A multi-sensor research program to improve tsunami forecasting

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Abstract. While the warning systems do an increasingly good job of warning of all probable events, there are still apparent false alarms and a lack of magnitude prediction. History shows that major advances in technology occur when several components mature to be combined into a final system. An example is the communications satellite: around 1960, the silicon solar cell, the RF transistor, the integrated circuit, the large rocket, knowledge of the synchronous orbit, reliable components, and supporting systems came together to produce systems so workable that the early ones are still usable and the current ones just have more channels.

We are now in a "1960 position" in tsunami work. Deep ocean sensors are in place, numerous tide gauges and sea level gauges are telemetered (via satellite), real-time numerical analysis programs are under development, M_w can now be calculated in an hour and M_{wp} in a minute, a global infrasonic network has been deployed, T-phase data are readily available, and so are ionospheric sounders. We have the capability to cheaply and quickly record, correlate, analyze, transmit, and discard data from all these sensor systems. Thus, we should have the means to develop the ability to evaluate a tsunamigenic earthquake and early tsunami waves, reliably and even quantitatively.

I suggest the ideal way to accomplish this is to establish a small, dedicated laboratory which will bring together a selection of data from these sensor systems to evaluate every possible tsunamigenic event. It is now easy to temporarily store these data in volatile memory for analyses, retention, and discard. An earthquake that would be checked and discarded by the warning center can provide the trigger for storage and evaluation. Most of the data are low frequency, and easy to transmit (part of it is on the internet now) and store.

Information on prior experiments with some of the components, current status, and processing estimates is provided, along with ample references.

1. The Warning Problem

While the warning systems do an increasingly good job of warning of all probable events, there are still false alarms and a lack of magnitude prediction. Warnings are binary, with a very fine line between "warn" and "no warn"; the decision is usually conservative and produces false alarms from the public viewpoint if not in fact. This occurs because we still have not achieved the ability to forecast a damaging event accurately and rapidly. Yet, we have more seismic stations than ever, more sea level stations, more computers with faster, more capable programs, and better communication systems. Our use of modern technology is good, but more can be incorporated into a systems approach. Curtis (1993) reviewed the progress at that time and pointed out some research which might be cost effective. How can we accomplish more improvements?

History shows that major advances in technology occur when several components mature to be combined into a final system (Curtis *et al.*, 1986).

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An example is the communications satellite: around 1960 the silicon solar cell, the RF transistor, the integrated circuit, the large rocket, knowledge of the synchronous orbit, and highly reliable components, came together concordantly to produce systems so workable that the early ones are still usable and the current ones just have more channels.

We are now in a "1960 position" in tsunami work. Deep ocean sensors are in place, numerous tide gauges and sea level gauges are telemetered (via satellite), real-time numerical analysis programs are under development, M_w can now be calculated in an hour and M_{wp} in a minute, a global infrasonic network has been deployed, T-phase data are readily available, and so are ionospheric sounders. We have the capability to cheaply and quickly record, correlate, analyze, transmit, and discard data from all of these sensor systems. Thus, we *should* have the means to develop the ability to evaluate a tsunamigenic earthquake and early tsunami waves, reliably, and even provide a quantitative warning. If we bring all appropriate technology to bear on the problem, we can surely advance that capability nearer to the goal.

2. The Concept

I suggest that the ideal way to accomplish this is to establish a small, dedicated laboratory which will bring together a selection of data from these sensor systems to evaluate every possible tsunamigenic event. It is now easy to temporarily store these data in volatile memory for analyses, retention, and discard. An earthquake that would be checked and discarded by the warning center can provide the trigger for storage and evaluation. Most of the data are low frequency, and easy to transmit (part of it is on the Internet now) and store. A precept was provided by Najita and Yuen (1978). The reference includes a full description of tsunami generation by earthquakes and of detection of tsunamigenic events by HF ionospheric sounding. The laboratory they set up at the University of Hawaii (UH) is described; the sounding was continuously plotted on a chart recorder at slow speed activated to a high speed when seismic waves from the UH seismometer exceeded a threshold—similar to the alarm at the Pacific Tsunami Warning Center (PTWC). A significant problem was in disregarding the natural perturbations occurring at dawn and dusk. These could only be partially removed by the band pass filter used, and the project was eventually discontinued.

