Collaborative Proposal: Development of New Electronics, Repair and Testing Procedures for Very Broadband STS-1 Seismometers

Project Description

Introduction

The great Sumatra earthquake (December 26, 2004, Mw9.3), the largest earthquake in at least 40 years, provided a spectacular opportunity to demonstrate the usefulness of long-term, global seismic broadband observatories. In particular, the on-scale recording of very long period seismic signals, obtained at over 200 very broadband (VBB), three-component STS-1 instruments deployed worldwide, has provided crucial constraints on the total energy release in this earthquake [Lay et al, 2005, Ammon et al, 2005, Park et al, 2005, and Tsai et al, 2005]. The length and duration of the source rupture were both very large. Ruptures of several segments occurred over a total length of 1300 km. The observed source processes lasted for at least 10 minutes, (and possibly an hour or longer). Much of the energy release occurred at periods longer than 200 sec, beyond the bandpass of more conventional broadband seismometers. Information obtained from this earthquake is forcing seismologists to reconsider their previous inferences regarding historically large earthquakes (M9.6 Chile earthquake in 1960, M9.2 Alaska earthquake in 1964, etc.) and more generally, the importance of VBB sensors to the understanding of these large events.

The STS-1 VBB [Wielandt and Streckeisen, 1982; Wielandt and Steim, 1986], widely viewed as the finest VBB sensor in the world, is currently the principal broad-band seismometer used by the Global Seismographic Network (GSN), GEOSCOPE, and several other global or regional seismic networks operated by members of the Federation of Digital Broad-Band Seismograph Networks (FDSN). The installed base (approximately 750 sensor axes) represents a very significant international investment for low frequency seismology. Unfortunately, many of the STS-1 seismometers, which were manufactured and installed 10-20 years ago, are encountering both operational failures [Bob Hutt et al, 2005, private communication and Bill Karavas, 2005, private communication] and age-related errors [Ekström and Nettles, 2005]. This problem is exacerbated by the fact that sensors are no longer being produced or supported by the original manufacturer, G. Streckeisen AG (Pfungen, Switzerland). The nature and severity of this problem has been discussed widely. For example, a report from a recent broadband seismic sensor workshop [Ingate et al, 2004] highlights the unique value of the installed base of STS-1 sensors, as well as the current lack of replacements with sufficient long period performance. In the absence of focused action by the seismological community, the state-of-health of the existing STS-1 instruments will continue to decline. With this decline comes the risk that the user community will be unable to accurately record signals from future giant earthquakes, at sufficiently long periods.

Numerous efforts, both commercial and government-funded, are underway to develop future replacements [IRIS Workshop, 2004]. Regardless of how one views the potential of these new approaches to deliver a manufacturable, STS-1-equivalent product, given the present funding environment, it is clear that they all would mandate outright replacements of the existing STS-1 sensors. None are focused upon maintaining the installed base.

The Berkeley Seismological Laboratory of the University of California at Berkeley (BSL), in collaboration with its commercial partner, Metrozet, LLC (Redondo Beach, CA), proposes the development and test of new electronic hardware, and methods for mechanical repair, for the Streckeisen STS-1 Very Broad-Band (VBB) seismometer. The intent of this effort is to develop simple and economical long-term solutions to current and anticipated problems with the existing STS-1 sensors. A primary aim is to develop a fully-tested, modern electronics module that will be a drop-in replacement for the original electronics. This will provide users with a legitimate option for replacing old modules that are no longer functioning. This new electronics design will address environmental packaging problems that have led to operational errors and failures in the existing instruments. This effort will also provide the opportunity to implement a set of electronic improvements that will make the installation and operation of the sensors more efficient. These include the addition of remote switches to

control the sensor corner frequency (for easier conversion between 20 second or 360 second mode) and the application of modern control electronics to the boom centering motor and its position estimation. In parallel, the program will also develop solutions to the most important of the known problems that plague the aging mechanical sensors. Foremost among these will be fully-tested methods for the development and installation of new mechanical hinges. Finally, the work will develop a fully-qualified calibration methodology that can be implemented easily by seismic technicians, using conventional recording systems. In addition to providing the potential for improved data quality within seismic networks using the STS-1, this will offer greater flexibility with which the sensor can be installed and maintained. For example, these improved calibration methods will allow individual STS-1 electronics modules to be switched between sensors, without loss of measurement accuracy. This is not currently possible, with the existing STS-1 instruments.

