SEISMIC DETECTION UTILIZING A MINI SENSOR

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ABSTRACT

There is a need for a low cost, miniature, low power short-period sensor with the flexibility of packaging, not only for detection systems for nuclear treaty monitoring, but especially for the demanding requirements of free standing ocean-bottom (OBS) applications like offshore seismic monitoring and oil exploration. In this case, the very tight dimensions of the glass sphere or cylinder restrict the total assembly size, including seismometer, data acquisition systems, acoustic release, and batteries. Ideally, total sensor size should be less than the commonly used geophone size (several cubic inches) and power consumption should be very low, below 500 mW for a triaxial sensor and the digital recorder, while sensor self-noise should be close to or below the USGS Low Earth Noise Model, with dynamic range at least 120 dB to provide meaningful data. Such a sensor could provide valuable information by accurately recording signals far beyond the dynamic range of ordinary geophones.

The proposed sensors would also find applications in the area of earthquake engineering. The availability of miniature, very low-power, easily-installed, ruggedized, high-quality instruments costing *significantly less* than seismometers currently on the market would make the general instrumentation of structures in earthquake-prone areas affordable. Data from structures, which are susceptible to collapse, or significant damage, would enable engineers to better understand their nonlinear behavior and failure modes of structures. This would lead in turn to improved designs and building codes. In the interim, such data would identify those structures, which need to be reinforced. These sensors would also facilitate the instrumentation of historical structures in these earthquake-prone areas. Local networks of seismic or vibration detectors could prove an extremely cost-effective means of improving the safety of existing nuclear and other facilities. These applications require that the instruments be both reliable and inexpensive, so that they could be deployed even in today's environment of reduced utility budgets.

This technology would also lend itself to the extension of nano-g sensitivity. Nano-g sensors are of great interest to the space program. For example, their deployment on satellites offers the only practical means of monitoring satellite drag.

OBJECTIVES

This project, if successful, would lead to the implementation of miniature, affordable, rugged, reliable, easily installed high-quality instruments, well suited for mass production and use in all of the above areas.

Based on our investigation, we summarize below to meet the following requirements to such a seismometer as detailed in the original research specifications:

- miniature size – about 1 cubic inch
- power consumption should be below 100 mW for a basic analog sensor
- dynamic range - at least 120 dB
- high resolution in the required passband of 0.2 to 40Hz: below the USGS Low Earth Noise Model (e.g., approximately 0.5 ng/sqrt(Hz))
- the sensor must be capable of operation at any selected orientation of its axis of sensitivity.

RESEARCH ACCOMPLISHED

The last several decades have witnessed revolutionary changes in seismology and seismic-related applications like earthquake engineering, oil exploration, and nuclear plant monitoring. These changes caused by tremendous progress in the capabilities of advanced geophysical instrumentation coupled with the ever-growing power and accessibility of computers, networks and multi-channel compact low-power data acquisition systems. These new tools have provided large volumes of invaluable information on near-field and remote earthquakes or man made events such as explosions, the dynamic processes in the mantle, and the behavior of structures subjected to seismic activity. Their usefulness to seismic-related applications has been amplified by the use of large networks of low-noise seismic sensors. The use of these sensors, both in networks and in a wide variety of standalone applications, has been limited by the high cost of such instruments, especially given the reality of current budgetary restrictions. All commercially available high-performance seismometers are large in size, heavy and have a high power consumption. The user must often face a difficult choice: use instruments with significantly lower performance characteristics (geophones), or reduce the size of the network.

Using its proprietary technology, eentec was the first manufacturer to offer a low-cost medium-period seismometer. Prior seismometer models available jumped from short-period (1Hz and above) to broadband instruments. This medium period seismometer (eentec was the first to "coin" the medium period seismometer term in the market) instrument generated a steadily growing flow of requests and orders from all over the world. The sensor was originally intended as a low-cost replacement for the old-style short period passive instruments. Continuing internal research efforts have led to significant improvements in performance with only slight increases in cost. With continued development of its technology eentec has introduced the first low-cost field rotational seismometer (R-1). This new instrument has opened up many new avenues of scientific research.

