ROBUST REMOTE SEISMIC STATION

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ABSTRACT

The United States government sponsors and supports various programs to monitor nuclear explosions through seismic, hydroacoustic, and infrasound data collection stations. These stations are typically deployed in remote areas all over the world. However, current remote data acquisition station technology is limited by (1) poor data quality and reliability and (2) high installation, operation, and maintenance costs. This project was initiated to begin the development of a new generation of compact, remote, seismic data acquisition hardware and software using advanced low power electronics, packaging, and power source technologies. It specifically addresses the problems of data quality and data communications reliability and will reduce deployment, operational, and maintenance costs.

This paper describes the work conducted in Phase I of this project that investigated new technologies and evaluated the feasibility of using these technologies to successfully achieve this project's goals. Specifically Phase I investigated the following: (1) new low power high-resolution analog-to-digital converter (ADC) devices and configurations, (2) overall size and power reduction using low power highly integrated miniaturized components, (3) integrated most of the major subsystems of the station into a single electronics package, (4) new low power satellite and wireless commutations options, and (5) advanced power supplies such as fuel cell technologies. Phase I found that due to the convergence of these technologies driven by the consumer mass market, it was feasible to develop a much improved seismic data acquisition platform for future needs.

Continuing forward into Phase II, this project will result in a working prototype system for a new generation of robust remote seismic stations that will integrate the technologies investigated in Phase I. Using the conceptual designs developed in Phase I, prototype hardware and software will be designed, fabricated, and tested in Phase II. This project specifically pertains to land based borehole seismic data collection stations, however the concepts developed are equally applicable to surface vault type seismic, hydroacoustic, and infrasound data collection stations.

In addition to national security and nonproliferation applications, the hardware and software developed in this project will be directly applicable to commercial earthquake, strong motion, infrasound, and hydroacoustic data acquisition and monitoring. By providing high quality reliable data, more data will be available for monitoring and study activities that should bring about advances in these areas. Also, by providing lower overall installation, operation, and maintenance costs, more stations should be able to be fielded with higher productivity. All of this will improve seismic data acquisition coverage and monitoring capabilities that in turn will improve the assessment of nuclear nonproliferation and seismic hazards and reduce the associated risk of each.

OBJECTIVE

The United States government sponsors and supports various programs to monitor nuclear explosions by means of seismic, hydroacoustic, and infrasound data collection and analysis. These data collection stations are typically deployed in remote areas to remove them from culturally generated noise signals. Also, to perform their monitoring functions, they may need to be located in politically sensitive areas. These requirements give rise to several problems encountered with past and current station designs. These include the following:

- High installation, operation, and maintenance costs.
- High physical profile because of the equipment and infrastructure required to support the station.
- Low reliability of intrasite data communications in remote areas as well as communications back to a central data collection center.
- Power availability, consumption and generation.

The objective of this Small Business Innovation Research (SBIR) Phase I grant was to research and assess the feasibility of using current and emerging new technologies to develop a new generation of Robust Remote Seismic Station (RRSS) hardware and software to mitigate these current shortcomings. The working goals for this new generation of equipment are as follows:

1. High quality 24-bit or better data.
2. Remove the need for a central hub data collection point by having the individual stations connect directly to a global or wide-area network (GAN/WAN) to eliminate a large physical presence and cost. It also removes a large power requirement and a possible single point of failure.
3. Very low power (<5 W peak, <1 W average at each seismic station).
4. High level of integration to reduce size and provide a very low physical profile.
5. Direct low power low Earth orbit (LEO) satellite communication to “Internet in the sky.”
6. Two-week persistent data buffer in case of communications outages.
7. Autonomous power operation (off the grid).
8. One-year operation between servicing.

Specifically, Geotech Instruments, LLC (Geotech) performed research in the following areas:

- **High Quality Data**: Using new low power analog signal conditioning and high-resolution delta-sigma (Δ∑) ADC techniques to deliver high quality, low noise seismic data.