Was an important opportunity missed when this work was not carried further? Most of the technology involved has now grown and advanced so it will be much easier to carry out the work in the future. Plus, with more geophysical sites in use, far more good data are readily available. In fact, it is likely that this and other ideas can be done as a hindcast experiment with the large amount of sensors and recordings from them currently stored in accessible data banks.

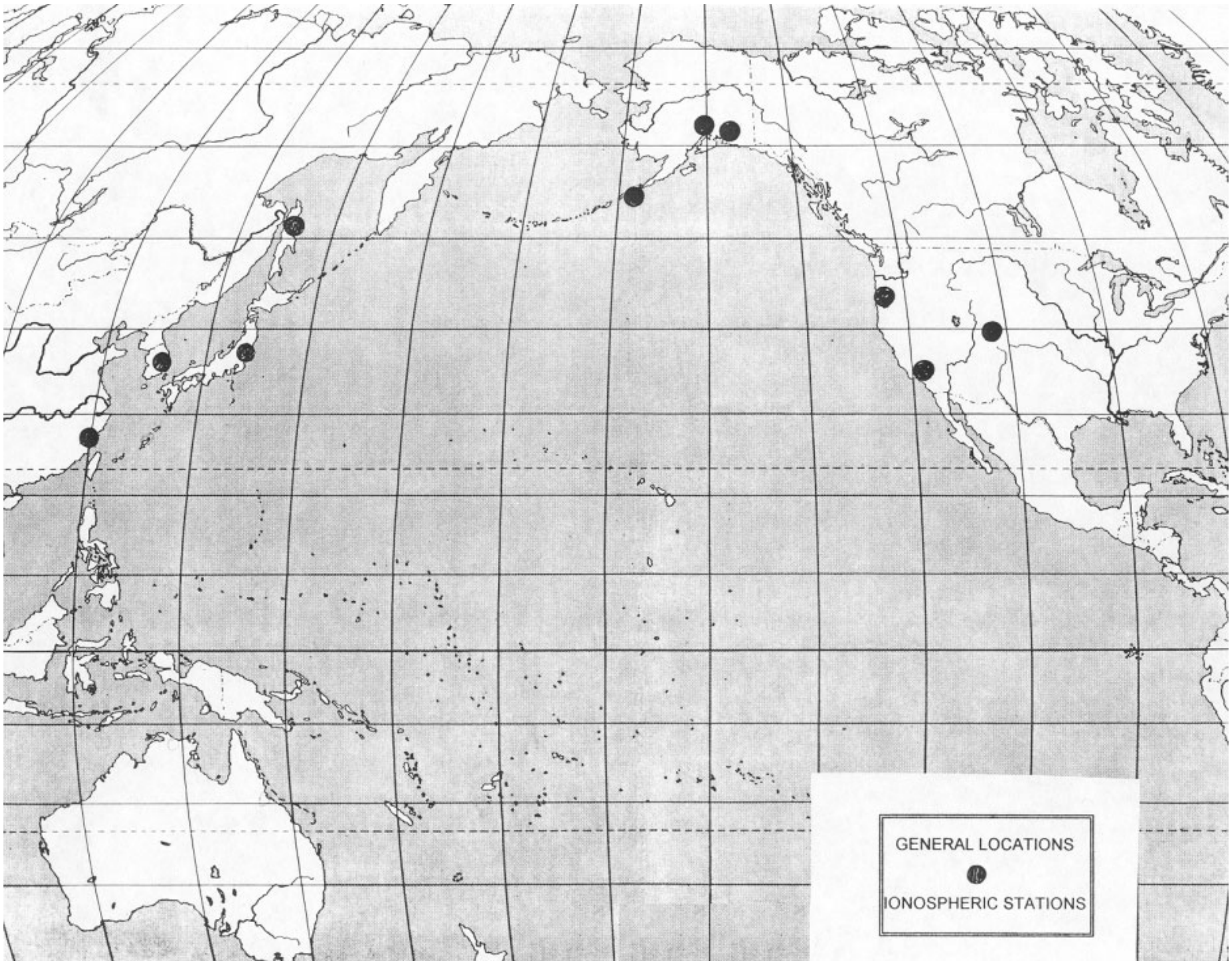

Figure 1: General locations, ionospheric stations.