Seismometer Characteristics

Seismometers designed for the above applications must satisfy a number of stringent requirements: miniature size, low cost, long term and environment-dependent parameter stability, ruggedness, ease of installation, very low power consumption, wide frequency band, high sensitivity, and wide dynamic range. We demonstrate below that no instruments based on current technology on the market satisfy all these requirements. The primary goal continued research and development of this technology will be the design of a conceptual prototype ***miniature low-cost medium-period low noise seismic sensor based on new technology derived from eentec's current proprietary technology and suitable for all of the above mentioned applications.***

Rotational seismometers

It has often been assumed that the movement of a small section of the ground surface is only translational. While this is approximately correct in the case of teleseismometry, the ground motion near the seismic source contains well-pronounced rotational components. Numerous observers have confirmed this. Our new technology will also allow development of the first direct readout miniature rotational seismometer, with a rather limited additional effort beyond that for the proposed linear seismometer.

Rotational motion for detection systems for nuclear treaty monitoring may be very useful by using measured rotations that can be used for better identification and separation of Love from Rayleigh waves. In addition enable better and more unique interpretation and identification of P versus SV versus SH wave components.

For structural monitoring of nuclear facilities, rotational motion could be very valuable by analysis of recorded rotations in and near foundations of structures can provide for the first time means to separate the effects of soil-structure interaction from the total recorded (translational) response. Simultaneous recording of 6-degrees of freedom (DOF) of accelerations will enable computations of permanent displacement in the structures, of soils and in the near field of shallow earthquake faults were the facility might be located. Recording of permanent rotations in structures and in soils will open new possibilities for accurate interpretation of non-linear deformations in the field and for verification of analysis that simulate those deformations. The boundaries of many structures coincide with their supports. At these boundaries the displacements are either small or zero, and so the measured translational data (accelerometers) brings little or no experimentally defined constraints to check theoretical or empirical models. Rotations on the other hand are often largest near supports (e.g., consider a simple beam) and therefore measuring rotations will provide excellent and the most direct data to compare against theory.

Proof of Concept in Phase I

Other competing technologies that were awarded Phase I funding for this topic.

We believe that the other technologies, although creative, would basically fail to provide both sensitivity (low noise) and a rugged instrument suitable for field deployment.

Technologies that use a small mass would have a high natural frequency of over 100Hz. Our technology of Proto 1 had a natural frequency of 8Hz. When evaluating the 1/f noise of the electronics, a high natural frequency would have major limitations on the low frequency performance.

It is also desirable to have each axis independent of the others. Hence, true measurement in the X, Y, and Z motions. Using interdependent axis to resolve the X, Y, and Z motions can lead to problems and complete failure of the instrument if one axis fails.

We not only proved our concept as described in the Phase I objectives but have built the first stage prototypes that the latest ones are currently undergoing testing. After we conclude our internal testing, we will be sending the unit to UCLA for further testing and comments with the more sophisticated test equipment available to them. To achieve this point of development we had to overcome a few challenging problems with new creative solutions.

There are more challenges that lie ahead in the research to finally meet the end objectives. With our experience in our technology and the creativity we demonstrated in the past, we are confident that we will solve these new problems when encountered.

The Proto 1 Instrument

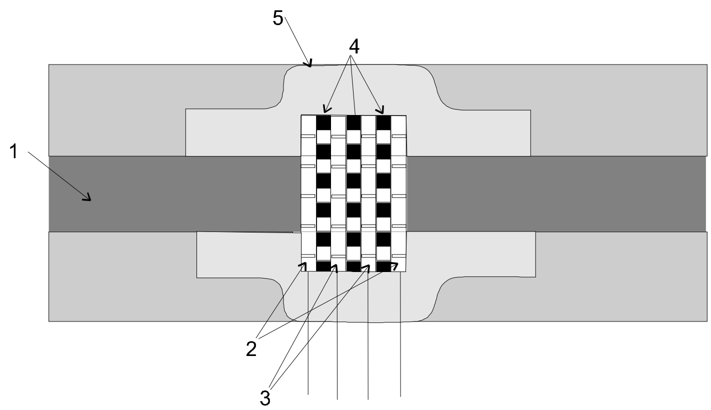
Today's top of the line electromechanical seismometers effectively utilizes the best of modern mechanical and electrical engineering technology. Bandpass of the sensor is directly influenced by the size and weight of the mass. It would be unreasonable, therefore, to expect that even significant modifications could result in noticeable price reduction or changes in their specifications. To fill the need for miniature seismic sensors which offer low-noise, wide dynamic range, broad frequency band, very low power consumption, very wide operating temperature range, and, suitability for use in seismology and earthquake engineering, it is necessary to develop new a technology based on physical principles different from those used in the traditional devices. For the last several years, we have been investigating and developing ***electrochemical transducers*** currently used in our seismometers**,** a technology which has shown great promise for the future implementation of the kind of instruments specified in this research. We proposed a research and development program aimed at proving the feasibility of the implementation of miniature seismometers using ***liquid inertial masses*** and ***electrochemical transducers.*** The main feature of these instruments is that they would have ***neither moving mechanical parts nor precisely machined components, while their noise performance is already in nano-g range***. In Phase I of the research program addressed some of the limitations observed in the very early stage prototypes of these sensors and the optimization of their conceptual design.

