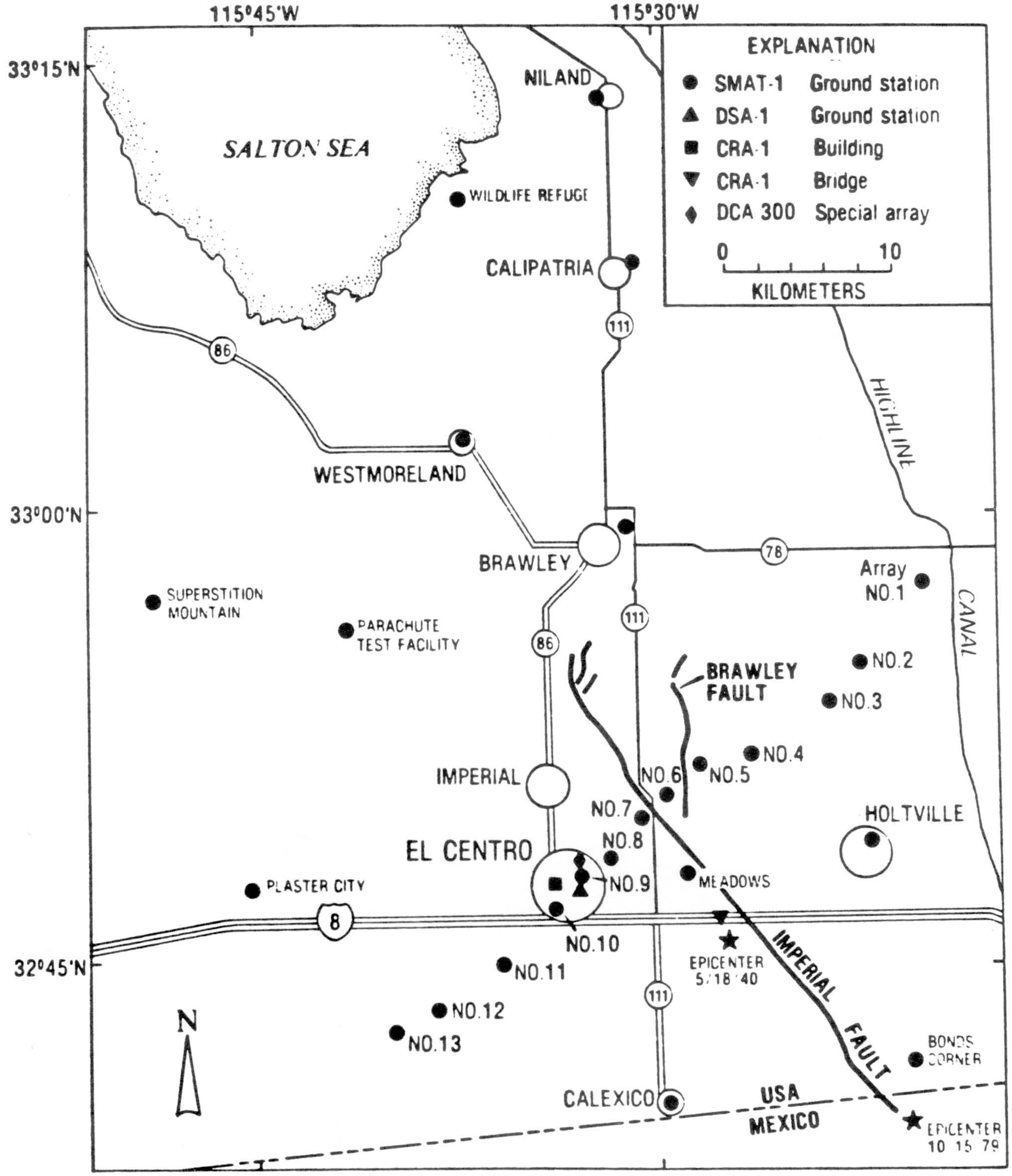

Figure 6: Strong-motion stations in the Imperial Valley (from Porcella and Matthiesen, 1979).

FIELD RELIABILITY AND MAINTENANCE

by

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I have had a lot of experience in this field and have made every mistake that possibly could have been made in the past 20 or 25 years. I'll start out with a few comments about one thing that happened about six years ago. A group of Japanese earthquake engineers were passing through San Francisco on their way to Washington as part of the Wind and Seismic group that meets every year in alternate countries. We were asked if we had some interesting structure that they could see which also had some strong motion instrumentation in it and I thought of the BART tube. At that time we were taking care of four accelerographs spread over about a mile length of the tube and in the vent structure. I contacted the people at BART and they arranged to have one of the engineers take us down into the tube and explain some of the details of construction to the engineers and then to show the strong motion system in the tube. We met there and went into the tube and the BART engineers explained to the Japanese what the design was and what went on. Then I said there are two accelerographs in the vent structure and we will look at them and I'll point out on the plans where all the other equipment is located. Well, one of the instruments was located in the bottom of the vent structure and I couldn't find it. I never did find it. So I said, I know there is one upstairs. We went upstairs and it was right there. I took the cover off and explained how it works. A lot of them really weren't familiar with the accelerographs and one of the Japanese said, "Well, could you turn it on and show us how it runs?" So I turned the key and it goes click, click, click and nothing happens. About that time I'm really embarassed. Then one of the Japanese engineers tapped me on the shoulder and he said, "Don't worry about that, the accelerographs in Japan don't work either."

What I'm going to talk about mostly is what I'm familiar with in the USGS and the associated programs we are involved in--those that we maintain on a reimbursable basis and those other programs that we are affiliated with and act as advisors. So, this is almost exclusively concerned with analog film recorders and basically the late model film recorders. I would consider that field reliability is a sum of good instrument characteristics and the techniques of maintenance. I would like to direct my comments to four specific areas: 1) What kind of instrument characteristics in analog recording systems lead to high reliability, including hardware modifications used by USGS that may or may not be used by other organizations; 2) What kind of transition in the problems have occurred in the history of the programs as it has evolved since 1933; 3) What are the general maintenance procedures that we are following and a few sample cases drawn from the past three years; 4) How is a general philosophy of effective maintenance generated in any particular organization. First, as far as instrument characteristics, the most desirable thing would be to have an optimum instrument that never needs maintenance until an earthquake is recorded. This is clearly an ideal but unattainable goal. The objective then is to perform maintenance on accelerographs as seldom as possible yet keeping an acceptable number of operational instruments. With analog type recorders an important positive factor which produces a high reliability is the low power requirement of the existing film recorders. The second thing we would desire would be the simplest possible systems. The more complexity there is and the more things that can possibly go wrong. The third factor--have you got sites that are environmentally safe? By that I mean chiefly against vandalism, water and other types of accidental events. For example, consider instruments located in fire stations--firemen are great kickers and they tend to kick accelerographs, which is fine because it lets us know whether the instrument is mounted tight enough, but that is something you have to watch out for. The fourth thing which I think is really true of the modern instruments is that they are pretty much idiot proof. There are not a lot of things that can go wrong. If you have a simple inspection form which has certain criteria on it and fill it out carefully the chances are extremely good that you will have that instrument running for quite a while. The procedure that the USGS has followed, which I think is basically the same as the State of California has followed, as we have worked together with them and with other organizations on some of the modifications, basically involves the external power supply. We seldom operate equipment with internal batteries. The USGS uses external batteries, of much higher capacity than internal batteries, and with only two terminals instead of four. This reduces the chance of problems at a terminal. We put the batteries in a wooden box so there can be no short-circuiting to metal. They are locked in a box and it is bolted to the floor. Somebody can always disconnect the connection between a power supply and an accelerograph but I don't think it has ever happened that we know of. We also use a battery charger which we feel is the best one available having stumbled onto it through the program that Trifunac had at Caltech. We noticed a corrosion problem which shouldn't occur with sealed batteries and also noticed that statistics from the Caltech people showed that they weren't having the problem. So we simply changed and used their type of chargers and now don't have the problem. We constantly recalibrate film magazines and regularly change the film every year. But you can never tell when somebody runs off a lot of film and you are unaware of it. The supply gauges can't be expected to be very accurate on the simple film magazines, consequently, they are recalibrated frequently.

It used to be in the old days with the Coast and Geodetic Survey that every time the instrument didn't operate during an earthquake or on inspection the battery was dead. In the early days the available batteries required the frequent addition of water, they were unsealed, the instruments had higher power demands on standby, which then required more frequent maintenance than we are able to get away with now. When the AR-240's came along in 1963, there was a reduction in the number of battery problems but they began to introduce new problems. The drive mechanism was not as sure as the old Coast and Geodetic system. With the Survey instrument, if you stuck your finger in the gears, your finger went with it. That was kind of the way we liked it. We also began to get modern electronics. For the first time there were diodes and capacitors, at least smaller capacitors, transistors, smaller different type relays, adjustable resistors--they were just a new set of problems. But the instrument was really, I think, well designed and came at the right time and served very well at its time. I think it is still an extremely good instrument. The next generation of instruments were the film recorders which were considerably more modern. They were designed as concise, complete units in which the batteries were originally contained inside. They had far more electronics than before. They had a very good vertical triggering system. Initially, when we had trouble with batteries it was our own fault. The battery problems eventually disappeared and I see batteries now as basically an unproblem. There are at least 4 significant causes of instrumentation failure. The 4 basic problems we see now are: 1) instrument malfunction, electronic and mechanical; more than 50%, 2) the environment; vandalism, flooding--things you can't control unless you pick the site carefully, 3) technical errors and 4) batteries. Now it appears that instrument malfunctions, electronic and mechanical, are the most significant. This doesn't mean there are more such malfunctions--there are a lot less than there ever has been. The reliability of the modern instrumentation is so high that those malfunctions observed usually end up electronic or mechanical malfunctions.

DATA PROCESSING

by

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I should like to summarize for you the state of practice around the world in the processing of strong motion accelerograms, and I shall confine my remarks to paper and film records because they represent the vast majority of the records that are available. In approaching this subject, it is informative to look at the number of accelerograms that are processed by various countries. Out of the 1,400 accelerograms that I estimate have been processed around the world, over two thirds of them have been processed by two countries, the U.S. and Japan. Italy has processed about 200, mainly from the 1976 Friuli earthquake and aftershock sequence and the November 1980 earthquake. There are about 18 other countries with a combined total of processed accelerograms on the order of 200. So it might be expected that if you want to find out about the state-of-the-art in processing of strong motion accelerograms, you should look at the literature in the two countries that have done the most processing, Japan and the U.S.

In general, with regard to the digitization of film and paper records, the U.S. has progressed from manual or semi-automatic digitization methods to fully automatic methods. Fairly extensive studies have been done on the digitization noise in those two methods. Other countries seem to be using the semi-automatic or the manual digitization method, and there are very few, if any, digitization noise studies that have been done in these countries.

With regard to the corrections that are applied to the digitized records, I think that the procedures that were developed at Caltech are still in use today with some improvements to the corrections at low and high frequencies. Certainly, there have been no major overhauls in this processing scheme. Japan is perhaps in a different position. Four agencies in Japan are involved in the strong motion collection and processing business. The corrections that are applied by these agencies for short and long periods vary from no corrections to all to fairly extensive corrections. The two agencies that process by far the largest number of accelerograms in Japan are the Port and Harbor Research Institute and the Public Works Research Institute. I would estimate that they collect and process about 90% of the accelerograms in Japan. It is interesting that the Port and Harbor Research Institute is carrying out active research on the processing of accelerograms, but they haven't really decided what filters to use--whether they be fixed filters or variable filters--and just exactly what they should be doing as far as the instrument correction is concerned. On the other hand, I have found no published information that suggests that the Public Works Research Institute is doing something in the corrections at long and short periods. This is very surprising because the Public Works Research Institute was responsible for producing site-dependent design spectra based on a number of accelerograms that were recorded in Japan over the years. They apparently computed these spectra without doing any processing at the long and short periods. These spectra were published in a seismic design manual that came out in the late 1970's. Now, in all fairness to them, maybe they consider that for the period range that they were interested in, these corrections wouldn't have much influence, and there may be some truth to that.