The proposed BSL/Metrozet effort seeks to maintain the future value of this existing investment by extending the operational life of those STS-1 sensors already in place. We believe that this is a relatively straightforward technical development process, and that the overall cost and financial risk of this approach to the user community will be very manageable. While the BSL/Metrozet team is very experienced in seismic instrument development and testing, we are aware that there could be specific design and operational issues with the STS-1 that are currently unknown to us. *In order to mitigate these risks, the program will draw heavily on the expertise of the STS-1's co-inventor, Professor Erhard Wielandt (University of Stuttgart). Professor Wielandt will serve formally as a paid consultant to this effort. His consultant's letter is included with the proposal as a supplementary document.*

The team is committed to an inclusive development process. They are seeking to solve a problem that is widely viewed as being critical to the future of regional and global seismology. The letters of support from Dr. Robert Hutt (United States Geological Survey/Albuquerque Seismic Laboratory) and Professor Göran Ekström (Harvard University), two prominent users of the instruments and their data products, attest to this. Their letters are included with the proposal as supplementary documents. The BSL/Metrozet team views the entire STS-1 user community as stakeholders in this effort. Among them, there is a very deep operational knowledge base. We intend to solicit and to utilize this knowledge to best insure that the proposed developments will properly address the most critical problems affecting the instruments.

The primary products of this work will be a non-proprietary electronic design, published methodologies for making critical repairs to the electro-mechanical portion of the instrument, and fully-tested procedures for performing calibrations to the upgraded instrument. Each of these would be made available to any researcher or organization. Furthermore, it is anticipated that Metrozet, LLC would non-exclusively manufacture, sell, and support the upgraded electronics, and provide electro-mechanical repair services, at a cost that is significantly below that of hypothetical replacement sensors. In this way, the current operators of STS-1 networks would be given a new and compelling option for maintaining the operational capabilities and quality of their legacy instruments. A further benefit of this work is that it will allow reconditioning and re-deployment of the known set of instruments that have already been retired, for lack of replacement electronics or viable repair options.

Broader Impacts: This work will also provide significant educational opportunities to interested graduate students in seismology at UC Berkeley. It will contribute directly to the training of one graduate student, who will assist with the testing activities at BSL. Indirectly, the program will expose a larger group of UC Berkeley seismology graduate students (approximately 10) to the detailed workings of an advanced broadband seismometer. This larger group will benefit from informal interactions with the program team and through the dissemination of the products of this work. The program will allow these students to better understand the design and operation of state-of-the-art instrumentation. This is viewed as a critical need in a field where the gap between those concentrating on experimental measurement techniques and instrumentation, and those concentrating solely on digital data processing, is increasing. While these local-scale educational opportunities are important, it is important to stress that the proposed development will also benefit the entire global seismological scientific community in that it will provide the means to sustain the acquisition of high quality data required for low frequency seismic research.

Importance of STS-1 VBB to Seismological Research/Concerns Over Present and Future State-of-Health

Importance of STS-1 VBB to Seismological Research

The unequaled performance of the STS-1 VBB enables cutting edge research into a wide range of topics within long-period seismology.