For those readers who are not familiar with the technology used in the research the following is a brief description of our innovative electrochemical sensor technology.

Seismometers with Electrochemical Transducers

The first seismometer using a very simple electrochemical converter ("solion") was built and tested in the late 60's. Despite significant funding and multi-national research efforts, which lasted for almost three decades, the results turned out to be too modest to lead the development of a commercially viable product.

In the core of such seismometer is an electrochemical transducer, which is shown in Figure 1. The transducer is generally contained in a channel, (1), filled with a specially prepared electrolytic solution. It consists of fine platinum mesh electrodes – two anodes, (2), and two cathodes, (3), separated by thin, microporous polymer spacers (4). This stack is tightly held together by housing (5). The motion of the fluid caused by an external acceleration must be converted into an electrical signal. One way of achieving this is by using the convective diffusion of the ions in the electrolyte.



1 - Electrolyte channel
2 - Platinum mesh anodes
3 - Platinum mesh cathodes
4 - Microporous spacers
5 - Housing

Figure 1: Electrochemical Transducer

When a small dc offset is applied between the anodes and cathodes, the flow of ions of each type is given by the following expression:

$$\mathbf{j}_a = -D \cdot \nabla c_a + q_a \cdot c_a \cdot \mu \cdot \mathbf{E} \tag{1}$$

where D = diffusion coefficient, μ = mobility, q_a = elementary charge, transferred in electrochemical reaction, c_a = concentration of active ions, E = the electrical field vector. Since the strong electrolyte is an excellent conductor, the electric potential drops rapidly in the vicinity of the electrodes, and there is no electric field, E, in the bulk of the fluid. The second term in Equation 1 can therefore be ignored. Thus, the application of a bias voltage results *only* in a concentration gradient. This is in contrast both to conductors, in which the current is driven by the external electric field, and to semiconductors, in which both the field and the concentration gradient determine the currents.

An external acceleration, **a,** along the channel creates a pressure differential, **ΔP,** across the transducer, which forces the liquid in motion with a velocity, **v**. This flow of electrolyte entrains ions and causes an additional charge transfer between the electrodes:

$$\mathbf{j}'_{\mathbf{a}} = \mathbf{v} \cdot c_a \tag{2}$$

The total current from active ions, in the presence of acceleration, will thus be:

$$\mathbf{j}_{\mathbf{a}} = -D \cdot \nabla c_a + \mathbf{v} \cdot c_a \tag{3}$$

The transducer thus generates an electrical signal in response to an input motion. The symmetric geometry of the transducer cell ensures its linear behavior over a wide range of input signals.

With a highly concentrated electrolyte, the electric field is non-zero only in a narrow boundary layer adjacent to the electrodes. In this case, the electric current is fully determined by the diffusion. If such a transducer cell is incorporated into a motion sensor, the latter can be used, for example, to respond to linear motion (or to angular motion in a different sensor design). Electrochemical transducers are characterized by a very high conversion coefficient of mechanical motion into electrical signal. That is why the electronics noise plays a noticeably smaller role in the total signal-to-noise ratio than in the traditional electromechanical seismic motion sensors. In addition, this results in low power consumption, typically several times smaller than in any other active seismometers.

In practical the sensor design transducer is placed in a mechanical oscillating system that consists of two elastic membranes, which close the ends of electrolyte channel in Figure 1. Since electrodes and their assembly are relatively small in size (less than ¼ inch) there is no restriction to reduce the size of such a sensor to 1 cubic inch or even less.