- **Size and Power Reduction**: Using low power surface mount electronics and miniaturized packaging technologies to reduce overall size and power requirements.

- **Integration**: The integration of the electronics modules into one borehole installable instrument package to allow the physical profile of the station to be reduced. By minimizing the total number of components and instrument packages, cabling and interconnects was minimized thus reducing installation, operation, and maintenance costs significantly. The ultimate goal was to achieve a near zero maintenance system that could be quickly deployed by inexperienced personnel. The system would be plug and play requiring few if any field configuration or adjustments.

- **Communications**: Using new low power and low cost satellite and wireless communications to connect each station directly back to a data center removing the need for a remote central data hub. This eliminated problems encountered with intrasite communications and a possible single point of failure. Eliminating the central hub also reduces installation, operation and maintenance costs. Data from the new seismic station will be delivered in standard CD 1.1 formats and protocols to maintain compatibility with and preserve the investment in current data center processing hardware and software.

- **Advanced Power Supplies**: Using new fuel cell technology as the power source for the station. By significantly reducing the power consumption of the station from current levels, new smaller power source options can be used. This allows for a large reduction in the installation, operation, and maintenance costs associated with the power subsystem.

RESEARCH ACCOMPLISHED

High Quality Data

The Phase I goals in this area were to investigate:

- Reduction of system induced analog noise.
- New lower power, low noise analog front-end components.
- New lower power, high-resolution ADC components.
- Discrete Δ∑ ADC and digital signal processor (DSP) processing methods.
- Matching sensors, analog front-end, and ADC for optimized performance.

Prior to proposing this SBIR program, Geotech's standard 24-bit data acquisition products were its line of D-Series instruments. These instruments used 1st generation Δ∑ ADC chips. The total power requirements for a three channel ADC (analog front-end, Δ∑ modulator and DSP finite impulse response [FIR] filter) was 1630 mW and required 43.7 sq in. of printed circuit (PC) board space.

Development of Geotech's newest line of 24-bit data acquisition products, the SMART-24™, and this SBIR program proposal phase and Phase I activities occurred concurrently. In this effort, 2nd generation Δ∑ ADC and analog front-end chips were designed in and evaluated. In this hardware, the total power requirements for a three channel ADC (analog front-end, Δ∑ modulator and DSP FIR filter) was drastically reduced to 258 mW and required only 13.5 sq in. of PC board space. It was also found that this generation of devices was significantly less sensitive to induced noise from the digital portions of the hardware (see Figure 1). This greatly reduced the amount of isolation, shielding and special PC board layout required to obtain good performance results. A 3–6 dB improvement in dynamic range was also achieved.

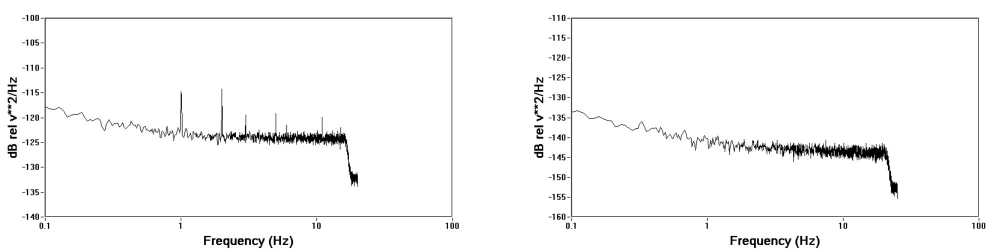

Figure 1. Input terminated noise of a 1st generation ADC (left, showing a small amount of digitally induced integer hertz noise) and a 2nd generation ADC (right, showing no digital pickup).

In evaluating this design further, it was found that additional improvements can be made by optimizing power supply voltages, matching the ADC to the sensor and by moving the DSP FIR filtering functions into underutilized field-programmable gate array (FPGA) and DSP processor resources that are consuming power but not being used effectively. This could reduce the power and PC board space even further to 150 mW and 4.7 sq in., respectively. These results are summarized in Table 1.