3. Sensors and Sources

3.1 Ionospheric

Ionospheric sounders indicate the height of the ionosphere, the upper portion of the atmosphere that is heavily ionized and which enables "short wave" radio transmission by reflection of the signals. Earthquakes with a significant component of vertical deformation perturb this layer in a manner that is readily measured using precise radio signals in the high frequency region broadcast by standard stations around the world. The vertical displacement travels toward the ionosphere (100 m altitude or more) as a Rayleigh wave, faster than the speed of sound; the radio measurements are of course instantaneous.

Weaver *et al.* (1969) report such measurements for an earthquake in the Kuriles and Furumoto (1970) discusses using them to evaluate the source mechanism of tsunamis. These investigators used 5 and 10 MHz transmissions from WWVH on Kauai, received in Honolulu and utilized as described by Najita. Fitzgerald and Walcott (1985) reported the ionospheric disturbances from the Coalinga earthquake; there are numerous other similar recordings. The actual data of interest is between 2 seconds and 300 seconds. It appears that there are at least 12 HF sounding stations around the Pacific in the U.S., Canada, and Japan which can provide real-time or recorded data for this purpose. Figure 1 shows the location of some.

A newer but widely used method of measuring ionospheric changes is by their subtle changes in SHF radio transmissions from satellites; Navstar GPS is usually used. Calais *et al.* (1997) obtained signatures from a mine blast by this method while others gave described the effects of earthquakes on the signals. Romans and Hajj (1996) give a general view of the methodology. Since the satellites transmit on two frequencies, it is feasible to obtain an excellent differential measurement. These receivers can be set up for real-time use wherever telemetry is available.

3.2 Infrasonic sensors

Project "Vela"—a set of ARPA programs to detect nuclear explosions—produced many standard seismic systems around the world, but also a number of infrasonic receiving systems (microbarographs) were established. (Of course many such geophysical labs had existed for years.) These sensors added to the ability of research in atmospheric detection of events such as hurricanes, tornados, earthquakes, and other disturbances. It was known that earthquakes sometimes were reported to produce a noise, and Nakamura (1988) described the sound of an approaching tsunami and analyzed how it might be produced. Miller (1968) had earlier brought up the possibility of predicting tsunami height from atmospheric wave data, mentioning the effect of the vertical component. In the same symposium, Donn (1968) discussed sources of infrasonic waves and their detection. (This writer developed the sensors then in use by Donn at Lamont Geophysical Observatory and recalls their detection of hurricanes as well as nuclear explosions.)

Bedard and Georges (2000) and Bedard (1998) discuss the varied applications of infrasonic detection (the 1998 paper alone has 31 references), including earthquake detection and analysis. An example of recording both infrasonic and acoustic waves for geophysics is provided by Tihara *et al.* (1997). There are a number of microbarographs around the Pacific of varying capability whose records might be used for analysis, if not in real time. Ironically, the Honolulu Observatory (which became the Pacific Tsunami Warning Center) had a microbarograph, which apparently was discarded long ago.

The Comprehensive Test Ban Treaty (CTBT) has resulted in the establishment of an enhanced Vela-type global network by the U.S. Department of Defense. These microbarographic stations are extremely sophisticated, have a large wind noise reduction system (detection is limited by wind noise, not the sensor elements), and are well equipped and manned. The pass band of the microphone is 8 to 0.02 Hz (period of 0.125 to 50 s) less some noise reduction effect, and the data are telemetered to a central location in Virginia. There are systems now reported to be in operation in the Pacific