Therefore, an electrochemical sensor may comply with the requirements set forth for the miniaturized seismometer. On the other hand, such commercially available seismometers manufactured by eentec, do not qualify in several other areas. In particular, like traditional high performance seismometers they employ additional solid inertial masses and springs to support them; their size, which is critical to the sensor operation, is noticeably larger than specified. A significant research and development effort is required to achieve the required high resolution in a device with much smaller cross-section.

In Phase I of the program, we enhanced and refined our model of the transducer; investigated several possible implementations of the noise reduction and selected the most promising; investigated and selected the best miniaturization technique; and, built a Phase I intermediate prototype instrument. This same prototype are expected to be made suitable for field-testing, which will be conducted in Phase II. Then the further miniaturization and increase of operating specifications will be researched. From this Phase II research and the testing of the proto 1 created in Phase I we will create a few Phase II prototypes until the complete specifications as originally outlined in this program's announcement are achieved or exceeded.

Below we present data that we have obtained so far. Final modifications and further test data will be submitted in our future reports.

Phase I Work Description

Main tasks of our SBIR Phase I project have been completed successfully. A new, miniature electrochemical seismic prototype sensor element has been developed which is shown on the photo in Figure 2.

Figure 2. Picture of Proto 1 sensor element

This sensor element is only about 1/3 cubic inch in size. Significantly smaller dimensions of this sensor forced us to develop a transducer cell with a significantly different geometry as compared to that of the standard device. As it will be discussed below, theory of operation of an electrochemical transducer cell is very complex. In many ways we were fortunate to have come up with an apparently viable design after only a few attempts, although more then a decade of working and improving similar transducers has provided a solid practical foundation and large amounts of data for this success. Implementing a well behaving sensor was the key to the overall success of the proof of concept and prototypes for the project. Still another difficult problem, which under the stringent limitations imposed by the timing and budget had to be solved by relying mostly on approximate calculations, was the design of the membranes (Figure 3). There are two major mutually contradicting difficulties to be overcome: the membranes must be soft enough in order not to introduce strong premature attenuation of the lower signal frequencies, and still sufficiently strong to support external inertial mass without additional expensive suspension. However, we also were reasonably successful in both respects, which saved time and money.

Prototype sensors have been initially calibrated on our precision shake-table. Typical frequency response is shown on Figure 4 (red curve). Other tasks involved mechanical design of the external inertial mass and spring that would further increase the sensitivity (blue curve on figure 4) and thus reducing the noise of the sensor to the levels below USGS new low-noise model (NLNM). Inertial mass placed inside a spring to reduce the total size of the assembly to about 1 cubic inch (Figure 5).

We also developed a design for rotational and horizontal sensors, which does not require membranes, masses, springs and other moving mechanical parts, while being close to 1 cubic inch. This prototype is shown on Figure 5.

Figure 3. Standard membrane and two designs of a shrunken membrane.