Table 1. Three Channel Δ∑ADC Power and PC Board Space Requirements.

	1st Gen. Δ∑ ADC	2nd Gen. Δ∑ ADC	SBIR 3rd Gen. Δ∑ ADC
Analog Front End	940 mW	99 mW	75 mW
Δ∑ Modulator	630 mW	99 mW	75 mW
DSP Filter	60 mW	60 mW	N/A
Total Power	**1630 mW**	**258 mW**	**150 mW**
Board Space	43.7 $in.^2$	13.5 $in.^2$	4.7 $in.^2$

In addition, Geotech is currently cooperating with various vendors in the development of new 24-bit Δ∑ ADC devices that will be available in the late 2005 and 2006. These devices promise to further reduce power, board space and cost while improving the dynamic range performance and they will be evaluated more fully in Phase II of this project as they become available.

Discrete Δ∑ ADC topologies were also reviewed and studied in Phase I that have the potential to push ADC resolution past the 24-bit barrier. This evaluation will continue under Phase II where prototype circuits will be designed, built, and tested.

Size and Power Reduction

The Phase I goals in this area were to investigate the following:

- Reduction of PC board size using new miniaturized components (see Figure 2).
- Reducing power requirements to a minimum.

Given recent advancements in both miniaturized and low-power integrated circuits driven by the wireless phone, personal digital assistant (PDA), and digital camera industries, smaller, more-compact low-power electronics can be designed. While FPGAs typically use more quiescent power, the overall power requirement is lower if 1.8-V I/O, peripherals and System on a Programmable Chip (SoPC) modules can be used and integrated into a larger device. Many of the peripheral building blocks, DSPs, and microcontrollers used in Geotech's current SMART-24™ system can be integrated into a single FPGA to significantly reduce size and overall power. This reduced size will result in an overall reduction in cost, power, physical size, and weight. Currently, Geotech's borehole digitizers have a 3.5-in. diameter and are roughly 26 in. long. The reduction in size will result in a new generation of borehole digitizers, which will be targeted at a 3.5-in. diameter and a length of 8 in. This reduction in size will reduce the weight by an estimated 75%–80%.

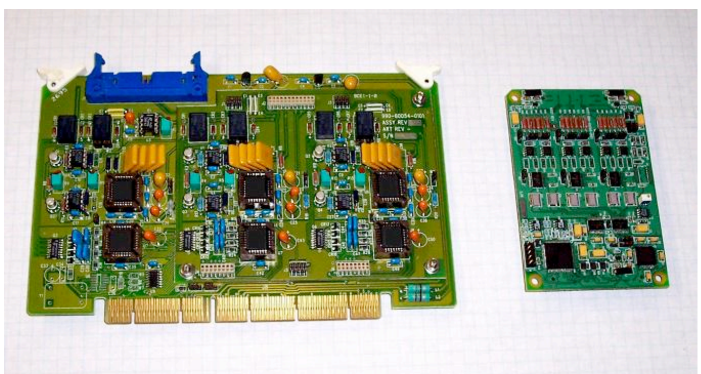

Figure 2. This figure shows a 70% reduction in PC board size from a 1st generation ADC (left) to a 2nd generation ADC (right). Another 50% reduction in size is anticipated going to a new 3rd generation of ADC.

Hardware developed in Phase II of this program will be the building block for Geotech's next generation surface digitizer to replace the SMART-24™ instruments carrying forward Geotech's intellectual property and innovations respected around the world. This investment in intellectual property will allow Geotech to advance its hardware platform as newer, faster, and lower-power integrated circuits come to market; all this with maximum portability via very high speed integrated circuit hardware description language design tools and methodologies. FPGAs where selected over application-specific integrated circuits (ASICs) because of a more rapid migration to newer technology and programmability. By letting the FPGA industry invest time and money into the semiconductor devices, Geotech can stay 2 to 3 years ahead of the ASIC based competition. The current borehole digitizer contains nine boards and consumes 188 sq in. of board space. Under this program, the next generation borehole digitizer is targeted for two boards and a 39-sq-in. area.