I shall next consider a couple of aspects of processing at the long and short periods. First, I will discuss the long period problem and the treatment of digitization noise. One of the things that interested me was the comparison between the original Caltech accelerograms processed between 1969 and 1975 and then the reprocessing of certain of those accelerograms by M. D. Trifunac and Vincent Lee at USC around 1978. Mainly, Trifunac and Lee's processing had to do with picking a variable filter for the long period processing that was dependent on the record. If you notice the record in Figure 1, processed originally at Caltech and later at USC, the acceleration traces are basically the same as we have seen in some examples other speakers have shown. When you integrate again to get the displacements, the differences are very obvious and in many cases there may be a factor of ten difference in the maximum displacements. This difference was somewhat alarming to people who weren't really aware of what was going on. Some structural engineers came up to me, and knowing I had graduated from Caltech during when a lot of this processing was going on, they asked "You mean to tell me that Caltech did something wrong?" So I tried to explain to them the problem with long-period noise that can affect the displacements. I said this problem was stated in the Caltech reports but was not corrected because at the time it was considered more desirable to uniformly process the data over one frequency band and quickly publish the data, rather than spend a greater amount of time identifying and removing the noise in each record as Trifunac and Lee subsequently did.

Let us consider the studies that have been done on digitization noise. Most of the studies have been done in the United States, and the only other study that I could find on digitization noise was a very limited one from Japan. Curve 3 in Figure 2 is the original study done by Trifunac, and what I have plotted is the average noise spectrum for a given duration of record plotted as a function of period. You can see that the general trend is for the digitization noise to increase with period. Trifunac's study was based on the repeated digitization of a very thin, straight line that A. G. Brady referred to. Later in the 1970's Trifunac also did this same experiment using the automatic digitizer and he came out with the result that we see as Curve 2. When I searched around the world for anything comparable, the only thing that I could find was by Japan's Port and Harbor Research Institute. They did repeated digitizations of a fixed trace and got about the same result (Curve 1) as Trifunac. One of the interesting things that I pursued recently was to look at the noise from another angle. If there aren't any direct experiments on digitization noise, an indirect approach is necessary. It turns out that if you take the records which are unprocessed--i.e. they are digitized and are essentially taken through Caltech volume-one stage processing--and if you plot a smooth version of the Fourier amplitude spectrum of a given record as in Figure 3, you see that at some period the spectrum begins to diverge upward. This characteristic seems to apply to nearly all of the records that we have looked at from our Japanese data base and also for many records in other countries as well. What I was interested in doing was seeing how the noise levels from these records in Japan compared to the noise levels that you might get from 70 mm film records from SMA-1 and RFT-250 instruments in this country. So what I did was approximate a straight line through the spectra (e.g. Figure 3) using the acceleration axis as a reference and defined a noise level for each of these records. Figure 4 shows the noise level determined in this manner for the U.S. records as a function of the duration of the records. Also, superimposed on this plot are the mean plus one and minus one sigma bounds on the digitization noise from the automatic digitization machine, based on the fixed trace digitization noise studies by Trifunac. It is interesting to note here that the mean of this data sample from the SMA-1's and RFT-250's is about the same as the one you get from the completely automatic digitization method. This was encouraging in one respect in that the semi-automatic digitizations done at Caltech on the Benson-Lehner digitizer probably are pretty good. At least they were as good as the digitization done on the automatic device. Now when we compare this noise with the noise inferred from the Japanese records (Figure 5), where the Japanese noise data are given by triangles and the U.S. noise data are given by the crosses, you find that there is quite a bit of scatter in the data but essentially it is hard to distinguish between the two data sets, i.e. There are no significant differences in the digitization noise between the two countries.

In the second part of my talk I would like to spend a little time on the instrument correction. There are three things that this correction depends on; one is the transducer characteristics; another is the time interval of the data--the equalized time interval spacing; and the third one is the correction algorithm that is used--whether it is central difference of some other scheme. If you look at the transducer response characteristics for most of the instruments that are in operation throughout the world, I think it is fair to say that in general, the transducer response characteristics will fall in between the limits indicated in Figure 6. This figure shows the response curve for the SMAC-B2 accelerograph in Japan which has a natural frequency of 7 Hz and a critical damping of 100%--that instrument, by the way, records about 70% of the ground motions in Japan today--and the SMA-1, which has a natural frequency of 25 Hz and a damping of 60% critical. During our studies of the Japanese data base, we made this instrument correction on a Japanese record and compared the results to an instrument correction done in Japan on the same record. The top trace of Figure 7 shows the uncorrected record, the middle trace shows the published Japanese correction of the same record, and the bottom trace shows the correction using a program that, at the time, was currently in use by the USGS. Now, at first we were disturbed by the differences in the two corrected records because we thought we were doing things exactly the same as the Japanese. They had given us enough information on where they filtered the record and how they did the instrument correction but we noticed that the peak values were quite a bit different. When we looked at it a little more carefully we found that the delta T's, the time intervals, were different. The Japanese used a spacing that was .01 sec whereas we were using the standard spacing of .02 sec. More on this in a minute. To give some idea as to the difference the instrument correction makes in the response spectra, Figure 8 compares the spectra of the corrected record processed by the Japanese agency and the response spectra of the uncorrected record. The instrument that recorded this motion was a SMAC-B2, and it is interesting to see differences in the response spectra of as much as a factor of 2 over a fairly wide frequency band. When we performed the correction and compared it with the Japanese correction (Figure 9), we saw that there was still a considerable difference in the spectra; the dashed line being our correction and the solid line being the Japanese correction. We then asked, "What happens if we change the delta T to .01 sec?" We were hoping that things would come out the same because if they didn't, it would be a disturbing situation to know that processing in two different countries, using what we think to be the same filters and the same methods, would produce two different results. Fortunately, that wasn't the case--when we went to that same delta T spacing of .01 sec, the results were virtually identical (Figure 10). At longer periods there were some discrepancies, but we really didn't have enough information about how the processing was done at the long periods so I wasn't too concerned about that.

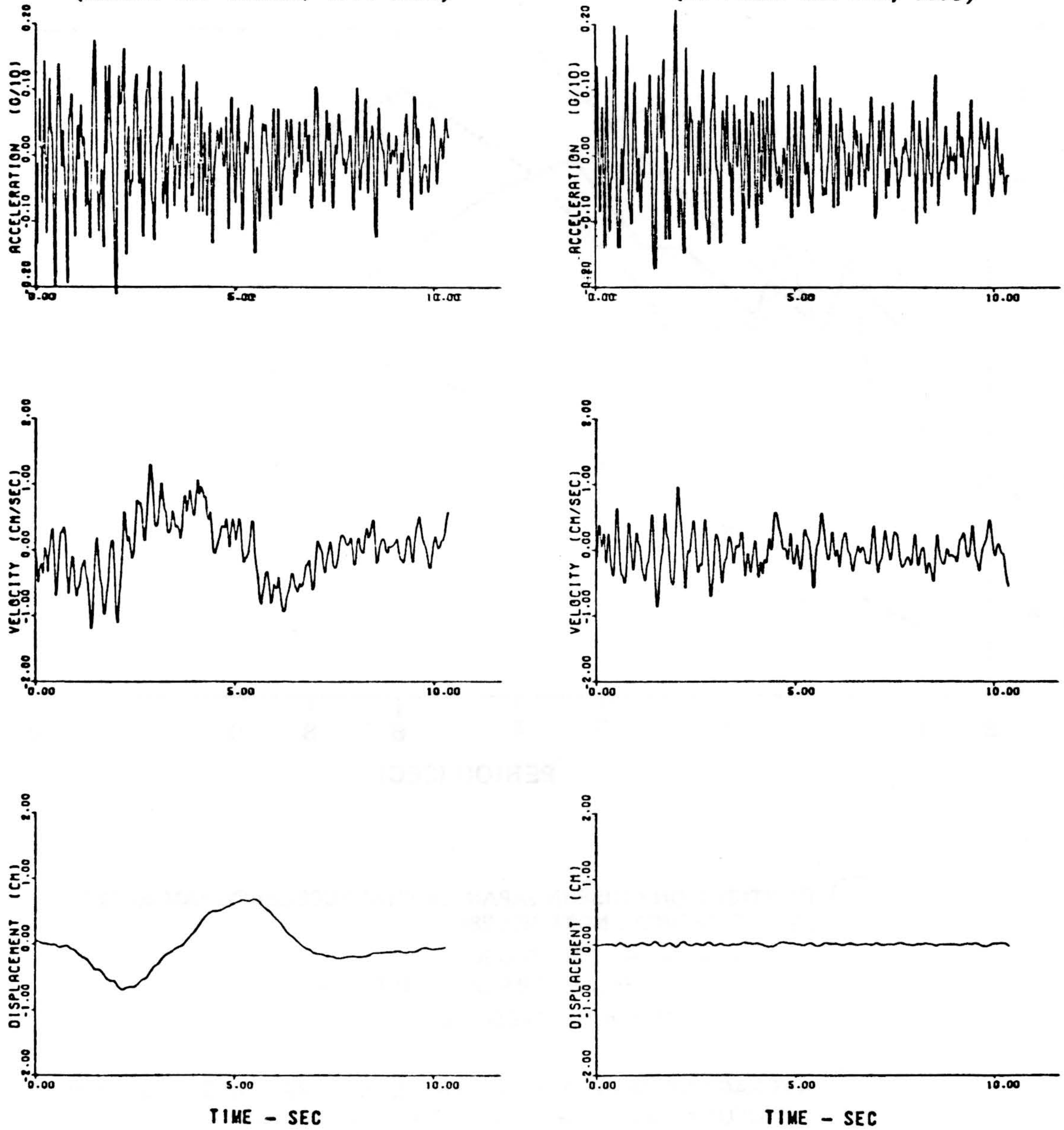
Some research at MIT has shed some additional light on the problem of instrument correction. Figure 11 shows a plot of the correction needed to account for the instrument response. Figure 11 shows data for two different types of instruments--one has a natural frequency of 10 Hz and a damping of 100% which is typical of the Japanese SMAC-B (not SMAC-B2); the other instrument is more in line with what we have in the U.S., i.e. it has a natural frequency of around 20 Hz and a damping of 50%. For the Japanese instrument, for example, the ideal correction would be the dashed line in the figure; whereas if the central difference scheme with a delta T of .02 sec were used, the corresponding correction shown by the solid line would be underestimated and it would get worse as the frequency becomes higher. For the U.S. instrument, a similar divergence is also seen at higher frequencies. The effect of going to a smaller delta T is to multiply the frequency scale in Figure 11 by a factor equal to the ratio of the larger (.02 sec) and smaller delta T, so that a better agreement over a wider frequency range is obtained.

In conclusion, I have a couple of recommendations. One, limited research of the processing should be continued. If the past is any quide to the future, this research will have to be done in the U.S. because I don't think other countries, due to economic reasons and other priorities, are likely to undertake it. This continued research should look for ways to extend the usable frequency band, always being aware of special problems that may result. Some of the old assumptions and standard processing subroutines may no longer be sufficient, especially in light of newer instrument design, which needs to be examined in more detail from the standpoint of record processing. Even if the other countries do not engage in detailed studies of digitization noise and processing methods, at the very least we should encourage them to document what processing they are doing in enough detail so that others can make proper use of their records.