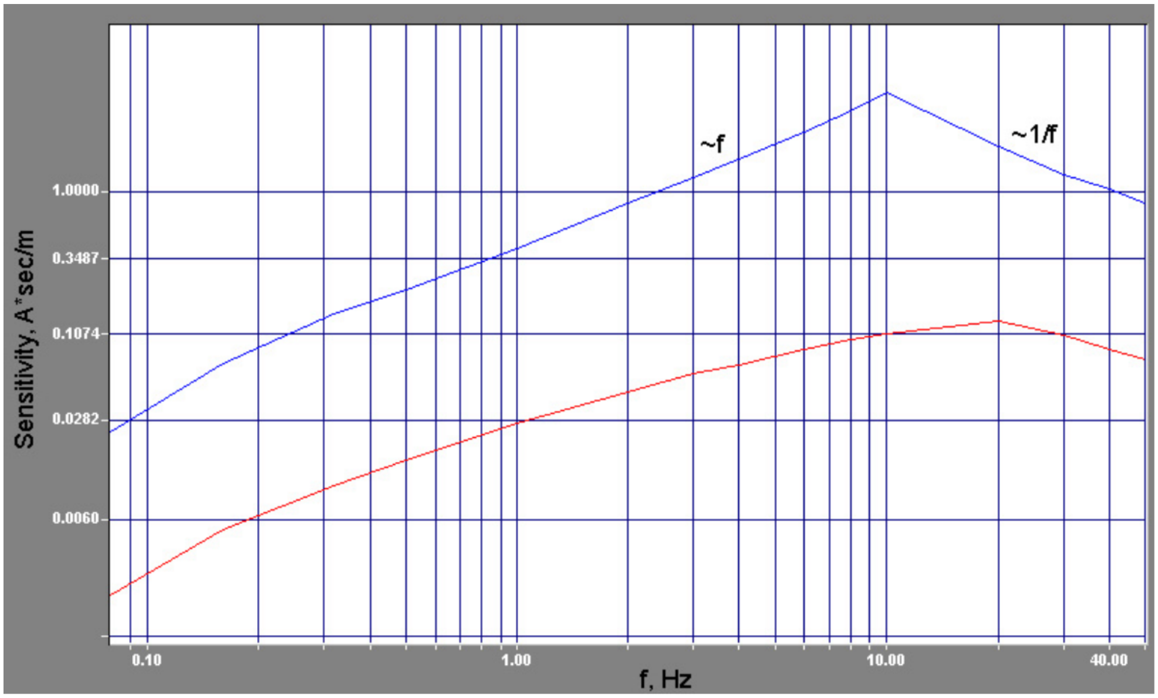


Figure 4. Effect of the additional inertial mass (blue) on a Proto 1 (red) sensitivity and form of the frequency response.

Figure 5. Vertical and horizontal/rotational prototype sensor assemblies.

The remaining tasks still require tedious and, at times, ingenious work; however, they were relatively routine and, at least partly, not as challenging. One of the most demanding was the design of the electronic circuit that should provide proper frequency correction to the new sensors. The electronic design was not as trivial a task as it may seem to those who are not familiar with rather complex transfer functions of electrochemical seismic sensors. Finally, with great difficulties, we squeezed the new electronic circuitry in a quad operational amplifier with few external components (see Figure 6). These efforts resulted in reduced power consumption to about 32 mW, which is 3 times lower than was proposed, and there is a potential of its further reduction since the sensor element itself consumes about 0.3mW.

Figure 6. Prototype sensor with electronics.

Testing the Prototype Sensors

All six produced sensor elements were initially calibrated on the shaketable and tested to evaluate their noise characteristics. All of them demonstrated reasonably similar transfer functions and noise levels; therefore, one of them was selected at random and used to build the prototype. The latter was tested rigorously after the assembly against standard eentec SP-400 seismometer, which was used as a reference for in-house testing. All major characteristics proved to be very close to those targeted in the Phase I proposal (see Figure 7). Signal spectra recorded at eentec's facility shows a good correlation between the prototype sensor and the reference seismometer. Noise level of the prototype sensor is measured by fixing its inertial mass to minimize influence of background seismic signals. However we discovered some things that have to be improved. First of all, sensor noise level, while being below USGS NLNM or very close to it on most frequencies, has to be reduced by several dB in the middle of the passband. Most probably this should be attributed to getting much stronger membranes or the 1/f noise in the electronics, although at the moment, until more complicated and detailed computer tests and analysis are performed during future research, some of the "blame" may be placed onto the transducer cell itself. Also, frequency response of the prototype sensor is not perfectly flat over velocity, being within +/-3 dB from the reference sensor. These small deviations will be easily corrected later, mostly in electronics or in sensor design, if required.