This integration of SoPCs onto a single FPGA will allow Geotech to lay the foundation for an integrated Δ∑ ADC, which could expand the range of the current 24-bit digitizers beyond the 24-bit limit. Having the core instantiated internal to the FPGA, the Δ∑ ADCs and Δ∑ DACs can be dynamically scaled for lower speed ADCs and DACs. In seismology, sometimes 24-bit resolution is excessive. Lower resolution customers could benefit by the power savings of a 16-bit or 20-bit system; all this without investing in changes to the hardware design. Also, multiple 10-bit and 12-bit Δ∑ ADCs and Δ∑ DACs can be instantiated for state-of-health (SOH) type digital signaling.

Integration

The Phase I goals in this area were to investigate the following:

- Overall station size reduction to reduce its physical profile.
- The integration of components into a single package.
- Providing simple installation and user-friendly operation.
- Near zero maintenance and configuration, easy to identify failures and to repair.

Reduced PC board size requirements allow for more components of the station to be integrated into a single package. This will allow the pre-amplifiers, global positioning system (GPS) receiver, and data authentication to all be integrated into a single digitizer package with fewer boards and interconnects. This in turn will increase reliability and lower manufacturing and maintenance costs. Reducing the number of total components and interconnections will allow for a smaller overall physical profile of the station. Stations will be installed in such a way so that only the GPS and communications antennas are exposed to reduce its above ground profile (see Figure 3).

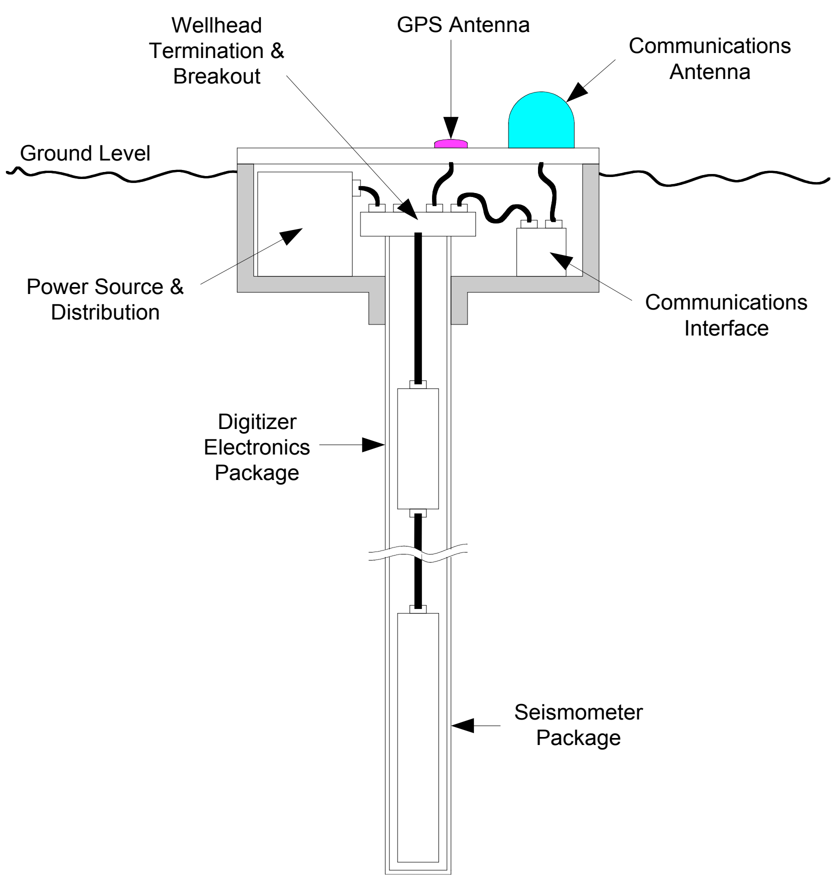

Figure 3. Typical RRSS system integration.