CORRECTED ACCELEROGRAM F102, COMPONENT N90E

CIT ORIGINAL CORRECTION (HUDSON AND OTHERS, 1969–1975)

USC REVISED CORRECTION (TRIFUNAC AND LEE, 1978)



BAND-PASS FILTER FREQUENCIES

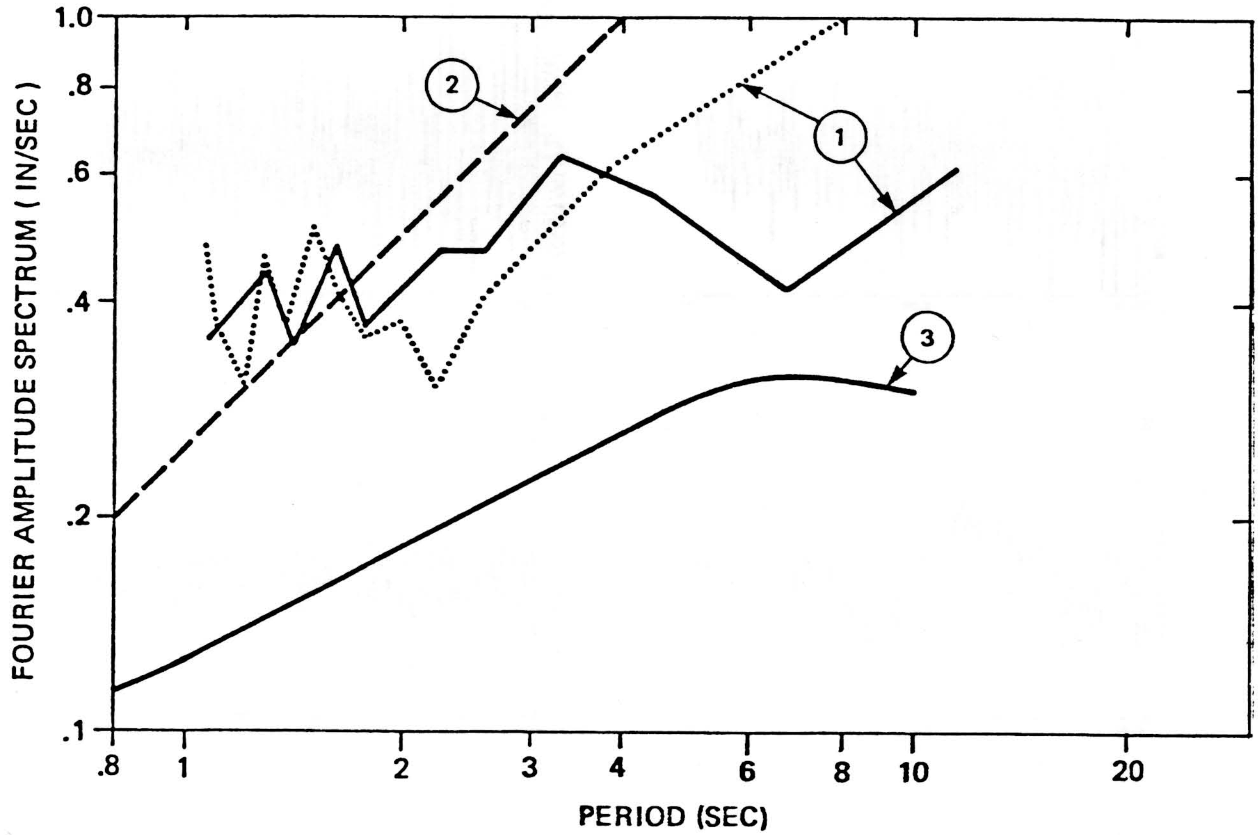
CIT ORIGINAL: 0.05–0.07 AND 25.–27. CPS

USC REVISED: 0.70–1.0 AND 25.–27. CPS

REFERENCE: CROUSE ET AL (1980)

COMPARISON OF ACCELEROGRAM CORRECTED BY CIT AND USC

FIGURE 1



(1) DIGITIZATION NOISE IN JAPANESE PHRI ACCELEROGRAM M–125 (PHRI TECHNICAL NOTE NO. 286)

——— NS COMPONENT

·········· FIXED STRAIGHT–LINE TRACE

DURATION = 12.5 SECONDS

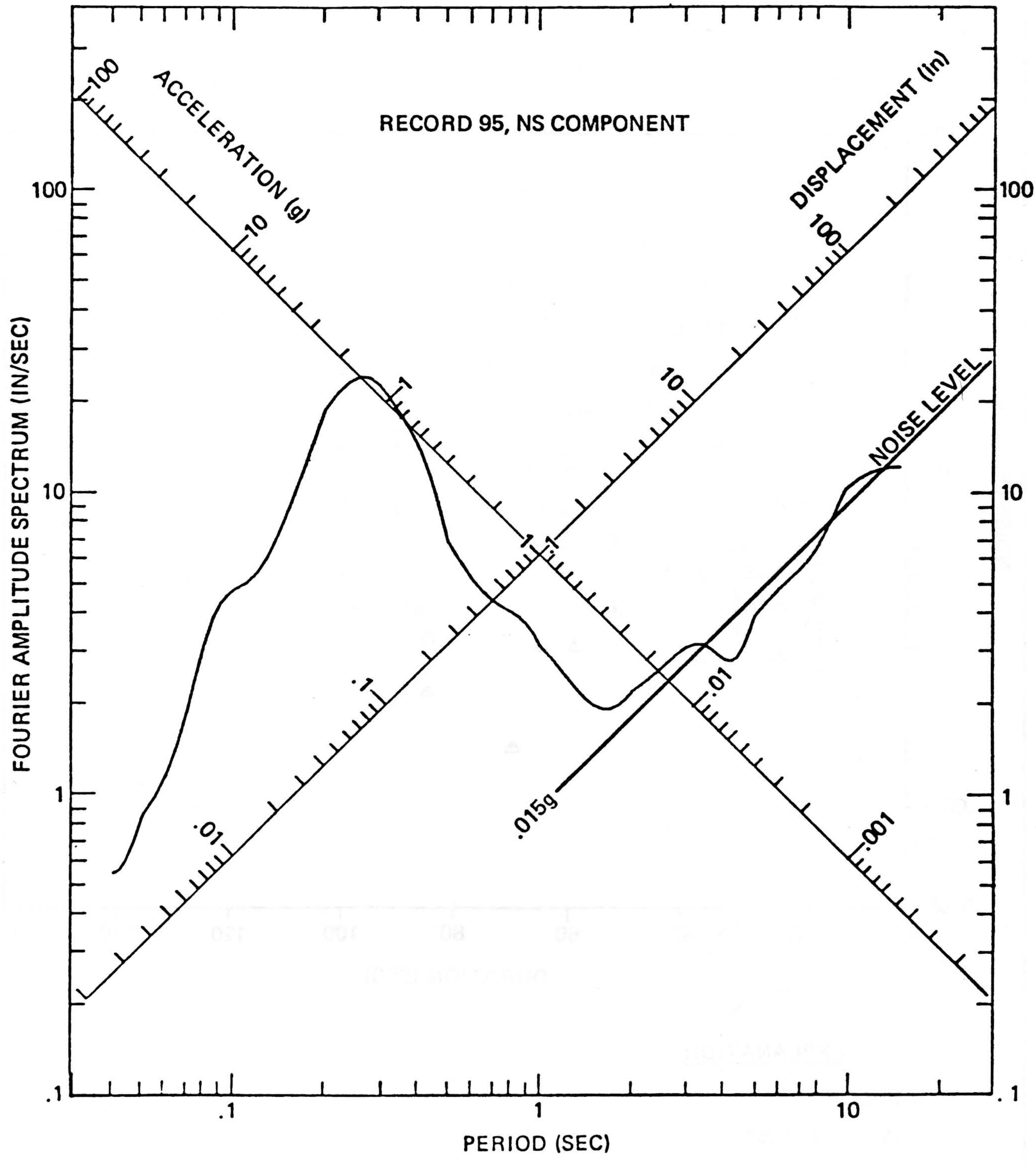
(2) AVERAGE NOISE FROM FIXED TRACE DIGITIZATION OFF 70 MM FILM (TRIFUNAC & LEE, 1979), DURATION = 15 SECONDS

(3) AVERAGE NOISE FROM THIN STRAIGHT–LINE DIGITIZATION (TRIFUNAC, 1976). DURATION = 15 SECONDS

REFERENCE: MORI AND CROUSE(1981)

COMPARISON OF DIGITIZATION NOISE FOR JAPANESE AND U. S. ACCELEROGRAMS

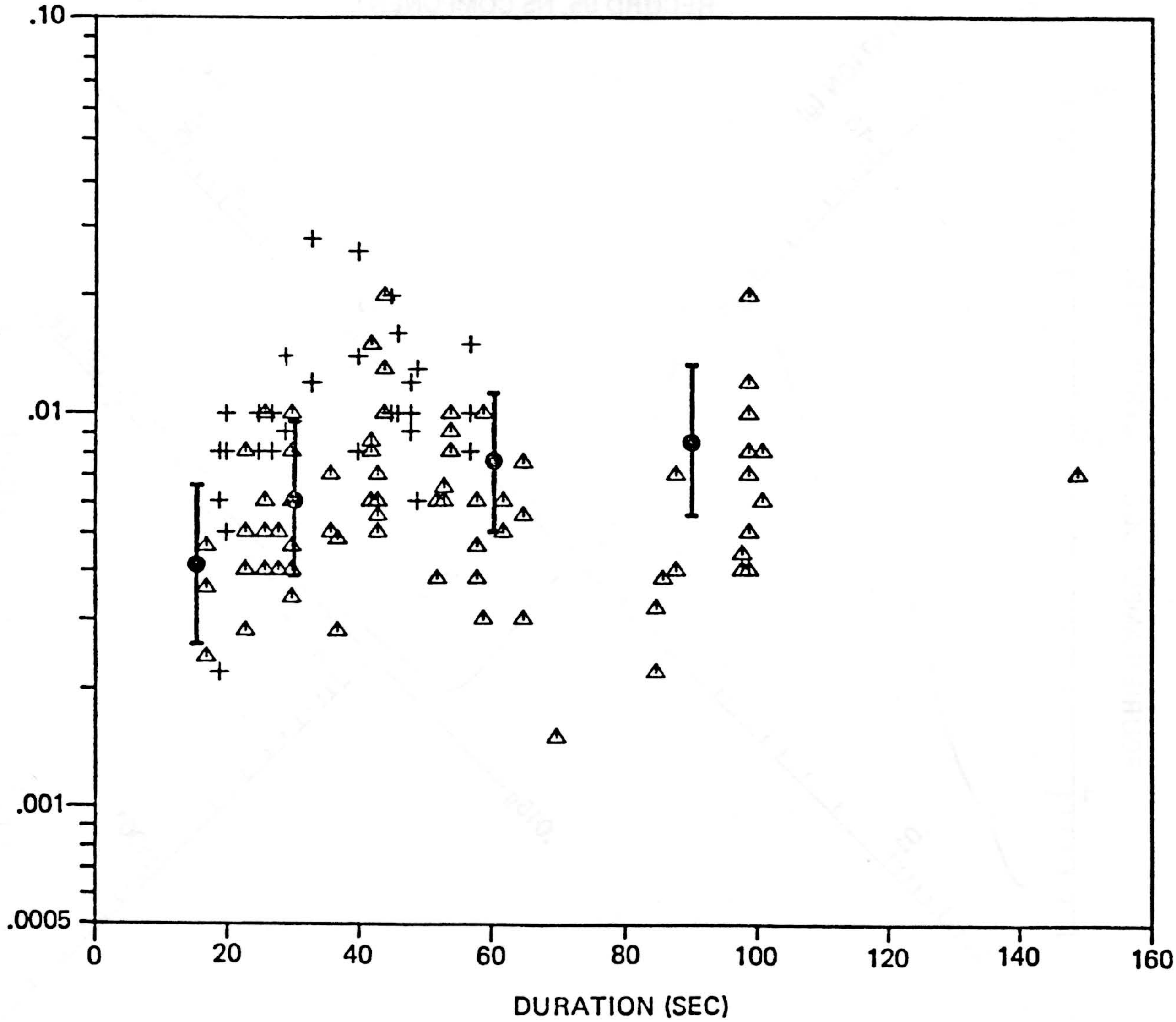
FIGURE 2



REFERENCE: MORI AND CROUSE (1981)