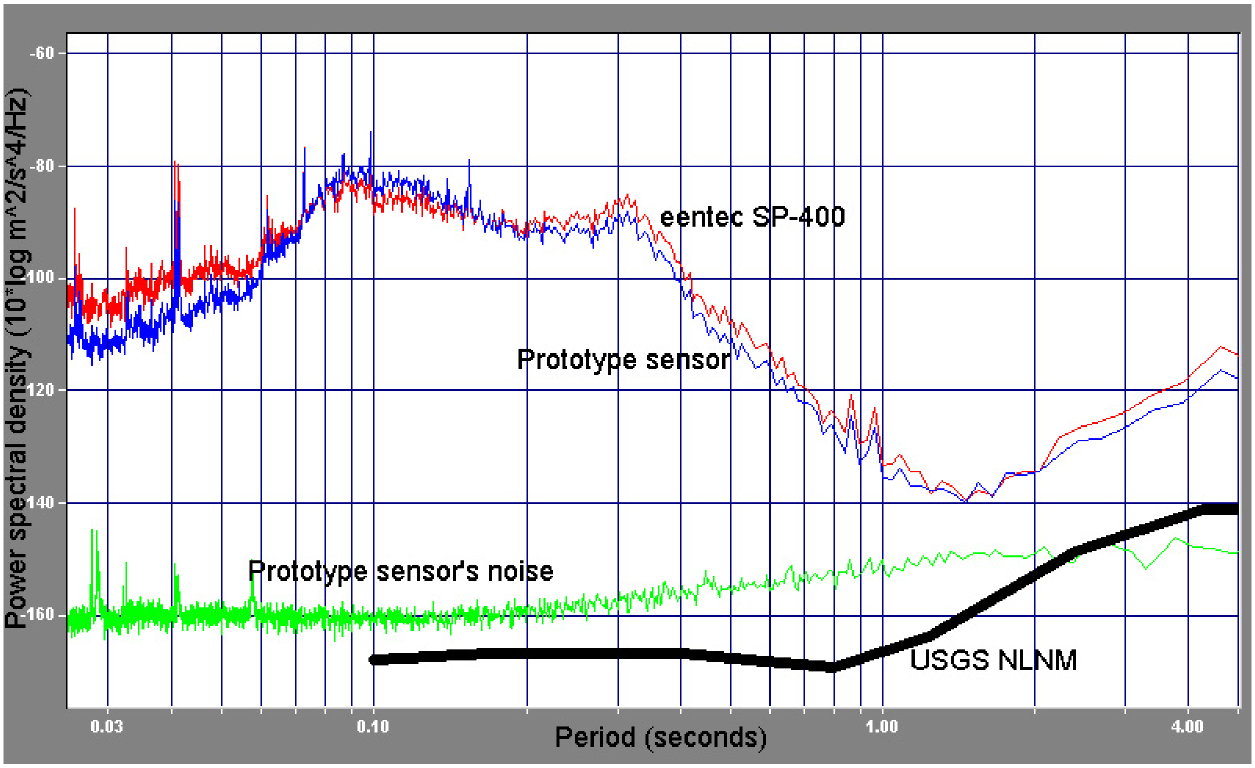


Figure 7. Signal and noise spectra of a prototype sensor.

Phase II Project

Technical Objectives

The goal of the Phase II effort is to prove that the technology developed in Phase I research can provide a sound foundation for practical implementation of miniaturized, inexpensive, high performance short-period seismic sensors. In order to achieve this goal, the following technical objectives will be met during the Phase II research:

1. Fabricate and test in the laboratory conceptual prototype 2 of miniaturized electrochemical sensor with the following parameters;
2. Miniature size – about 1 cubic inch;
3. Dynamic range of ≥132 dB;
4. Passband of 0.07Hz to 50Hz;
5. Self-noise in the required passband: below 0.5 ng/sqrt(Hz);
6. The sensor will be capable of operation at any selected orientation of its axis of sensitivity;
7. Demonstrate that the cost of such sensor will be significantly less than that of traditional mechanical instruments;
8. Develop and test a miniature prototype rotational accelerometer with translational sensitivity <0.5% and a frequency band of 0.07Hz to 50 Hz.; and
9. Identify commercialization and manufacturing plans to be performed in Phase III of this project.

Future Research

Evaluation of Phase I Test Results

We will initiate Phase II research with the analysis of data that has been collected in tests of our Proto 1 unit along with UCLA data and comments. During experiments in Phase I, large volumes of data were collected, but less than half of these data were analyzed in the limited time available. The Phase II program will therefore begin with a detailed analysis of all of these data, whose objective is aiding development of a more accurate mathematical model. Based on the results of the analysis of these experimental data, we expect to refine and carry out the tasks required for successful completion of a working unit, thereby meeting all the required objectives.

Further Refinement of Electrolytic Liquid for the Transducer

While there exists a possibility of noise reduction of a translational sensor by increasing attached solid inertial mass, this approach is not applicable to rotational sensor, where toroidal sensor element is completely filled with the electrolyte solution. For such a sensor increasing electrolyte density is the direct solution to the increase of signal-to-noise ratio. We investigated several heavy liquids in Phase I and found only one suitable electrolyte to replace the currently used one. Such replacements, along with the increased concentration, may result in up to 6 dB noise reduction. However this new electrolyte should be thoroughly tested for stability. *We consider this stability as one of our most important tasks, since the unstable electrolyte contributed significantly to the demise of the earlier solion experiments*. During the two years of Phase II work we will perform our accelerated aging experiments on the electrolyte stability.