Following large earthquakes, the earth's free oscillations are observed as peaks in the spectra of long period seismic records in the frequency band 0.3-7 mHz. Spectral analysis of the earth's free oscillations has been instrumental in constraining the average (1D) structure of the Earth as well as the longest wavelengths of lateral heterogeneity. Eigenfrequency measurements have led to the development of reference 1D earth models for elastic velocities, density and attenuation (quality factor) that are still widely used today [Dziewonski and Anderson, 1981]. Most importantly, the little information we have about the radial density structure in the earth comes primarily from normal mode data analysis. International networks of STS-1 VBB seismometers have greatly enhanced normal mode research, and this work has been synergistic with advances in the theory of wave propagation in a 3D earth. High quality data from these instruments have made possible the observation of the static response following the great 1994 deep Bolivia earthquake [Ekström, 1995], as well as more accurate mode splitting measurements which have helped to put definitive constraints on the possible rate of relative rotation of the inner core with respect to the mantle [Laske and Masters, 1999]. These improved splitting measurements are also used to analyze more detailed constraints on core structure and anisotropy [Romanowicz and Bréger, 2000 and Ishii et al., 2002].

Constraints from normal modes have been used in the development of the latest generations of tomographic models of the earth's mantle [Masters et al., 1996 and Resovsky and Ritzwoller, 1999a], where they provide unique constraints on the longest wavelength (degree 2 and 4) heterogeneity. They also hold the only hope for constraining long wavelength lateral variations in density in the lower mantle, which recently have been the subject of a vigorous debate [Ishii and Tromp, 1999, Resovsky and Ritzwoller, 1999b, and Romanowicz, 2001]. Normal mode constraints on the density change at the inner core/outer core boundary, critical for the understanding of core formation and dynamics, have been reanalyzed and improved [Masters and Gubbins, 2003].

There is still a wealth of information about low degree elastic structure (particularly odd degree structure), as well as density, anelastic and anisotropic structure, that can be obtained from free oscillation spectral data. This requires high quality, low noise measurements at the lowest frequencies (i.e. below 3mHz). For these studies, high-quality observations from numerous, globally-distributed, three-component instruments will be necessary over the next few decades. Also, large deep earthquakes, which excite the gravest, low angular modes sensitive to the deepest parts of the earth (such as the 1994 M8.3 Bolivia, M8.4 Kurile Island or the 2001 Mw8.4 Peru events), provide different and unique constraints (due to different source depths, mechanisms, and locations), and they need to be observed at many different stations so as to allow the separation of source and propagation effects.

Perhaps most spectacular is the recent discovery of the "hum" of the earth. These are faint fundamental mode peaks observed on the vertical component of STS-1 recordings, in the period range 2-7 mHz [Suda et al., 1998 and Tanimoto et al., 1998] and on SG recordings, in the period range 0.3-5 mHz [Nawa et al., 1998], in the absence of earthquakes. The source of excitation of this hum is still the subject of vigorous research, with the existence of seasonal variations in the signal levels indicating an atmospheric or oceanic origin [Tanimoto and Um, 1999, Fukao et al., 2002, and Ekström, 2001]. The discovery of the "hum" was made from the analysis of many days of stacked power density spectra at quiet stations. Recently, an array technique utilizing properties of propagating surface waves has shown promise in determining that a significant portion of the hum originates in the oceans [Rhie and Romanowicz, 2004]. This study was made possible thanks to the existence of large aperture very broadband arrays of STS-1 seismometers in California and in Japan. Further investigation of this intriguing phenomenon, as well as possibly yet undiscovered "signal" buried in the low frequency noise, depends in particular on the availability of data from other large aperture (2000km or more) arrays of STS-1 (or better) instruments, particularly in the southern hemisphere.

Recently, it has been shown that the structural Green's functions between two stations can be retrieved using cross-correlations of seismic noise at these two stations [Campillo and Paul, 2003]. This provides quite accurate models of 3D shallow crustal structure [Shapiro et al., 2004]. While the studies so far have focused on relatively short period energy, there is no reason to believe that they will not be extended to low frequencies (i.e., periods greater than 100 sec) in the near future, to constrain deeper mantle structure.