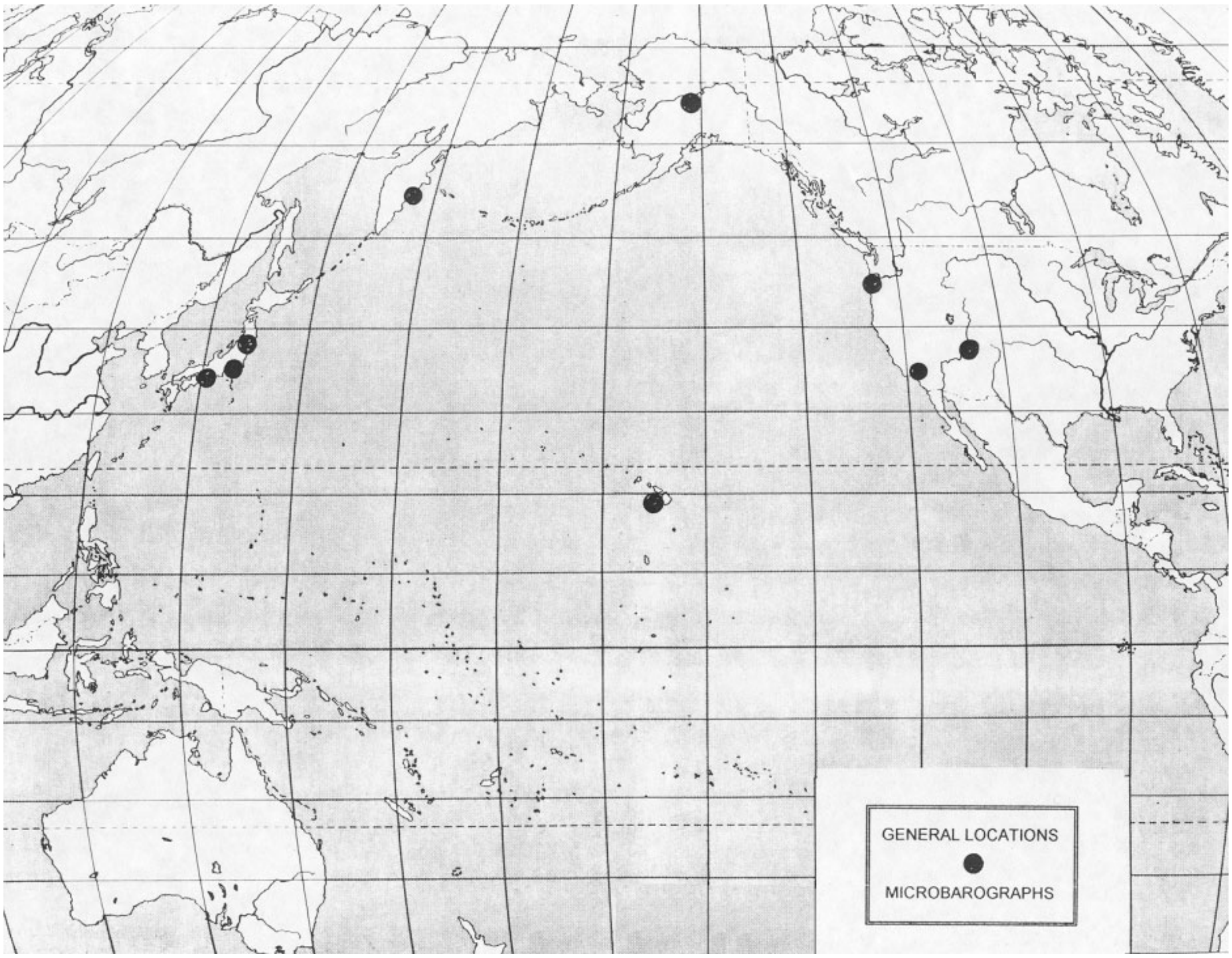

Figure 2: General locations, microbarographic stations.

region, as part of the International Monitoring System (IMS). Because they are wide band, low noise, and on line, they are probably the best sources of earthquake-effect data. Figure 2 maps some of the various microbarographs in the Pacific. Since the signals travel at roughly the speed of sound, it is necessary to utilize sensors as near the source as possible.