Further Optimization of the Membrane Design

Background: Optimization of the membranes for the miniaturized sensor presents a formidable task. Description of dynamic properties of even simple flat membranes calls for the use of complex mathematics; smallest irregularities in such a membrane complicate such description much further. In our application where the membranes should work at very low frequencies they have to be as soft as possible. Therefore traditionally goffered configuration is technologically most preferable and when designed properly would possess the required frequency response. However, such proper design is very difficult to achieve. Sophisticated and very expensive programs exist which could be used to analyze various configurations. However, our long experience shows that the results may still not be sufficiently accurate and the true membrane performance can be evaluated only experimentally. Therefore, the more economical approach, both in term of time and money will be the gradual modification of the already developed membranes.

Phase I effort resulted in the two designs of membranes, 24mm and 16mm in diameter (Figure 3). The first design is implemented in a Proto 1 sensor, and as the tests have proven, would be marginally acceptable for further use, although its relatively large effective area requires heavy inertial mass to achieve noise levels below NLNM. Second smaller design proved to be not as soft as expected while it is most promising for the desired noise level. Initial calibration data and field test results of the sensors with these membranes indicated that the frequency cut-off of the sensor is not adequate for the target application and even less so for use in high performance broad-band seismometers. Therefore, one of the key tasks of the Phase II will be such modification of the membranes that would allow for stretching the sensor low cut-off frequency to 0.07Hz.

Based on our previous analyses the transfer function of an electrochemical sensor can be described within an approximately 3% accuracy by the following empirical expression:

$$W = \frac{en_0(\rho L + \frac{m}{S})}{R_h} \frac{1}{\sqrt{1+\frac{\omega_d^2}{\omega^2}}\sqrt{1+\frac{\omega_l^2}{\omega^2}}\sqrt{1+\frac{\omega^2}{\omega_h^2}}} \qquad (4)$$

Where: e = elementary change; n_0 = concentration of charge carriers in equilibrium; ρ = electrolyte density; L = height of the electrolyte column in the sensor; m - additionally attached mass, S - effective area of the membrane, R_h = hydraulic impedance of the transducer cell; ω_d =diffusion frequency, ω_h and ω_l = high- and low-frequency cut-offs of the mechanical system correspondingly.

The low cut-off frequency of the sensor depends on the volumetric rigidity, μ, of the membrane:

$$\omega_l \propto \frac{Eh^2}{R_h S^3 \left(1-\mu^2\right)} \tag{5}$$

Where E = Young's modulus; h = thickness of the membrane and S = membrane effective area.

Membrane diameter cannot be increased without increasing the diameter of the sensor itself; the elasticity is more or less the same for the short list of the elastomers compatible with the highly volatile and chemically active electrolytes filling the sensor. Effective area can be manipulated slightly by changing configuration of the membrane. But a truly noticeable reduction of the rigidity can be achieved by decreasing h that is presently 0.5mm. While technologically the thickness can be reduced significantly, one has to be careful in doing so because if the membrane becomes too thin, the electrolyte may slowly escape over time even through membranes that are made out of elastomers with extremely poor permeability. We are less familiar with the volatility of other possible electrolytes that will have to be investigated for each particular compound of interest.

Development of the Force-balanced Feedback

Force-balanced feedback is implemented in all modern low-noise seismometers including sensors presently manufactured by eentec. It provides extension of the dynamic range; flat to velocity transfer function and long-term stability of all parameters. Development of the closed-loop sensor is the necessary task in Phase II to achieve at least 132dB of dynamic range.

The transfer function of the closed loop sensor can be described as:

$$S_S(\omega) = S_{sen}(\omega) \cdot S_{ff}(\omega) \cdot \frac{1}{1 + S_{sen}(\omega) \cdot S_{ff}(\omega) \cdot S_{fb}(\omega) \cdot K_F} \tag{6}$$

where $S_{sen}(\omega)$ = the transfer function of the electrochemical cell; S_{ff} , S_{fb} represent transfer function of the feed-forward and feedback electronic paths respectively; and K_F = the transfer coefficient of the current-to-force converter, like MHD or coil-magnet systems.