Finally, as mentioned in the introduction, the recent M 9.3 Sumatra event demonstrated the importance of low frequency data for the study of the source processes of great earthquakes. In addition, over the next year, as the analysis of the Sumatra VBB data continues, scientists will obtain new constraints on the frequency, splitting and attenuation of the gravest modes. However, as the 2004 Sumatra earthquake was shallow and ruptured on a very shallow dipping plane, it was not optimal for the observation of radial and high phase velocity modes. In the future, we expect great earthquakes with more favorable source mechanisms and depths. Previous events of this type (e.g., the 1970 Mw8.0 Colombia and the 1977 M7.7 Sumbawa earthquakes), occurred at a time few high quality digital stations were yet available. In the future, it is expected that the global array of STS-1 VBB instruments will be instrumental to expanding our understanding of large events of this type.

While there are several commercially available broadband seismometers that satisfy the needs of the community at periods shorter than 100 sec (Figure 1), only the STS-1 covers the entire range in frequency and dynamic range suitable for both modal studies and weak motion, teleseismic recording.

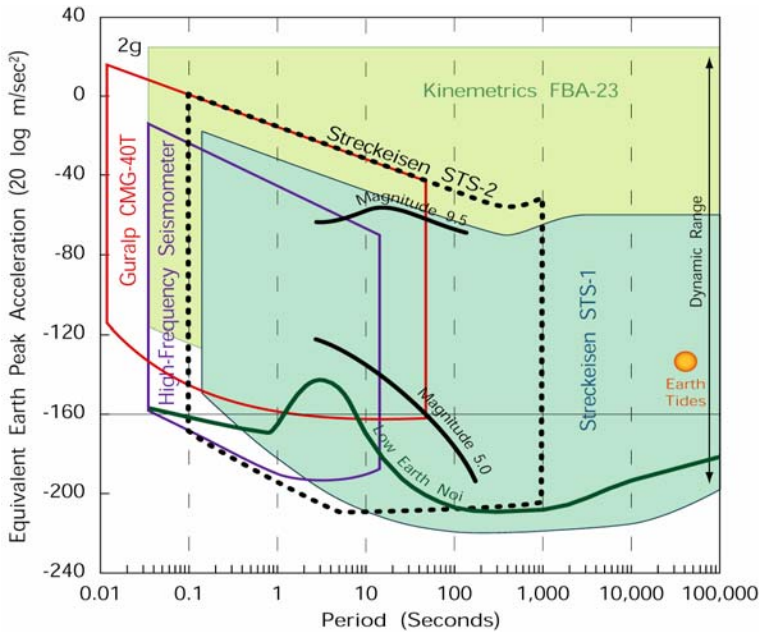


Figure 1 Idealized recording range for a GSN station. [Ingate et al, 2004] The composite, lowest and highest acceleration levels shown utilize an ideal combination of Very Broad Band (STS-1), High Frequency Broad Band (STS-2 and CMG-40T), Low Gain Seismometers (FBA-23), and 24-bit digitizers. While low-gain sensors do have a response down to DC, their higher noise levels preclude the measurement of the majority of the signals that occur at very long period.

Concerns of Present and Future State-of-Health of Instruments

While the STS-1 VBB has proven itself to be a reliable instrument, many of the systems are 15 to 20 years old. Not surprisingly, a number of complete instrument failures, as well as a gradual decay of data quality, have been observed. There have been a number of outright sensor failures due to problems with their electronics or electro-mechanical systems. Although obvious operational failures are a fact of life for any field-deployed instrument, those that affect the STS-1 VBB can be very disruptive, due to the fact that the instrument is no longer sold or supported. While the actual failure rate might be relatively small (at or about 1% per year [Valerie Peyton, 2005, private communication]), the effects of even a single instrument failure on the data quality and data recovery factor for a network can be significant. Also, the cumulative effect of the permanent loss of even a few sensors per year, worldwide, will eventually lead to a very large data recovery problem.