3.3 T-phase sensors

The T-phase signal from an earthquake is propagated via the SOFAR (SOund Fixing And Ranging) channel in the ocean and couples into the earth near the coast to be detected by a seismograph. Since most of the path is acoustic ($\sim$1500 m/s) it arrives after the P and S waves and so is referred to as the tertiary wave. It can, of course, be readily detected by hydrophones in the sound channel (U.S. Navy) and also by other hydrophones. The use of the T-phase signals in the warning system was proposed by Ewing *et al.* (1950). Considerable work was done on seismic T-phase evaluation for that purpose (Johnson, 1970) but with limited success. Johnson pointed out that

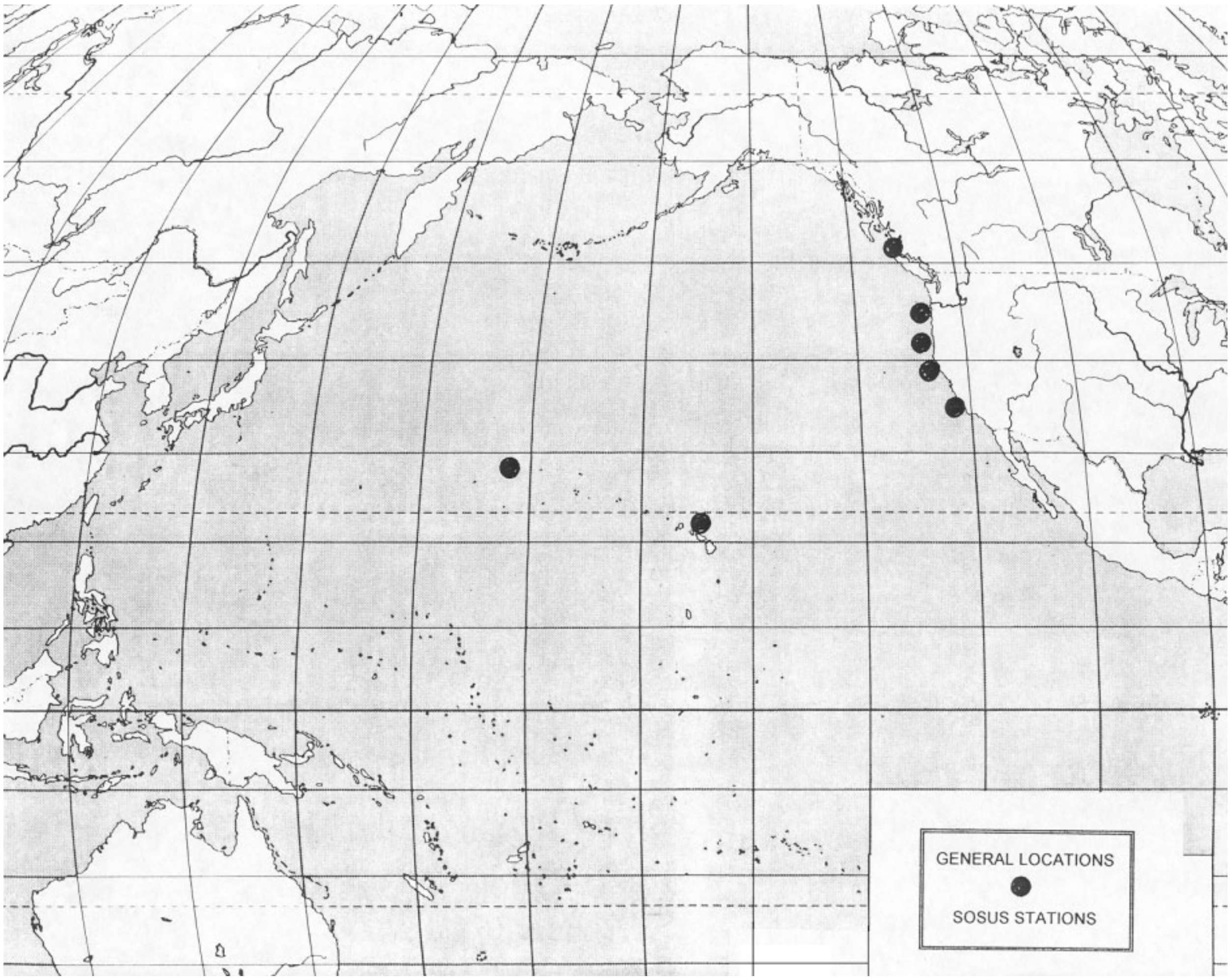

Figure 3: General locations, SOSUS/hydroacoustic stations.

if an array of hydrophones were available, he could have combined directivity with duration and accurately determined rupture length. The SOSUS (SOund SUrveillance System) can now provide just what Johnson needed, in the desired band of 2 to 30 Hz.