NOISE LEVEL DETERMINED FROM SMOOTHED FOURIER AMPLITUDE SPECTRUM OF UNCORRECTED (VOL. I) RECORD

FIGURE 3



EXPLANATION

SYMBOL

△ RFT-250

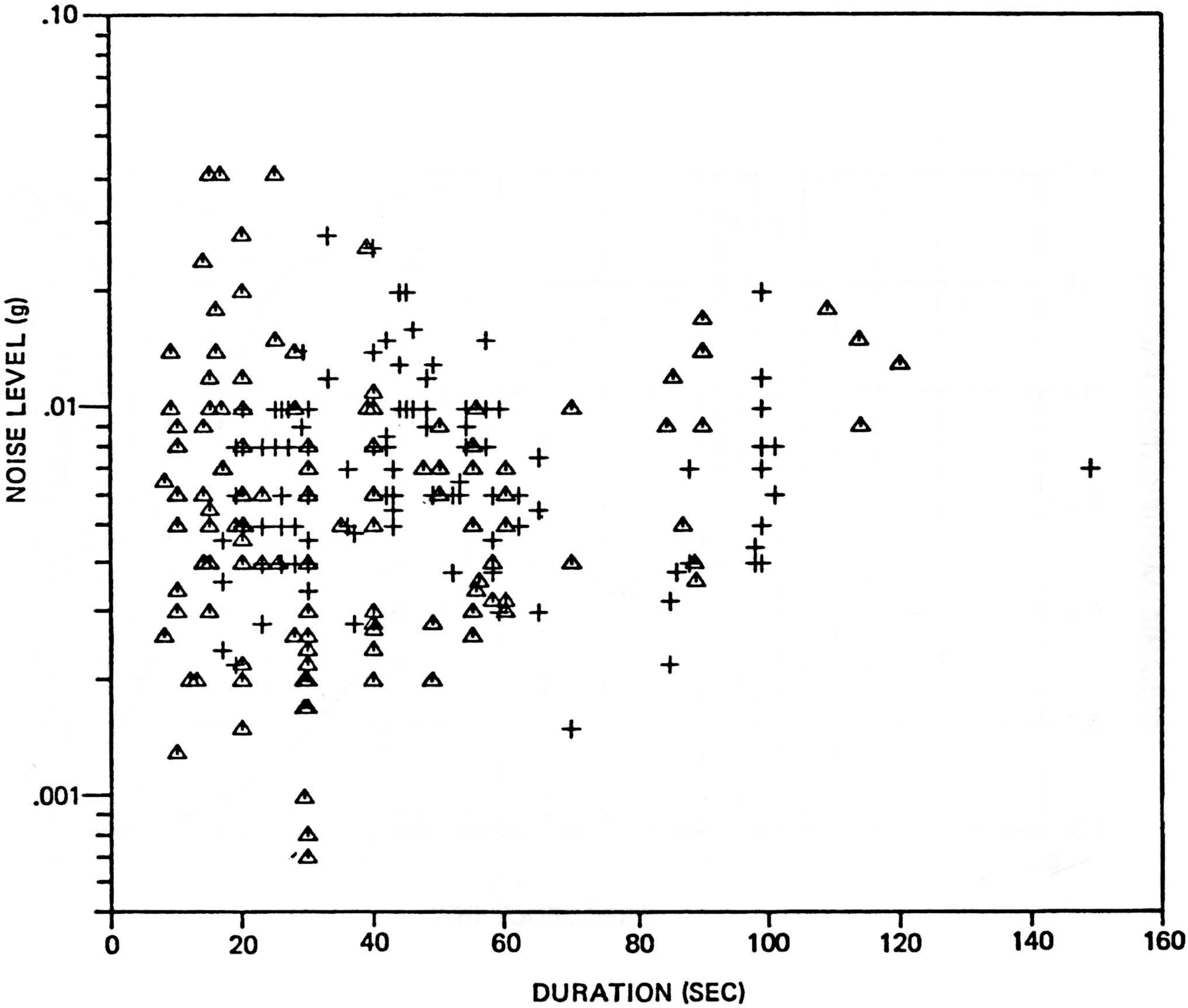
+ SMA-1

MEAN ± 1σ BOUNDS ON DIGITIZATION NOISE (TRIFUNAC & LEE, 1979. LOG-NORMAL DISTRIBUTION ASSUMED)

REFERENCE: MORI AND CROUSE (1981)

LONG PERIOD NOISE LEVEL VS DURATION FOR U.S. ACCELEROGRAMS RECORDED ON RFT-250 AND SMA-1 INSTRUMENTS

FIGURE 4



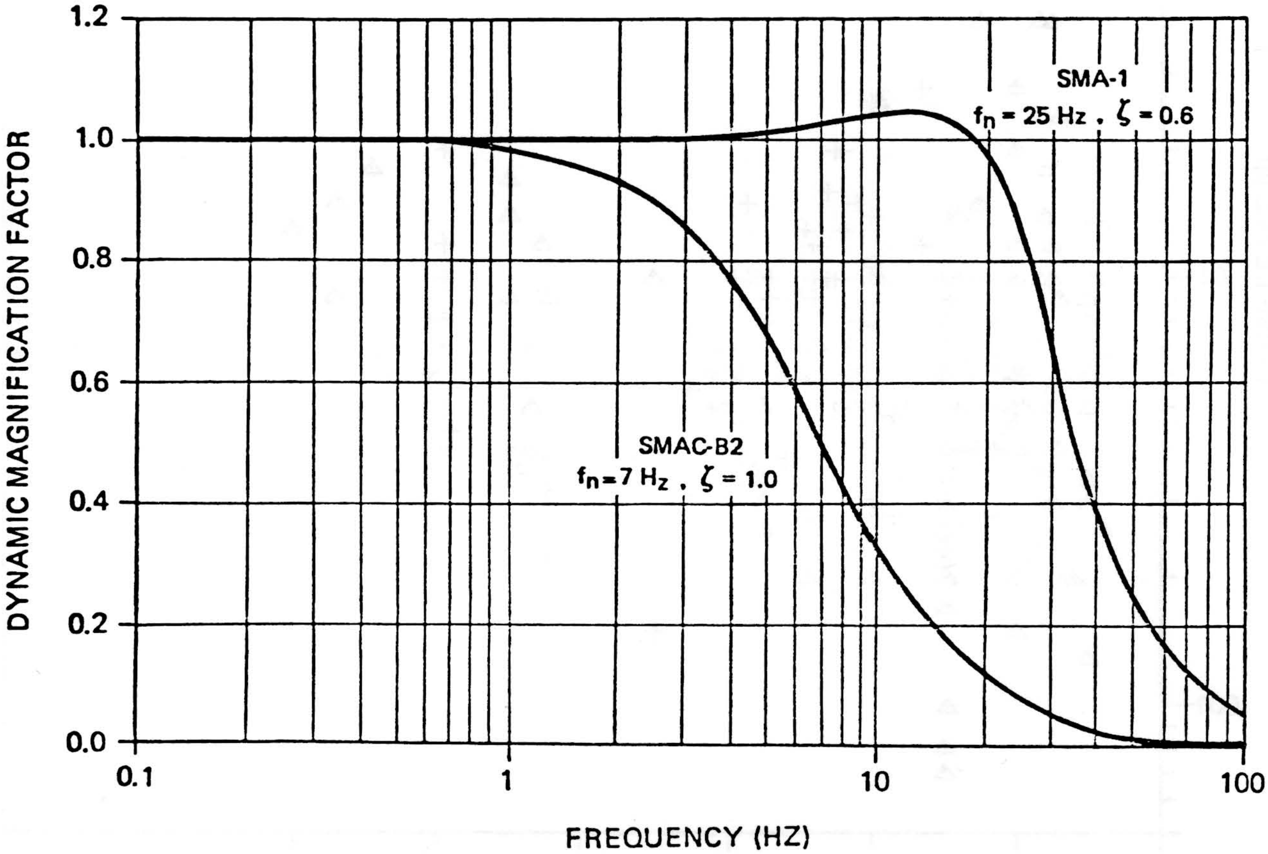
EXPLANATION

SYMBOL	DATA SOURCE
△	JAPANESE
+	U.S.

REFERENCE: MORI AND CROUSE (1981)

COMPARISON OF LONG PERIOD NOISE LEVEL VS DURATION FOR JAPANESE AND U.S. DATA

FIGURE 5



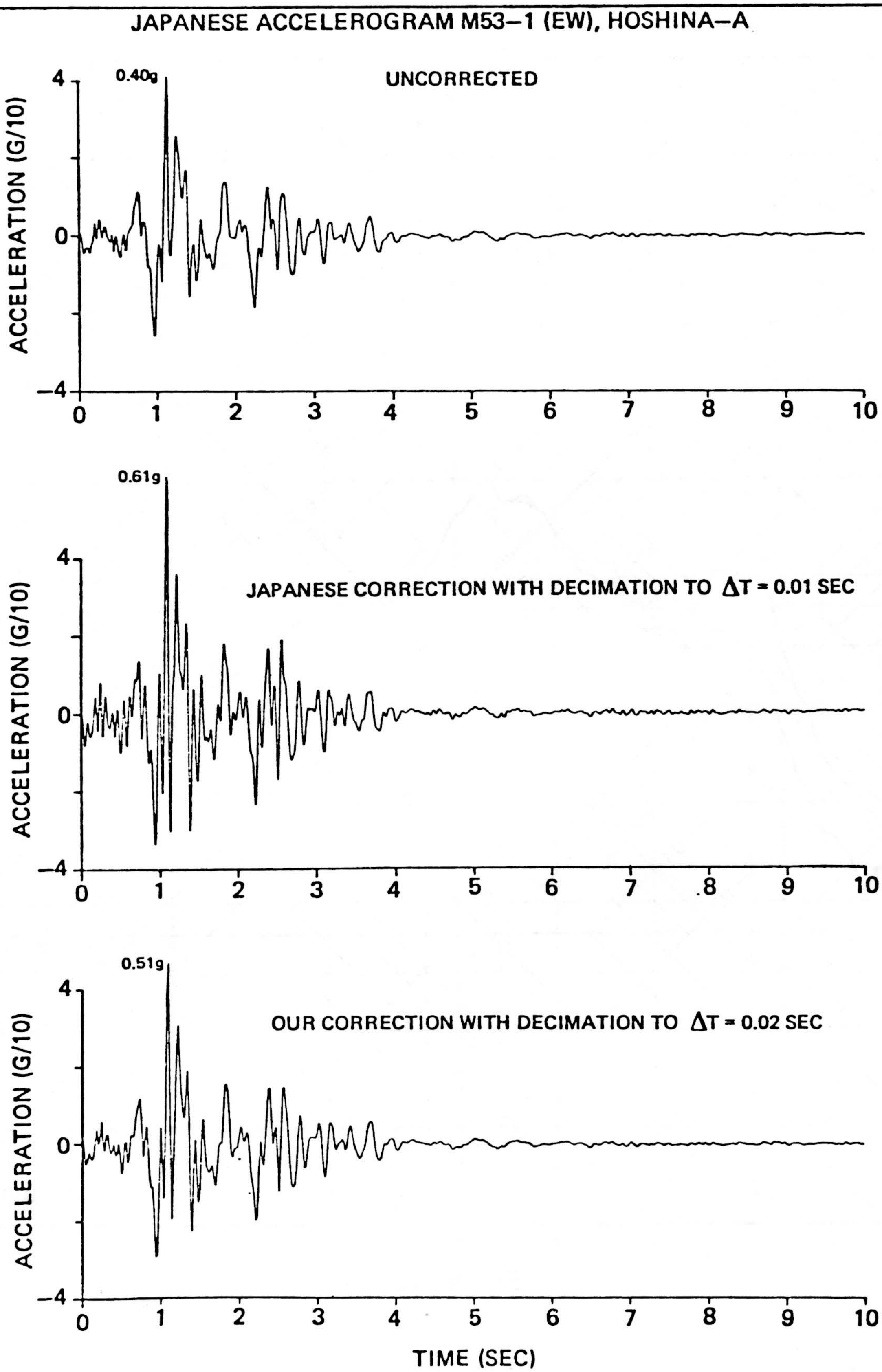
f_n = NATURAL FREQUENCY

ζ = FRACTION OF CRITICAL DAMPING

REF: PHRI TECHNICAL NOTE NO. 236
AND HUDSON (1979)