In contrast to obvious instrument failures, the gradual degradation in sensor performance can be a serious, but easily neglected, problem. Not surprisingly, a number of indications of the declining health of STS-1 VBB instruments have begun to appear in the measured data. The Incorporated Research Institutes for Seismology (IRIS)-funded, Harvard Waveform Quality Center (WQC) has systematically correlated an extensive set of long-period seismograms from a large number of earthquakes, with their synthetic ones. This analysis has begun to detect what is believed to be monotonically increasing errors in amplitude scale factor, at long periods. These are often small, systematic errors that can easily be overlooked when looking at a single earthquake. The effects are observed at 50 or 150 second periods, and sometimes both. The WQC report [Ekström and Nettles, 2005] indicates that a significant number of STS-1 instruments may be plagued by such problems. The report suggests the cause as being the well known effect (discussed below) of moisture-induced electrical leakage in the sensor's electronics module, and its interconnecting cables and connectors. It also hypothesizes that failing electronic components (particularly capacitors) may also be contributing to shifts in a given instrument's corner frequency, away from its nominal 360 seconds. Professor Göran Ekström of Harvard is clearly concerned with this evolving problem, and he supports a focused development program that can address it.

These concerns relate mainly to how the end users (seismologists) are affected by both catastrophic and gradual failures to the STS-1. As such, they are essentially high-level issues. There is no doubt that the loss of individual instruments, and degraded data quality, are critical problems for these scientists. On a more fundamental level, however, the observed issues are symptomatic of a number of technical problems that contribute to the declining state-of-health of the installed instruments. These are the actual problems that confront seismic technicians, who are responsible for installing and maintaining broadband sensor networks. While technicians have been able to solve (or at least cope with) some of these problems, the long-term options for maintaining the STS-1 instruments are very limited. This is due to the lack of replacement components and the absence of technical support from the sensor's manufacturer. The proposed development specifically targets these fundamental problems. In order to best understand them, and their possible solutions, it is necessary to discuss the STS-1 VBB sensor in some detail. Section 2 provides a technical overview of its design and operation. It highlights a number of shortcomings of the existing sensor, and it points toward some very realistic options for improving them. The section also summarizes the major failure modes that have been observed in these sensors.

2. Technical Overview of Existing the STS-1 VBB Sensors

The STS-1 VBB sensor is an electro-dynamic, force-balance, seismometer. It provides very high fidelity measurements of ground ("frame") motion. The sensor has demonstrated exceptional performance with regard to a number of critical specifications. These include incoherent self-noise, dynamic range (the ratio of full-scale measurable signal to self-noise), linearity, and cross-axis sensitivity (the unwanted contribution of orthogonal vector ground motions to the sensor's output signal). Among these, the self-noise performance is normally viewed as the most important. The STS-1 VBB has demonstrated the lowest self-noise (consistently below the Peterson New Low Noise Model [Peterson, 1993]), at very low frequencies (0.001 Hz to 0.1 Hz). The STS-1 VBB achieves superior low-noise performance largely through a very well-designed mechanical system. It implements an ultra-low natural resonant frequency (e.g., $f_o < 0.05$ Hz) spring-mass system. This provides exceptional mechanical sensitivity at low frequency (where the mechanical displacement to a given ground acceleration is proportional to f_o^{-2}). Higher mechanical response has a number of very important benefits. It makes the measurement of inertial mass displacement easier: the STS-1 utilizes a very simple and reliable magnetic position sensor (Linear Variable Differential Transducer, or LVDT) to detect displacements of the mass. Higher mechanical response also reduces the input acceleration-equivalent effects of some thermally-induced displacements (expansions and contractions) within the system. Lower temperature sensitivity is essential to reducing low frequency noise within the sensor, as environmental thermal fluctuations are very difficult to shield in many field measurement locations.