Because the individual stations can connect directly to a network, the need for a central data hub in an array is removed. This eliminates a large installation, maintenance, and power cost from the system. The use of SMART-24™ plug and play technology in the digitizer allows it to automatically detect the components connected to it and to take the appropriate configuration actions. HTTP web, Telnet, and FTP access to each station allows for easy setup and operation remotely without special user software. Software updates can be accomplished remotely over the network connection.

The stations will be designed with a one-year service interval in mind. SOH monitoring and logging allows the system to remotely notify the user in the event of any out of range conditions.

Communications

The Phase I goals in this area were to investigate the following:

- Direct satellite network communications.
- Short haul wireless network communications.
- Methods of data compression and error recovery.

Satellite communications at this time consist mainly of two types; geosynchronous earth orbit (GEO) and LEO, as shown in Figure 4.

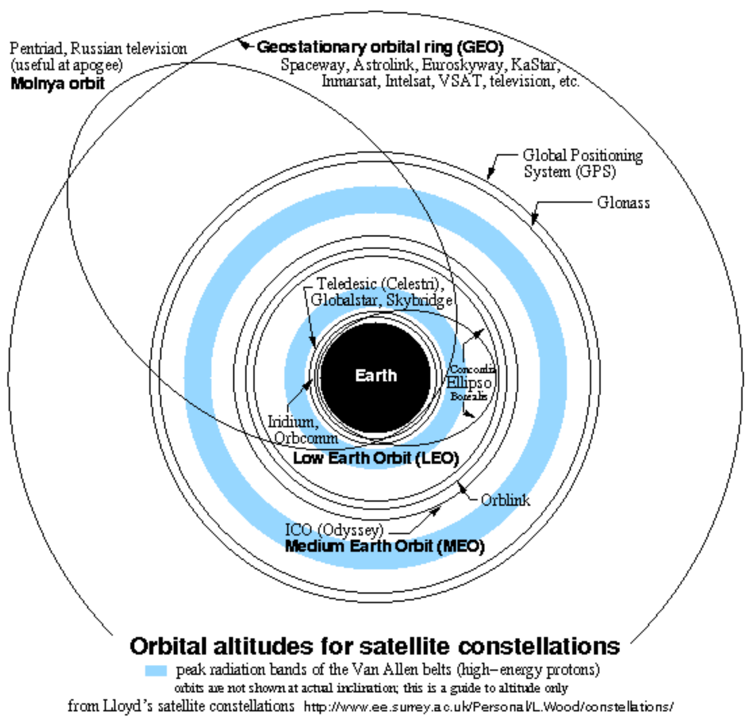

Figure 4. Satellite constellations and orbits.

GEO satellites can provide large coverage with a few satellites (but poor coverage in the polar regions) and can provide high data rates. However, they generally require a relatively large dish antenna, have large power consumption, and have large transmission delays to cope with. Examples of GEO systems are very small aperture terminal (VSAT) systems from various providers and Inmarsat.

Geotech currently provides VSAT solutions to its customers and has an on site VSAT link for testing. However, VSAT would not be the ideal solution for this project due to its large antenna and power requirements.

Inmarsat Broadband Global Area Network (BGAN) service is an interesting option for a GEO system since it only requires a small flat panel antenna (similar in size to a small laptop computer) making it much more portable and easy to setup. It can provide data rates up to 432 Kbps, but current data terminal modems require high power at around 50 W. However, as the BGAN service is rolled out for global coverage in 2005 and 2006, smaller lower power data terminals should become available.