FREQUENCY RESPONSE CHARACTERISTICS OF THE SMAC-B2 AND SMA-1 ACCELEROGRAPHS

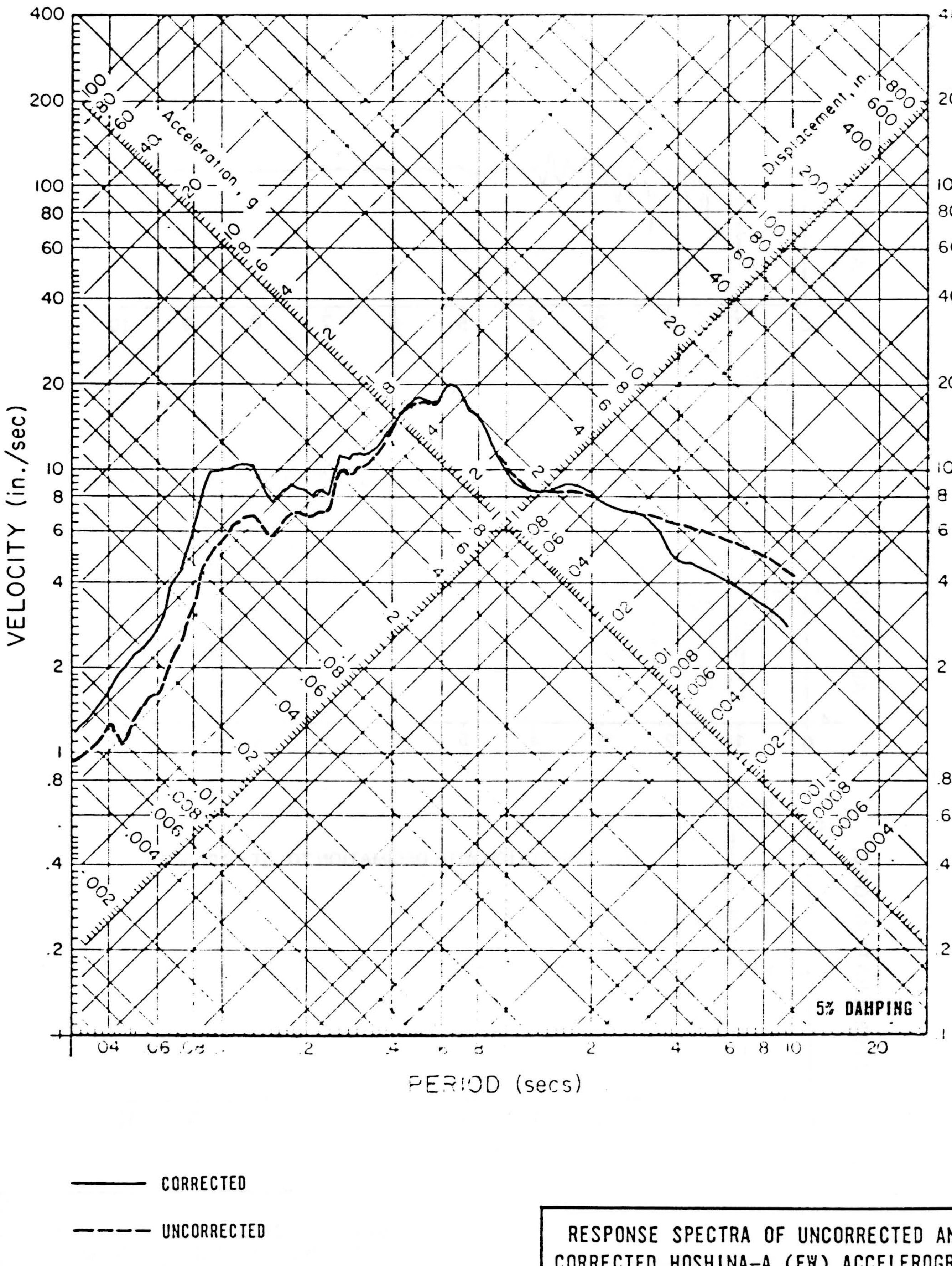
FIGURE 6



REFERENCE: MORI AND CROUSE (1981)

UNCORRECTED ACCELEROGRAM
VS CORRECTED ACCELEROGRAMS
WITH DIFFERENT DECIMATION

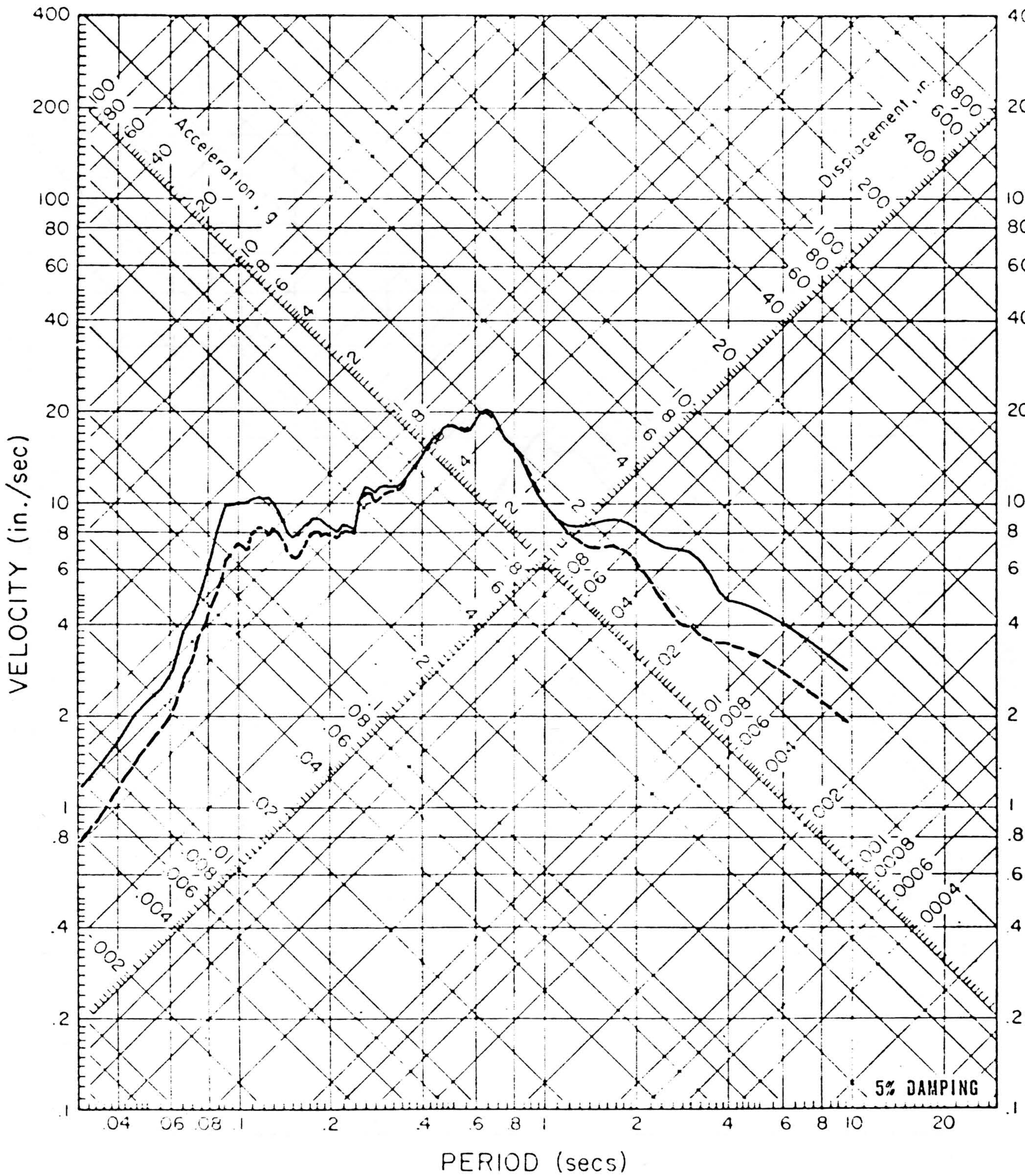
FIGURE 7



REFERENCE: CROUSE ET AL (1980)

RESPONSE SPECTRA OF UNCORRECTED AND CORRECTED HOSHINA-A (EW) ACCELEROGRAM PROCESSED BY JAPAN'S SEMOC

FIGURE 8



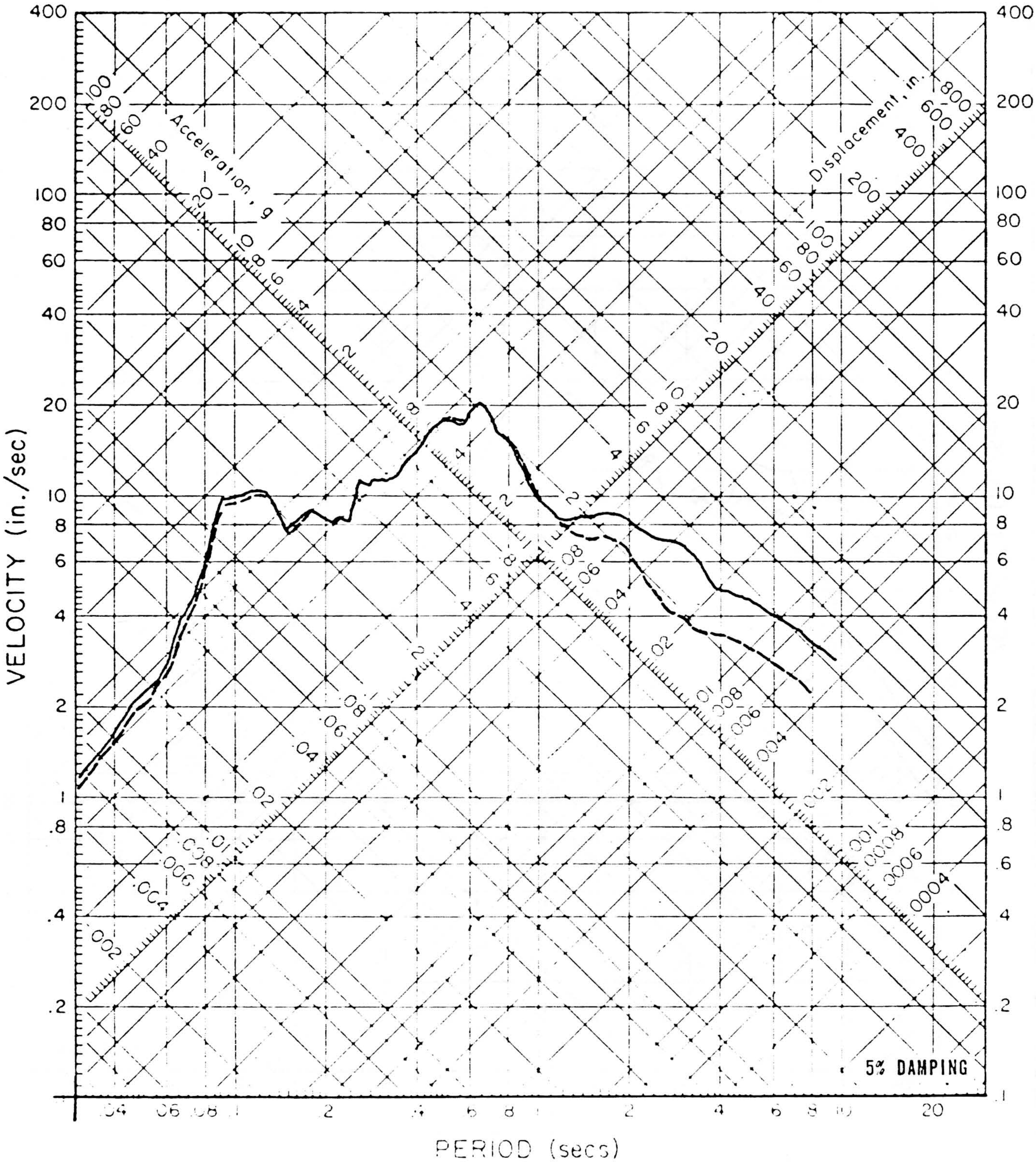
——— JAPANESE (SEMOC) CORRECTION
($\Delta t = 0.01$ SEC)

– – – – FUGRO CORRECTION USING USGS SEB COMPUTER PROGRAM
($\Delta t = 0.02$ SEC)

REFERENCE: CROUSE ET AL (1980)