As with many broad-band seismometers, the STS-1 utilizes the control concept of “force-balance” to dynamically re-center its spring-supported mass in the presence of applied, external vibrations. The forcing element is a conventional coil-magnet actuator. The net effect of force-balance control is that the spectral transfer function of the electrical output is made to be essentially constant (“flat”) to either applied velocity or acceleration, across a very wide bandwidth (0.0028 Hz to 10 Hz for the STS-1 VBB). This response is largely independent of the nominal, open loop characteristics (e.g., resonant frequency) of the spring-mass system. Force-balance feedback also increases the upper operating range (so-called “clip-level”) of the instrument to an acceptable range. The STS-1 clip level (~8 mm/sec peak velocity) is sufficiently high to allow it to provide accurate, “on-scale” recordings of very large earthquakes (a typical specification is M9.5 at 4500 km epicentral distance). The combination of a very low natural resonant frequency spring-mass system, and well-engineered force-balance control system, allows the STS-1 to provide very high linearity and dynamic range, as well as exceptionally low self-noise. The STS-1, like many seismic sensors, contains both a “feedback” actuator, and a “calibration” actuator. The former is used continuously as part of the aforementioned force-balance control system. The latter is used occasionally as part of a relative calibration routine in which test forces (proportional to equivalent ground accelerations) are injected through it into the sensor. The output response to this stimulus is used to measure the relative transfer function of the instrument.

This brief description of the STS-1 design is meant as an introduction. It certainly understates a number of important mechanical design features that allow the sensor to provide very high temporal and environmental stability. It is widely agreed that the overwhelming strength of this sensor is in the proven design of its mechanical transducer. Most users believe that competing sensor designs (including the STS-2, the CMG-3T, and the Trillium 240) do not match its performance mainly because of differences and limitations in their mechanical transducers. The design of the STS-1 electronics, while very good, is not its distinguishing feature. For this reason, it is extremely important to develop a capability by which the proven, and largely reliable, electro-mechanical system of the STS-1 can be maintained. As will be discussed below, most of the main failure modes and operational limitations of the sensor are not within the mechanical system, but rather in the electronics (and their interconnection to the mechanical sensor). Nonetheless, there are a small set of very specific issues that can affect the long-term reliability and performance of the mechanical sensor itself. These will be addressed as well in this program.

The commercial STS-1 VBB instrument is divided into two separate components: a mechanical sensor (“sensor”) and its matching feedback electronics unit (“electronics”). These are connected using a standard cable that attaches to military-type, circular connectors on each component. The entire system is shown in the photograph of Figure 2. The electronics is matched to a specific sensor in that it will provide a calibrated response (amplitude and phase response). Other electronics units may be interchanged with good performance, however, the transfer function calibration will not be maintained. Note also, that earlier versions of the STS-1 instrument (STS-1 Wide-Band) do exist which have a more narrow sensor bandwidth (0.05 Hz to 5 Hz). These use the same mechanical sensor as the VBB version. Upgrading the instrument to VBB (360 second corner) simply involves attaching a VBB electronics box. Currently, lack of availability of new electronics has prevented such upgrades, or maintenance, to these older STS-1 instruments.

Figure 2. Photograph of an STS-1 sensor and its electronics. At the top is the mechanical sensor placed on a baseplate surface (the standard environmental shielding is not shown). Below is the electronics module. The sensor cable (orange) is attached to the "Sensor" connector on the electronics and a to hermetic feedthrough on the baseplate. The "Monitor" and "Remote" connectors (unused) are also visible on the electronics box.