LEO satellites provide the advantages of small omni-directional antennas, lower power operation, negligible transmission delays, and full earth coverage (including the polar regions). However, because of LEO, satellite positions in the sky are not fixed and many more satellites are required for full coverage. Since the satellites are constantly moving, complex satellite signal switching and routing are also required. This all makes the cost of a LEO system far more than a GEO system causing them to be less economically viable. Many LEO systems have been proposed but few have made it off the ground (Teledesic being the most ambitious to have failed and gone out of business). Of those that have, only Iridium and Globalstar have potential application to this project. Two systems, Skybridge and S2Com, are still on the drawing board and hold great promise to provide true "DSL Internet in the sky" if they are launched in the next few years.

Iridium began with great fanfare in the late 1990s, but quickly fell into bankruptcy. Iridium has been reborn and currently provides voice and data services globally. There are several low power (<2 W) original equipment manufacturer (OEM) data modems available for iridium, but data rates are limited to the 2400–9600 bps range.

Globalstar also provides voice and data service at 9600 bps. However, because it uses a simpler "bent pipe" architecture, its ground stations limit its coverage. Coverage is currently provided to North America, South America, Europe, Australia, and most of Asia. Low-power OEM data modems and small antennas are also available for the Globalstar system.

Geotech is currently fielding wireless local-area network (WiLAN) solutions for connecting stations to the network at data rates from 1.5 to 11 Mbps over distances of 20 miles.

With its SMART-24™ instruments, Geotech has implemented and tested the following communications related technologies:

- TCP/IP based stack and transport providing error recovery and retransmission.
- CD 1.1 continuous data format providing error recovery, data buffering, and retransmission.
- Data compression providing up to 6:1 compression (low noise, 2-3:1 typical with high seismic background level).

The decision was made to not integrate the data modem directly into the digitizer package, but to rather provide standard ethernet and serial interfaces to a communication subsystem. Since at this time there is no universal communication solution to meet all needs, this provides the most flexible solution to allow any TCP/IP based solution to be used now and in the future as the need and technology presents itself.

In analyzing the communication requirements of a typical seismic data acquisition station with three channels running at 40 sps with authentication and compression turned on, the minimum required bit rate was found to be 9600 bps to account for data, commands, and protocol overhead at a ten second data frame interval. Larger data frame intervals do not appreciably increase transmission efficiency as shown in Table 2 and Figure 5. In Phase II of this project, Geotech will purchase and test various communication solutions that meet this requirement.

Table 2. Communication bandwidth requirements at various data frame intervals. This assumes three channels at 40 sps with 2:1 data compression and 50% overhead for command and protocol requirements.

Data Frame Size (sec)	No Compression (bps)	2:1 Compression (bps)
1	18048	14208
10	8716	4876
20	8198	4358

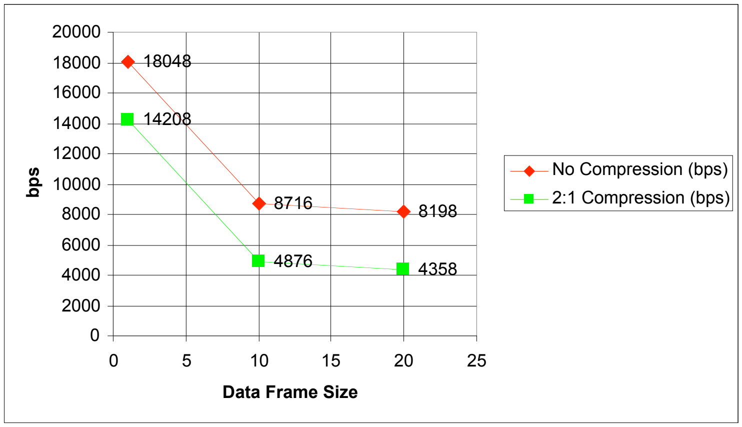

Figure 5. Communication bandwidth requirements at various data frame intervals. This assumes three channels at 40 sps with 2:1 data compression and 50% overhead for command and protocol requirements.