RESPONSE SPECTRA OF HOSHINA-A (EW) ACCELEROGRAM CORRECTED WITH SEMOC AND USGS SEB PROCEDURES

FIGURE 9



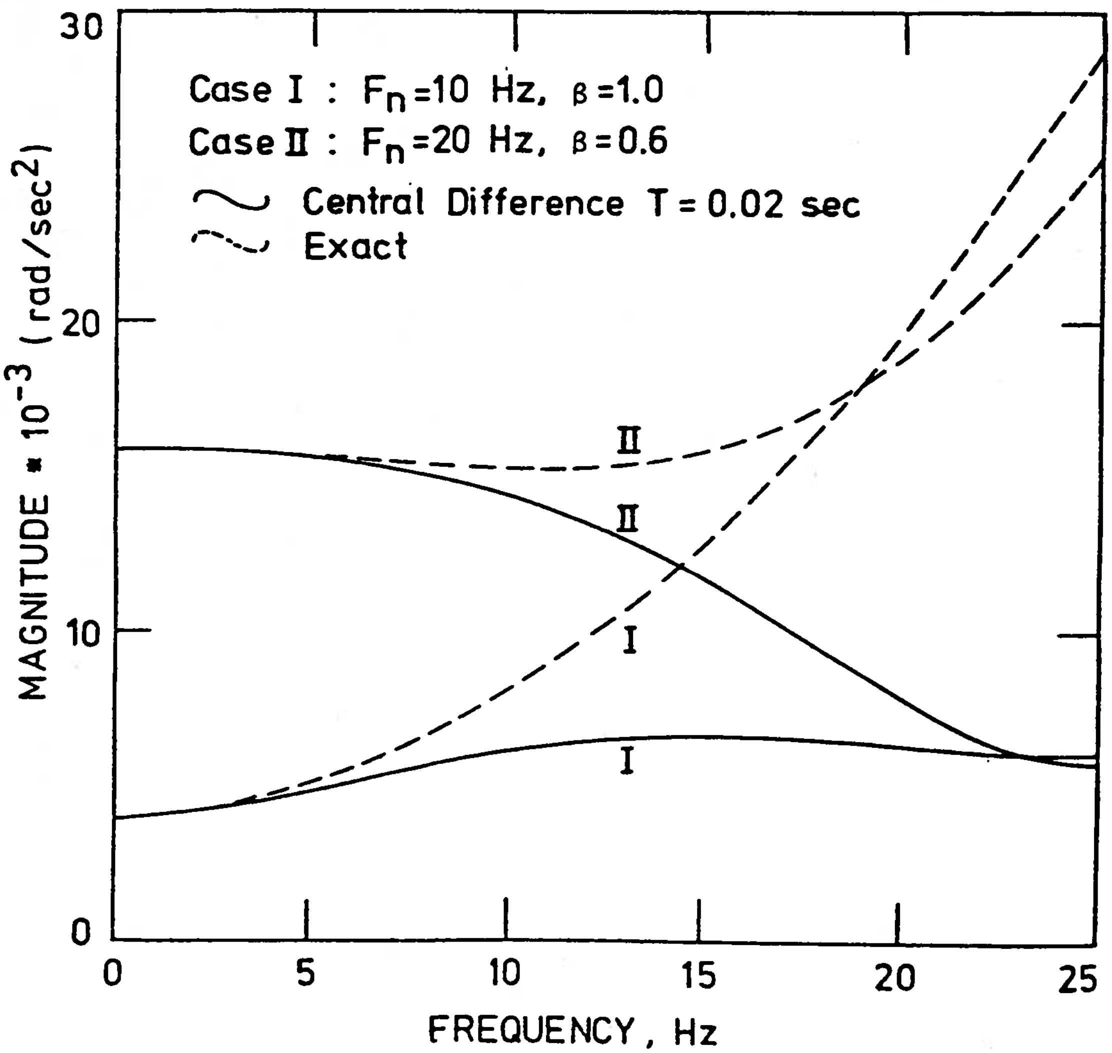
——— JAPANESE (SEMOC) CORRECTION
(Δt = 0.01 SEC)

– – – – FUGRO CORRECTION USING
USGS SEB COMPUTER PROGRAM
(Δt = 0.01 SEC)

REFERENCE: CROUSE ET AL (1980)

RESPONSE SPECTRA OF HOSHINA-A (EW) ACCELEROGRAM CORRECTED WITH SEMOC AND USGS SEB PROCEDURES

FIGURE 10



REFERENCE: S. SYAM SUNDER (1980)

MAGNITUDE RESPONSE OF EXACT AND CENTRAL DIFFERENCE INSTRUMENT CORRECTION FILTERS

FIGURE 11

DATA STORAGE, RETRIEVAL AND DISSEMINATION

by

M. D. Trifunac
University of Southern California

In the 1950's we didn't have enough data. In the 1960's we started getting the data so we had to work on digitization and processing. After San Fernando we realized that we didn't have good digitization systems because it took two plus years to digitize all the data and by the time we digitized all of the data, we were so tired we didn't feel like looking at it. In the 1970's and 1980's a different problem is appearing. We now have lots of data, and many organizations have capabilities to process and distribute the information. The usual procedure is to write to your friends and in a week you have a tape on your desk to play with. All of us have different machines, and all of us are presumably working in the same way, but if you really look at the situation, it turns out that it takes a lot of time to translate my tape into your computer and vice-versa. We are speaking from experience. The data that is available also varies in amount and quality of information and the way it is processed. At the present time there is no uniformly processed data set that covers all the recordings in this country. There are many similar data processing schemes but they differ in details which may or may not be significant. The degree to which information is available on the records varies quite a bit from one set of tapes to another. Not every organization can afford to maintain and run a computer facility that will read all of this information. If you are talking about a typical simple tape drive, 800 BPI, 9 track, you have a requirement of perhaps 20 or so 10 plus inch reels to maintain all the data. This takes a bit of disc space and not everybody can afford to have it. At the same time, with all the effort that is going into instrumentation, development, recording, processing and distribution, we would like to see that the data is at the disposal of all investigators as quickly as possible. We would also like to see that you have the opportunity of examining all of the data at the same time in a uniform way when you wish to do so. It is unfortunate to find that various studies are limited in their conclusions because certain data sets were or were not considered in full. So the objective that we are trying to work towards is to explore how we can set up a system which can deliver data quickly and efficiently to a broad class of users, not only concentrating on those who are experts in the field. A number of organizations are now working on data retrieval systems which have various degrees of data and information completeness as well as ease of access. What I shall do today is describe one such system in some detail as an example of current capabilities. The system to be discussed, called EQINFO, has been developed over the past two years at U.S.C., and for this development we are indebted to Professor Vincent Lee who developed all the programs and got the system into operation.

EQINFO stands for Strong Motion Earthquake Data Information System. The purpose of the system is to provide fast and efficient dissemination of strong motion data. The requirement is that the system has to be hardware independent. In other words, with the variety of little computers that you have at your disposal the system should not depend on the particular machine or terminal that you happen to have. Therefore, we would like to base the system on the telephone, ASCI and RS-232C, because those are so standard that you can't make things much simpler than that. The next thing that we would like to do is to facilitate access to the data in a limited way relevant to your specialized interest. In other words, you may want to look at a subset of that data subject to certain constraints. For example, you may want to look at all accelerograms having peak accelerations between 0.1 and 0.2 g. You may want to look at accelerograms between 10 and 20 Km away from the source or maybe accelerograms that are recorded on alluvium of depth of 1 Km plus or minus a couple of hundred meters, and so forth down the line. The system should be able to select the desired basic parameters for you so that you don't have to extract all of the data from the system. Another requirement is that you should not have to go to a particular center to acquire the data. We would like you to be able to take your telephone and dial a number and get the required information and data at your local site over the telephone. We would also like to have a distribution system which is intimately tied to a digitization system so that the flow of data is provided both ways.

The following outlines the current EQINFO system. This is how the present system works. EQINFO is built around as AOS Eclipse S 130 minicomputer, a 16 bit machine, which has a 190 megabite disc containing all the data. In the system, over the tape and over a direct line we have Nova 3 which carries the automatic digitization system, so the data that is digitized can immediately be fed into the system without ever getting out of it. The system can be accessed in two ways; by local users with a terminal, or you may dial a telephone to enter. The telephone number is (213) 743-4623. The user name is EQINFO and the password to EQUAKES. You need a full duplex and a 300 baud modem. Several different configurations of equipment can be used to interact with the system. One example is a terminal and a telephone. In dollar terms this would be something on the order of an $800.00 or $900.00 investment to be able to talk to the system, say a Heathkit terminal for $700.00 and a modem for about $100.00. A more advanced system would consist of a data terminal with a transparent or nontransparent floppy recorder, so that if you have the data that you want the system to deliver to you, you have a way of recording it by a floppy disk or cassette drive of some kind and, of course, a modem and telephone on the other end. A third possibility becomes almost an independent computer station that has everything that you may need, with some type of permanent record terminal. Also, if we want to record something on paper or print something out, then we would arrange for a recorder plus some kind of a controller that goes to a modem and telephone and a plotter. For our particular system the programs that we have operating at the moment will run with Houston instrument controllers and Houston instrument plotters. This controller can be transparent in that if you don't need to use the plotter, the information will go to the terminal just as in the simpler sytems. The most complete arrangement is under $10,000 but useful variations can be substantially cheaper.

Giving now a specific example, this is how the dialog proceeds. Once you have logged in and you get the ready bracket sign you type EQINFO and a return and essentially go through a question/answer session whereby you tell the program what it is that you want. The first group of questions deals with earthquake information. You have to select the dates, magnitudes, maximum intensities, locations, if you wish. You don't have to specify all of these things but you may have those parameters in mind when you are doing the search for whatever purpose you are using the data for. The second group of questions deals with the record location and information that is related to the station characteristics such as latitude and longitude of the station; for example, what are site conditions--is station on sediments, on alluvium, on hard rock, what is the depth of alluvium at a site, what was the local Modified Mercalli intensity, epicentral distance and so forth. All of these questions may by bypassed if you are not putting any constraints on the system. The questions can be answered with "greater than," "less than," or in between two limits. You have to decide which answer is most appropriate. The third group of questions deals with record and instrument data information. Perhaps you want only all horizontal components, so you will say that you are interested only in horizonal components in answering this particular question. You may want to look at records that came from instruments that have certain transducer characteristics. For example, if you want to look at AR-240 records, you will choose transducer natural frequencies that are less than 20 or 21 cycles per second and greater than 16 or 17. That will eliminate almost all of the other accelerographs, for example. You may specify what dampings you want to have, and digitized lengths of records--you may like to look at very long records or very short records. You want to say something about the digitization rates or RMS values, zero crossing frequencies, or times when peaks occur or information of this type. We tried to think of as many questions as we could, but I'm sure that if you sit down and go through the dialog, you will discover that there are certain questions that we have missed. In that case please get in touch with us so that we can add them to the system. Upon completion of the question process, the program will deliver information on which stations qualify under the constraints you have supplied and will give you a listing of where these stations are. Also, it will provide the names of data files where information on these recordings at these stations are to be found. The next step depends on the particular investigation. For example, if you would like to have for your particular project a set of records that are subject to your conditions and something appears on the list, you may ask the system to play back those files to you and you record them on your floppy disc drive. Suppose that you have a very modest system--a terminal and a modem, and you would like to have a rough idea of the shape of the spectra. In that case you would invoke a particular program that will provide a crude printer plot type display of the spectra on your terminal. You may have a paper terminal that has 132 characters per line. You may have a small dummy type terminal that does not exceed 80 characters per line, so you have to decide which you have there and you have to tell the system what kind of terminal you have. Then you have to say what you want. Do you want Fourier spectra or response spectra or maybe you like both. If you have a somewhat more elaborate system, say a Houston plotter or something equivalent to that, you can invoke two programs, M2PLOT and M3PLOT. M2PLOT, if given the name of the file that you're interested in, will produce for you over the telephone the plots of the volume two acceleration, velocity and displacement with all the peaks printed on it and M3PLOT will do the same for the spectra. Again, you have to provide the name of the file, but you have these names already from your previous session in searching what files you are looking for.

Next, we shall consider some aspects of remote data, recording and playback. Suppose you wish to record a file on a floppy disk--you will invoke the program FLOPPY and again after having specified the name of the file that you want, the system will play it back for you and record it on the local floppy disk. Alternatively, you may want to play your disk back into the system for some reason. In that case you will invoke playback and it will transmit the local information into the system over the telephone. Suppose we have the following situation. You have a floppy disk that you got from a friend or a colleague somewhere, but it has a different format than the formats that we are using. It contains a sequence of ASCI characters or you can create a sequence of ASCI characters locally that you wish to transmit over the telephone line. You can use the playback routine and play back information into the system over the telephone. You have created in the process a file on the disk. But that file doesn't look like anything that our software can recognize. In that case, you will invoke a Fix Volume One program in which you will want to know a little bit about the arrangement and the kinds of data that you have in your file. Things like the name of the file that you have to specify, the number of points in the sequence, the format of data-- if it is arranged in consecutive lines, number of pairs in lines and so forth. Fix Volume One will translate that into a file on the disc that our packages can read as if they are domestic files. So suppose you have a record that you have acquired in this fashion and you want response spectra and corrected accelerograms from the record. You have played it back over the telephone and it has been translated into a format that looks like our own. If you then would like to process the file, the two batch commands, Run Volume Two and Run Volume Three--Run Volume Two will invoke the suite of programs that represent the so called Volume Two processing, instrument correction, baseline correction, filtering, etc. Corrected accelerations, velocities and displacements can be plotted on your local system by calling one of the standard programs. If in addition you would like spectrum calculations, you need only invoke Run Volume Three and our standard spectrum calculations will be executed.