Walker *et al.* (1991, 1992) revived interest in application of T-phase data to tsunamigenesis by gathering extensive data from abandoned military hydrophones of the Wake Island MILS (missile impact locating system). They did extensive examination of the correlation of these waves (in frequency, amplitude, and duration) with source, path, and moment magnitude and concluded that variables such as the acoustic path limited reliable analysis of tsunamigenesis in many cases. However, he was limited to a single receiving location and no directivity.

With the end of the Cold War the Navy began to close many of their submarine tracking SOSUS stations, and made data from others available to the scientific community. Fox and Hammond (1994) describe the VENTS program under NOAA which provides T-phase and other data via SOSUS in the North Pacific. The several SOSUS stations, each with an array of many hydrophones, offers a means to deal with the path discrepancies encountered with a single location. It should be possible to evaluate predetermined paths to likely seismic locations and make a more valid analysis of the tsunamigenesis of an event in near-real time. Figure 3 shows the approximate locations of some SOSUS stations; some are part of the IMS and some are connected to NOAA via a Navy processing station at Whidbey Island, Washington.

3.4 Other sensors

An open scientific mind may suggest other sensors not yet considered or which, though not feasible in the past, may now be possible. Satellite altimetry has improved since Seasat and the fortuitous detection of waves may occur if we look and analyze carefully. The use of differential GPS on a buoy with satellite transmission is a possible method of observing a wave. Improvements in evaluating the source in real time—the seismic moment, the rupture length from wave arrival time at area gauges, the deployment of more deep-ocean sensors—will certainly continue and will offer more means to promptly evaluate a possible tsunami, while at the same time make the job more complex.

4. The Tsunamigenesis Experiment

The above descriptions of past and current programs related to tsunamigenesis indicate that (a) there are technologies available or known that can help define the onset of a significant tsunami, but (b) we have not combined them into a working system.

The other vital technology available but not mentioned as it is known to all is rapid data handling systems. We now have relatively cheap, fast, high volume, digital communication, storage, and analytical equipment not available to many of the investigators cited above. We should utilize these capabilities along with careful consideration of the science that has been done and that is now in use, to develop a more reliable tsunami forecasting system. This is the sort of concurrent approach outlined in the introduction and can move the 1960's point into this century.

I suggest that the ideal way to carry this out is to establish a small, dedicated laboratory that can gather, correlate, and evaluate a selection of data from every possible tsunamigenic event. The extensive and very capable seismic network now deployed provides the basis for experiments by triggering the data collection scheme. Inputs from several sensors temporarily stored in volatile memory of ample duration may then be stored for analysis, archiving, or discard. It is easy to save before as well as after. This writer designed a system 20 years ago that keeps four channels of data plus WWVH time for 4 minutes before and 6 minutes after an event. It is still in use but could be done much better with present technology. This is a good approach to our data problem. As in any good experiment, the negative data (no significant tsunami) can be as important as the positive results.