Advanced Power Supplies

The Phase I goal in this area was to investigate advanced power supply alternatives. Several fuel cell technologies are in the final stages of research and are developing into the first generation of fuel cell products. Four of these fuel cells technologies are direct methanol fuel cells (DMFCs), proton exchange membrane fuel cells (PEMFCs), direct ethanol fuel cells (DEFCs), and microbial fuel cells (MFCs). While each fuel cell technology has its own unique advantages, each also has disadvantages. MFCs are in a very infant stage and are not a viable option for the near future. While PEMFC has the highest energy density, the logistics of transporting and long-term storage of the hydrogen fuel eliminate PEMFC as a viable solution. In PEMFCs, converting H_2 energy to electric energy can be obtained at around 50%. If long-term storage and transportation issues are resolved in the next few years, this option could be revisited. DMFCs and DEFCs are the two promising options for near term implementation.

Figure 6. These are examples of 1st generation fuel cell products currently emerging onto the market.

The first generation of DMFC units will be released in 2005. Interest in DMFC (mainly due to the portability of the methanol fuel source) has accelerated the development of these units. Methanol can be transported similar to petroleum products. An estimated 10 gal. of methanol can run a 5-W station for one full year without refueling. This is roughly half the size of a fuel tank on a full sized American automobile. The weight of 10 gal. of methanol is approximately 66 lb, and that amount of methanol takes roughly 1.33 cu ft of space. This weighs less than and is much smaller than a solar panel. The only byproducts of a DMFC are water and CO_2.

Methanol does have some hazardous properties, while ethanol on the other hand does not. Ethanol has half the energy of methanol and would require a 20-gal. tank for storage of a year supply of ethanol. Ethanol is also transported as a liquid. A major disadvantage in using ethanol would be vandalism. Since ethanol is the consumable portion of an alcoholic beverage, great care would need to be taken to secure the storage facility. DEFCs are considered an emerging fuel cell technology. Since ethanol is generated with renewable fuel sources, this is an interesting technology to consider even for the near future.

With pros and cons evaluated for each fuel cell technology, DMFC seems to be the most viable option for the near future. The following positives outweigh any of the negatives:

- 1st generation available in 2005.
- Fuel is readily available.
- 10 gal. (1.33 cu ft) needed for 1-year operation (66 lb).
- Byproducts are H_20 and CO_2

As DMFCs rapidly mature, they are slated to be the preferred fuel cell technology for small portable devices. At <5 W, a completely operational seismic station would be considered a small device. A typical laptop computer consumes 30–50 W. The first generation of DMFCs requires a lead-acid battery for startup.

With enough forethought, the installation can be adapted to support DMFCs in the initial implementation and DEFCs as the technology advances.

CONCLUSION AND RECOMMENDATION

With the convergence of the development of Geotech's new SMART-24™ instruments and this SBIR Phase I effort, Geotech has developed, implemented, and proven several technologies relating to this SBIR effort including the following:

- A 2nd generation 24-ADC with better performance and much lower power.
- Matching of sensors and ADC to improve performance.
- SMART-24™ technology for "plug and play" operation.
- TCP/IP connectivity making the instruments true "Internet appliances" with HTTP Web, Telnet, and FTP access.
- Standard data formats with CD 1.1 and error recovery.
- Data compression.
- Remote software updates via the Internet.
- Reliable VSAT satellite communications.

These advancements are already implemented in Geotech's new instruments and are in use by customers in the field.

Consumer mass market products (cell phones, PDAs, MP3 players, etc.) are propelling the push for smaller, low power components that will allow for further significant reductions in size and power of these instruments. At the same time there are now some viable options for low power satellite and wireless communications that were not previously available. New and faster communications options are also on the horizon and will become available in the next few years. Advanced power sources such as fuel cell technology are maturing with many products coming on line in the next year or so. For these reasons, Phase I of this project has shown that it is not only feasible, it is the ideal time to push forward and continue the development of a RRSS into Phase II.