The above brief summary describes the configuration of EQINFO at the moment. It represents merely an attempt in the direction of facilitating the use of the data and in getting the data closer to the user. There are many things that it does not at the present do which we hope to add. At the present time the system is available free of charge on a trial basis. Free access cannot continue for long, but at the moment you can do it by just dialing the number given above to run all these programs. At the present time we have almost all processed strong motion data from the northern American continent on the system. The reason we do not have all records at the moment is that some of the records are not yet digitized, some of the records were digitized by others are are being reprocessed because we would like to have all of the records in the package of a uniform processing quality. They should all have the same filters and the same uniform procedures so that if statistical studies are made, there is no bias between one data set and another. Records are complete up to a few years back and in a short time, when some of the digitizations for the Mammoth Lakes sequence are completed and verified, the whole file will have been completed.

PANEL DISCUSSIONS

Panel Discussions

After the background papers on the various major topics of the workshop, a series of informal panel discussions were held. Each panel proceeded by first having each member present some of his basic ideas, which were then discussed by the panel, and summarized by the panel reporter. The subject was then thrown open to the audience, which engaged in a lively exchange with the panel members. The summaries given below were prepared by the editor from a transcript of a tape recording of the whole proceedings.

Panel No. I. Strong Motion Instrumentation Systems

Roger D. Borcherdt, D. E. Hudson (Chairman),
W. D. Iwan, William Rihn, Ta-liang Teng (Reporter)

For array stations which may be expected to record a considerable amount of data, and for which pre-event memory and accurate timing are usually essential, direct digital recording in the field is the optimum choice for future applications. For isolated stations, especially those with adverse environmental conditions and unusual maintenance problems, analog devices are probably still cost effective. A major limiting factor for digital applications is the relatively high standby power requirement and the consequent need for better and hence more expensive batteries. At present minimum standby power for digital systems appears to be of the order of 1 watt, with little immediate prospect of significant reduction – about five times the standby power of typical analog accelerograph systems. Since all current and presently contemplated systems, both analog and digital, use a force-balance type transducer, it is surprising that so little work has been reported on the charcteristics of such devices, and more should be undertaken. A pressing need is for a central evaluation facility with an accurate and convenient shaking table for calibration work. Such an instrumentation test table should be able to produce accurately defined wave-forms over a wide frequency range, should be free of extraneous modes of vibration and of significant cross-axis components, and should contain a reference transducer whose calibration characteristics can be accurately ascertained. The overall potential of telephone interrogation systems needs further study. There are no technical difficulties in the way of remote interrogation systems for monitoring instrument condition as a means for reducing field visits, but the cost-effectiveness is much dependent on the extent to which field visits are needed for nonrepair functions, such as routine replacement of film and batteries, and on the widespread adoption of such devices to reduce unit manufacturing costs. As the available dynamic range of instrumentation systems increases, there is more and more convergence of engineering strong motion systems and wide-range seismograph systems used by geophysicists. It may now be feasible to equip many of the existing seismographic stations in telemetered networks for simultaneous use as strong motion accelerograph sites.

Panel No. II. Existing Networks and Arrays in the United States

Bruce A. Bolt, David M. Boore, (Reporter),
Roger D. Borcherdt, Wilfred D. Iwan (Chairman),
Charles F. Knudson

The goal of obtaining at least one significant record from every destructive earthquake has probably now been attained for the United States, but the equally important objective of ensuring adequate near-field measurements for all magnitude ≥ 7 earthquakes has not. The general consensus is that while the total number of installed accelerographs in the U.S. is perhaps not far from sufficient, the distribution is far from optimal. There has been inadequate planning of arrays for specialized applications, particularly for engineering studies of special structures such as bridges, dams, and power plants. As a comparison, in Japan the emphasis seems to have gone more towards special arrays rather than general coverage with individual stations, with arrays often tied in to major construction projects. The present accelerograph installations in the U.S. comprise some 900 free-field sites, 500 building sites, and 400 special array sites. The general feeling is that to complete the U.S. network an additional 250-300 free-field sites might be contemplated, with another 15-20 dense arrays. At present in the U.S. down-hole arrays are few in number, and true three-dimensional arrays are nonexistent. Arrays for such studies as soil-structure interaction, liquifaction, and the response of special structures are limited in number and even more in scope. There is some difference of opinion as to the engineering importance of aftershock studies, and as to the importance of very rapid deployment of mobile arrays after a big earthquake. Experience in California has been that field deployment has been reasonably rapid, but that the recovered data, while useful for seismological investigations, has perhaps been of less direct importance for engineering applications.

Panel No. III. Field Reliability and Maintenance

John G. Anderson (Reporter), Rick Dielman,
Richard P. Maley (Chairman), B. J. Morrill, Francis T. Wu

Current standard analog accelerographs are now as reliable in the field (99%) as is likely to be attained by field instrumentation systems. Service intervals are governed more by standard replacement policies rather than by repair considerations, for example by USGS practice to replace film once per year and batteries at three year intervals. Basic inspection intervals can be extended to 9 months, but present policy is to visit critical structural array sites at 3-month intervals. It now appears feasible to plan for dual maintenance objectives at critical and noncritical installations. Unit maintenance costs have steadily decreased, with a bigger fraction of technician time going to other activities. Direct digital recording in the field has suffered the usual initial development pains, with the expected need for a retrained or more versatile type of field technician. Adverse environmental conditions of high and low temperatures, dust, humidity, and erratic power supply have posed problems for early generation digital systems. Many digital problems have been associated with the relatively high standby power requirement and the consequent need for better batteries. Transient power conditions have also been troublesome in field applications. An unexpected problem resulting from the ease of changing circuit boards in digital systems is a loss of calibration resulting from inadequate field records of such changes. A common problem with many accelerograph stations, both analog and digital, has been difficulties in maintaining accurate absolute timing. With either radio time or internal time-code generators recent experience has indicated a disappointing 50 percent reliability in the field. With time code generators and standard power supplies, drift characteristics are such that the station must be visited within 36 hours to maintain 0.1 sec accuracy with 95 percent reliability. There is a considerable difference of opinion as to the cost effectiveness of telephone interrogation systems to reduce overall maintenance costs. For some special situations, such systems might pay off in something like three years; in others they would be clearly inappropriate. It appears that there has been no systematic approach to the problem of updating and retrofitting of old instrumentation. As the accelerograph networks of the world continue to age, this will become a more pressing economic problem with increasing incentives for optimization. There should also be a more systematic interchange of information on field maintenance problems. The USGS has organized some technician meetings to bring together people from various organizations to exchange experiences and such activities should be supported and pursued on a more extensive scale.

Panel No. IV. Data Processing

John G. Anderson, A. Gerald Brady, C. B. Crouse,
Vincent W. Lee, Anthony F. Shakal (Reporter)
Mihailo D. Trifunac (Chairman)

After passing through an era of standardization there is now a tendency towards diversity in data processing methods, with many organizations introducing new procedures, some involving slight changes from past practices, while others may significantly modify the basic data. An increasing amount of accelerograph data is being obtained from other countries, for much of which the details of data processing may be unknown or uncertain. One point of view is that data processing methods should be flexible to adapt to the latest research requirements of the user, who should be able to exercise his own judgment as to the compromises to be made between signal-to-noise ratio and frequency range. Another opinion is that a unification of approaches would give the standard user the best chance of avoiding misunderstandings. Hopefully these two goals can be combined, with standard processed data available for general use and "uncorrected" data provided for the research user. A central item in any processing scheme is the filtering process used to control noise content. It is generally recognized that there are many different ways of carrying out essentially the same filtering process. What should be agreed upon is the definition of an acceptable filter and a general realization of how far standard characteristics could be departed from without significantly altering the data. At present various filters have been advocated in the literature without a clear indication of the conditions under which they might introduce significant improvements over the past standard procedures. There is a difference of opinion between some engineers who feel that any filtering operation should preserve the ground signal wave shapes, and some seismologists who for special purposes would like to distort wave shapes, for example, to sharpen up a phase arrival time signal. What can be agreed upon is first that the data processing should involve enough flexibility so that it can supply standard data for general use as well as specially treated data for research applications, and second, that whatever procedures are used should be so completely documented that the user can judge applicability without making a research project out of it.

Panel V. Data Storage, Retrieval, and Dissemination

Carlos A. Angel, A. Gerald Brady (Chairman), Ahmet S. Cakmak, Neville C. Donovan (Reporter), Nicolai A. Kaliakin, Anshel J. Shiff

The number of digitized accelerograms in the world in 1980 was of the order of 1,000; this had increased by 1983 to some 3,000, with every indication that an almost explosive growth of such basic data should be expected in the near future. At present there are no international centers attempting to archive such data, and in the two countries with the major accelerograph networks, Japan and the United States, there are literally dozens of separate organizations in the data management business, with no central group to coordinate efforts. Information is needed in several different forms and at several levels of detail and completeness. Of key importance is a general catalog of all recovered records, with such information as location of station, time of event, basic earthquake parameters, peak accelerations, and available data formats and source. Although a number of groups in several countries regularly publish such catalogs for their own installed instruments, the major attempt so far to issue them on a collected basis is that of the National Geophysical Data Center of the U.S. National Oceanic and Atmospheric Administration in Boulder, Colorado. This has been a useful service, but is far from complete - no data from Japan, for example, is included. Of special importance is the early and convenient availability of unprocessed acceleration-time curves from important earthquakes. A glance at these preliminary accelerograms is very informative to the experienced investigator, and can give the potential user a quick idea as to which records are likely to be important for special studies. Such plots are available in the preliminary reports issued by some agencies, but they are presented in many different formats and for some important earthquakes and stations may be incomplete or unavailable. Catalogs of the above type can be easily adapted to a computer search technique, so that the user with a terminal and a telephone link can ask, for example, for a list of recorded accelerograms with a prescribed distance of a prescribed location. At a higher level of information availablity, several systems have been developed which will present to the user with a terminal and plotter such additional items as integrated velocity and displacement curves, and frequency spectra in various standard forms. At least three different automated data retrieval systems of this kind have been independently developed in the U.S. Although they differ somewhat in completeness of data bank, ease of access, etc., the basic principles are similar, and it would appear that an increased cooperation in this field would improve the overall acceptance and usefulness of the systems. All attempts at computer processing of strong motion data have been hampered by the multiplicity of digital data formats. For example, the National Geophysical Data Center is now preparing to issue basic strong motion data on floppy disks in 80 different formats. Attempts to decipher tape records have consumed a large number of research man-hours that could certainly have been put to better use. As a final comment on the state of the basic data, it should be mentioned that important information on accelerograph site conditions is far from adequate for any part of the world. Some of the most significant California accelerograms, for example, are from sites that recent studies have reclassified from rock to alluvium.

EXHIBITION OF INSTRUMENTS, OLD AND NEW

Exhibition of Instruments, Old and New

An important feature of the Anniversary Workshop was an exhibition displaying a wide selection of historic instruments illustrating various stages in the development of the subject, including examples of the latest technology. Many of the early instruments have become quite rare, and some of them exist only in pieces or single models. It is to be hoped that the general interest which seemed to be stimulated by the exhibit will inspire effective means of preserving them, as they are at present scattered with a high probability of eventual deterioration and loss.

We are indebted to many different people and organizations for assistance in assembling the exhibits. Professor Paul C. Jennings and Raul Relles of the Earthquake Engineering group at the California Institute of Technology supplied a number of the old instruments from their collection. R. P. Maley of the U.S. Geological Survey provided several models of the original U.S.C.G.S. Accelerograph, as well as a very interesting display of the original 1933 accelerograms from Long Beach and Los Angeles, together with background pictures and documents. B. J. Morrill of the old U.S. Coast and Geodetic group supplied several transducer types, including what must be the sole remaining quadrifilar type transducer which was used for the first accelerograms. One of the original models of the classic Wood-Anderson torsion seismometer was loaned to us by Mr. John H. Lower of the Seismological Laboratory of the California Institute of Technology. Mr. Robert E. Griffith of Kinemetrics, Inc., kindly provided some historic transducers and pictures. We much appreciate the efforts made by Professor M. D. Trifunac of the U.S.C. Earthquake Engineering Group and his students on the transportation, arrangement, assembly and adjustment of many of the old instruments.