As had been expected and was confirmed in the Phase I research, this transfer function is essentially independent of frequency. When the second term of the denominator is sufficiently large, *i.e.*, when:

$$S_{sen}(\omega) \cdot S_{ff}(\omega) \cdot S_{fb}(\omega) \cdot K_F >> 1 \tag{7}$$

The frequency response of the system will be completely determined by the transfer function of the feedback path:

$$S_s(\omega) \approx 1 / [S_{fb}(\omega) \cdot K_F]. \tag{8}$$

In order for Equation 8 to be true, the feed-forward circuit must be such that Equation 7 is always satisfied within the instrument passband and the operating temperature range.

We have necessary practical experience in development of force-balanced feedback for translational and rotational electrochemical sensors. Their principles of operation are very common. We are going to use the same approaches to miniaturized sensors in Phase II of this project.

Further Improvement and Miniaturization of the Electronics

Implementation of the force-balanced feedback will result in significant modifications in the electronic circuit. One approach to the implementation of the feed-forward circuit would be to simplify it to a bare minimum, limiting its functions only to the coupling with the transducer and generating input to the feedback network. In this case, the feedback circuit would have to meet two criteria: provide the necessary frequency response, and guarantee that Equation 7 is satisfied no matter how low the $S_{sen}(\omega) \cdot S_{ff}(\omega)$ product becomes. Such an approach does not seem optimal, with respect to either the complexity of the feedback circuit or the overall system noise level. The other extreme approach would involve the introduction of a comprehensive frequency and temperature correction network in the feed-forward path. In this case, while we still could maintain the condition of Equation 7, the feedback will play no useful role, other than possibly provide the expansion of the dynamic range. Clearly, an intermediate approach is preferable. This involves inserting some simple frequency and temperature correction into the feed-forward path, thereby facilitating the operation of the feedback circuit. The optimal balance between the two paths will be thoroughly investigated and determine the final design of the electronics.

Regardless of the above considerations, each design will be subjected to a thorough stability analysis using standard methods of feedback system theory.

The electrochemical sensor transfer function contains temperature-dependent terms such as viscosity. Any sensor therefore requires temperature compensation circuits in the electronic amplifiers. We are going to run a set of tests in a temperature chamber for final prototype sensors. The newly designed temperature compensation networks have to be tested and proved to be quite accurate within the specified temperature range.

Since electrochemical transducers have well-defined transfer function, only a few components are changed during calibration. This allows us to make single custom ASIC for the electronic circuitry to reduce its size and the overall dimensions of the instrument.

Assembly and Testing of Prototype Sensors

Intermediate Prototype Sensors

In Phase I we proved our concept on vertical sensor design, since it is most difficult in implementation. In Phase II, we will continue the optimization of various features and components of the proposed seismometer. In parallel, we will gradually begin to incorporate them into more and more advanced prototype vertical, horizontal and rotational electrochemical sensors.

At the very outset of this program, we will design vertical and horizontal sensors containing coil-magnet feedback. Then we will create rotational sensor with feedback.

Each generation of prototypes will undergo exhaustive experimental evaluation including:

◊ Calibration on the shake table over a wide frequency and amplitude range of harmonic input motion.
◊ Comparative field tests *via* cross-correlation and against STS-2 seismometers. We have generally run such tests at the USGS ASL in Albuquerque, NM.
◊ Temperature testing over the full operating range described above.
◊

Pilot Prototype Seismometers

Two to three generations of intermediate prototype sensors are expected to be built and tested. Each such single axis experimental sensor will be placed into the housing of a production three-component seismometer. This approach provides us with a very flexible, inexpensive and quick way to deploy the prototypes.

By the end of the sixth quarter of Phase II, we expect to be in a position to develop the layout, design and build pilot prototype seismometers incorporating all the key features. This will be a difficult task, especially with the frequency band extended to 0.07 Hertz. In this design, we will rely upon our long experience in the development of broadband seismometers and the advice of our colleagues and customers. We will pay special attention to the minimization of environmental effects and to the avoidance of internal temperature gradients (although the inherent low power consumption should reduce this potential problem). Even this prototype design will eliminate a number of items necessary to almost every traditional seismometer, such as mass centering and arresting mechanisms, because it is as small and rugged as a geophone.

CONCLUSION AND RECOMMENDATIONS

All major objectives of the Phase I research project have been met. The technical feasibility of our approach to the implementation of miniature, highly sensitive and very low power seismometer has been clearly proven with the manufacturing of an actual prototype.