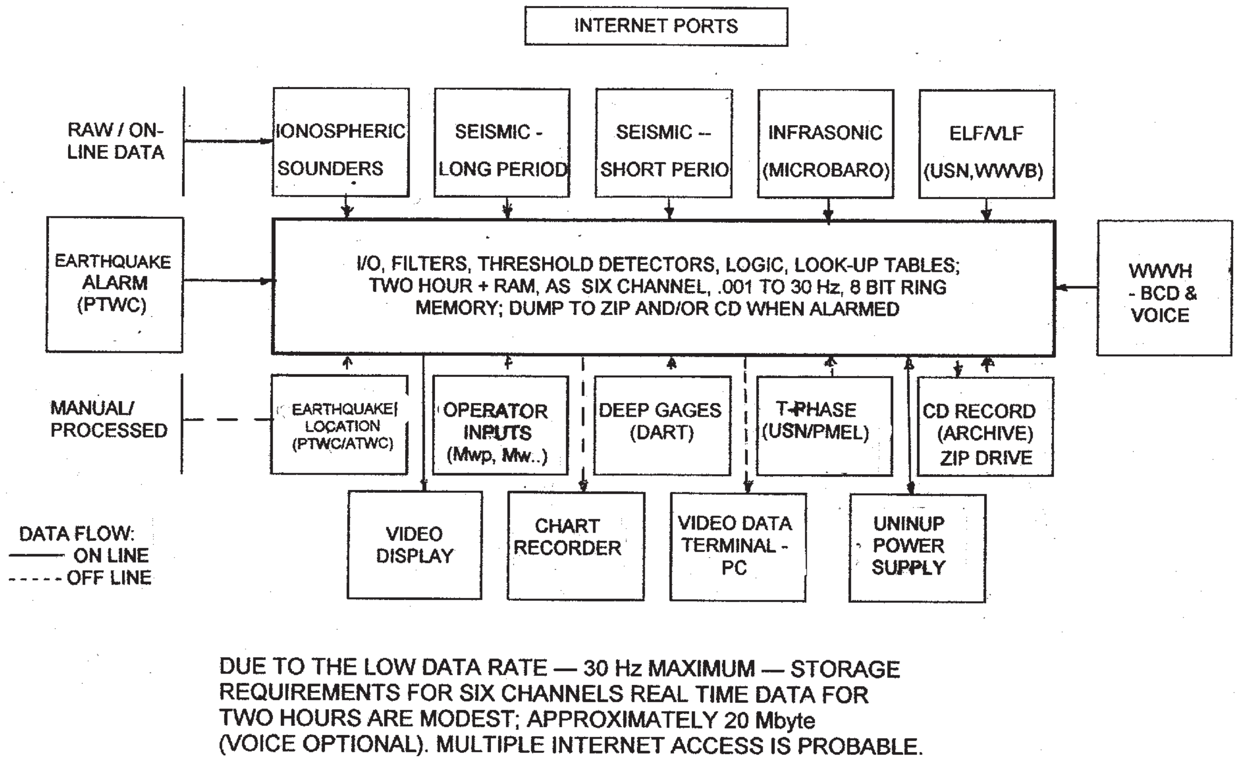

Figure 4: Data flow, tsunamigenesis experiment laboratory.

Examination of the possible sensors and data makes it clear that some very productive work can be accomplished by hindcasting with existing data. A good example already accomplished is the evaluation of moment analysis as a tsunamigenic indicator (Walker *et al.*, 1991; Tsuboi *et al.*, 1999). This has not provided a satisfactory answer yet, but if it is correlated with other data it may eventually yield a better solution. Other examples might be microbarographic data after an earthquake, from Japanese and U.S. archival sources.

The optimum approach is to establish a small, dedicated laboratory at a location where essential real-time data are available and staff and analytical capability exist—even part time. Because most pertinent data can be saved automatically by this system for later analysis, attendance would not be mandatory. Certainly, a combination of on-line data, recorded data, and retrievable data can be used to present the coordinated information to knowledgeable scientists, present or not.

Figure 4 outlines a system intended to be comprehensive—what should be planned for, not necessarily what can be done this year. But none of it is technically difficult. Funding for new projects is often difficult but we have far more available to solve this problem than we had 10 or 20 years ago (Curtis, 1993). Much of the data are "free" for the connection or retrieval.

A carefully chosen committee of "customers" (warning centers and advisors), experienced tsunami scientists, and data suppliers as overseers will enable the laboratory to achieve the goal of almost eliminating "false alarms" without endangering public safety. The cost of one unnecessary evacuation would pay for years of its operation.

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Note: copies of most of the above references are in this writer's files, and can be made available to other users.