For the modern instruments displayed, we are indebted to the following organizations and people. From the U.S. Geological Survey, Dr. Roger D. Borcherdt displayed a new digital accelerograph system being developed there. From Kinemetrics, Inc., a display of recent instrumentation arranged by Rick Dielman, Harry T. Halverson, George W. Patraw and Steven E. Pauly. Teledyne-Geotech provided several of their recent devices, arranged by Tom Trosper, Howard Thompsen and C. W. Camp. Terra-Technology, Inc. displayed their latest digital accelerograph, arranged by Charles Fitzgerald and Stephen Porell.

The accompanying pictures will give a general idea of the instrument display area. Pictures of the individual instruments, practically all of which were exhibited, may be seen in the background paper "History of Accelerograph Development."

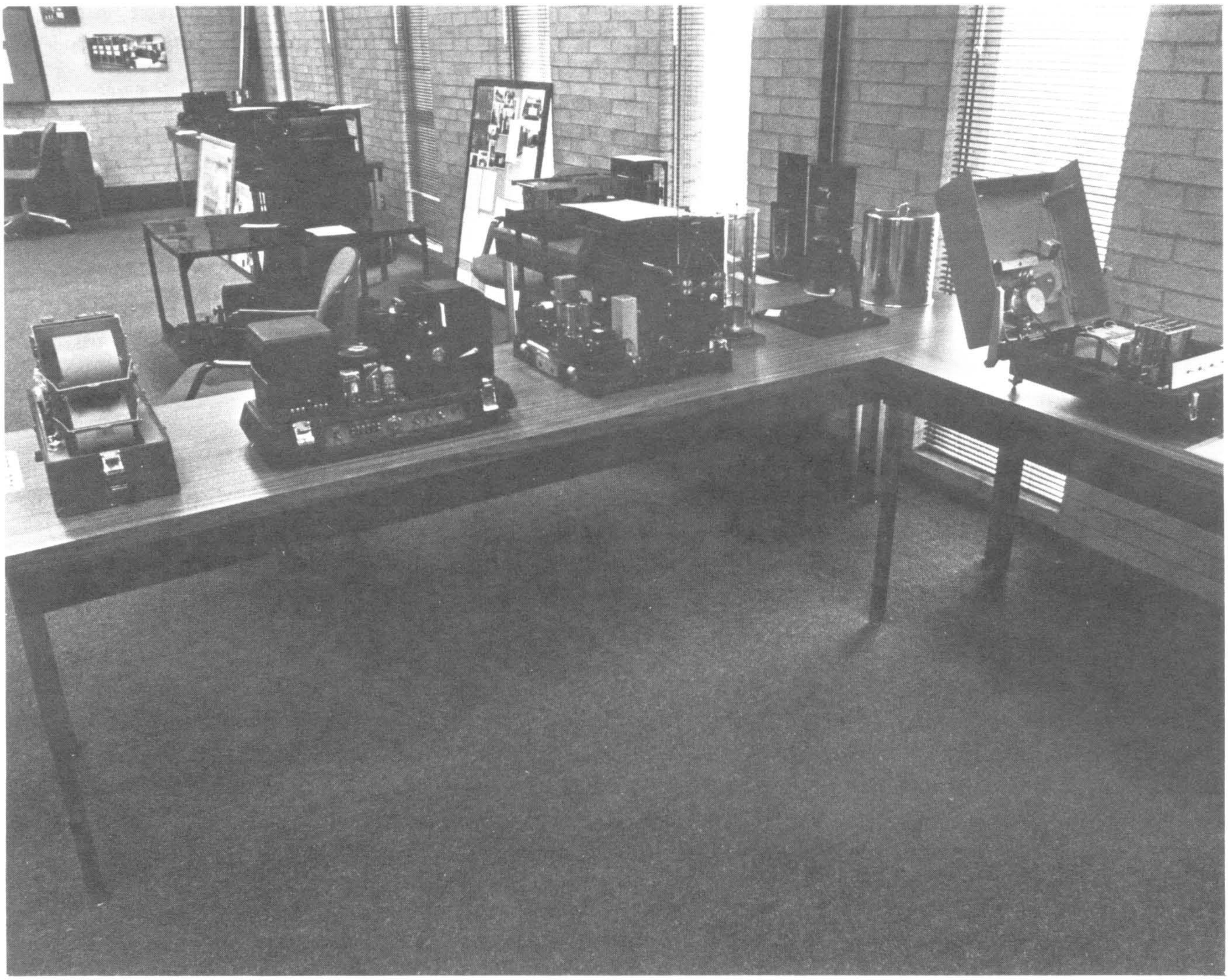


Figure 1: General view of historical exhibit of instruments.

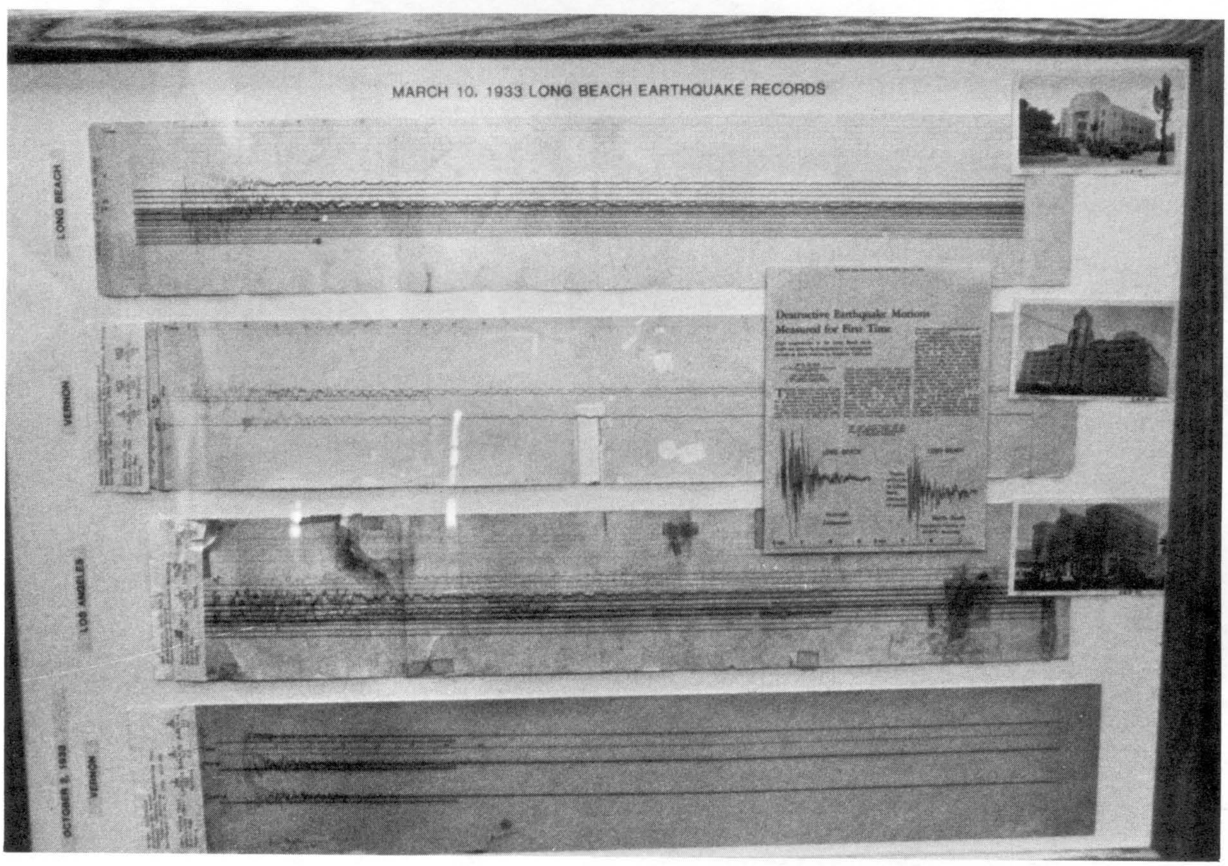


Figure 2: Original accelerograms of Long Beach Earthquake.

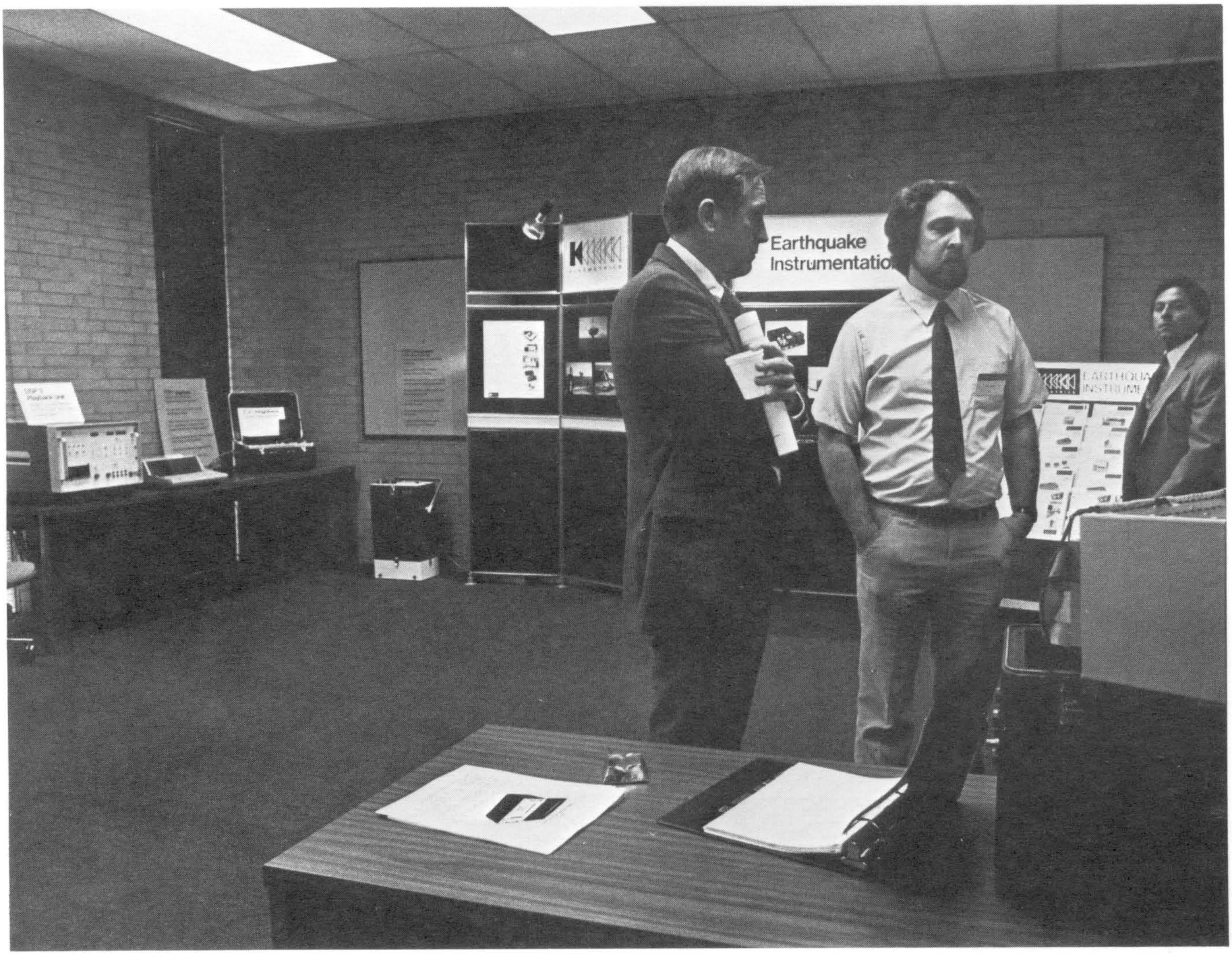


Figure 3: Exhibition of modern instrumentation - general view.

Figure 4: Workshop general session.

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