Under normal operation the sensor is environmentally isolated. It is mounted on a glass baseplate. An aluminum (thermal) shield is placed over the sensor. Within the vertical sensor, a permalloy (magnetic) shield is used as well. Finally, a glass bell jar is installed and the internal air is evacuated. This reduces the effect of convective currents, as well as buoyant forces, on the sensor. Evacuation also significantly reduces the amount of moisture around the sensor. This minimizes electrical leakage within the sensor, which helps to stabilize its performance. Over the long-term, this also reduces corrosion, which is known to damage critical parts (e.g., hinges and motors) within the sensor. Note that the electronics are normally kept well away from the sensor (in order to minimize thermal effects caused by its ~2W power consumption). While the sensor's environmental isolation system contains a hermetic bulkhead connector, neither the electronics box nor its electrical connectors, are strictly hermetic. As such, moisture-induced electrical leakage can often cause a problem in humid environments. This leakage can cause anything from small inaccuracies in the sensor response to total operational failure of the system. The electrical connectors in the system are often found to be the cause of this problem [Bill Karavas, 2005, private communication]. Some more experienced users will encapsulate ("pot") the inside portions of the connectors on the electronics box [Bob Hutt, et al., 2005, private communication]. While this may improve the situation somewhat, it does not eliminate it.

A block diagram of the sensor and its electronics is shown in Figure 3. The diagram relates to a complete, single-axis instrument. It should be noted that while there are distinct differences between the sensor modules for vertical and horizontal orientations, they are sufficiently similar to be treated the same. These differences do not significantly impact the proposed work. A primary focus of this program is the upgrade and replacement of the electronics module. There are a number of specific points to understand about its design and operation.

First, the power stabilization, which "regulates" input power down to the nearly constant voltages, +/-13.5V, used throughout the module, is antiquated. It can be replaced by nearly monolithic components that provide a much greater degree of regulation (strictly defined as insensitivity to input line voltages or to output current loads). One important point about the existing design, however, is that it does serve to maintain a constant level of power dissipation within the electronics. This reduces the magnitude and effect of thermal fluctuations within the module. An upgraded regulator stage may need to maintain this capability. Second, the main electronic signal path (propagating through the position sensor, feedback integrator, feedback components, and output line drivers) make use of a very sound, fully differential architecture. This has worked quite well in the current sensor and it would be most unwise to abandon it in the upgraded electronics. This architecture very prudently mixes low noise operational amplifiers, with lower power ones, in a manner that provides exceptional noise performance at a reasonable power consumption (by mid-1980s standards). Although not all of these amplifiers are still available (or recommended for new designs), there are modern replacements in all cases that provide equivalent of better performance. These performance improvements are related to input noise and drift, input common mode range, linearity, power consumption, output drive capability, etc. All of the necessary passive components (including low excess noise resistors, large film capacitors, etc.) are available today, at lower cost, in smaller packages.

A third point is that the electronics provide two external signal and control connections: a “Remote” connector (designed for operating the instrument on the end of a long cable) and a “Monitor” connection for attaching to an “On-Site Test and Control Box.” This box is a piece of support equipment that is used in installing and configuring the instrument. In order to maintain compatibility with the existing STS-1 infrastructure, these connectors would be retained (nearly unchanged) in an upgraded electronics package. A fourth point is that the current electronics utilizes a highly inconvenient method for switching the sensor between 20 second and 360 second period. This involves opening the package and moving jumpers on a number of separate boards. An improved electronics package would provide latching-relays (with zero quiescent power consumption) to allow the corner frequency to be adjusted via a single, external switch. In addition, control of these relays could also be added to the “Remote” connector to allow the sensor frequency to be adjusted *ex situ*. In a similar manner, the current damping control relays can be upgraded with state-of-the art latching relays with external mechanical switching. This would also maintain the existing remote access to these relays through the “Monitor” and “Remote” connectors.

A fifth issue is that the electronics that control the sensor motor (a DC motor for remotely centering the seismic mass) utilize 1980’s-era, discrete digital electronics. The motor control module also provides an innovative, but outdated, electronic circuit for simulating (predicting) the vertical sensor’s final boom position, once the motor has stopped turning. This is necessary to allow operator-in-the-loop centering, as the sensor output during adjustment can be very irregular. This circuitry is largely outdated. In a re-designed system, both motor control, and look-ahead prediction of the boom position can now be provided easily by a small microcontroller and a small amount of driver circuitry. One point is that the actual operational sequence for the motor is distinctly different between the horizontal and vertical STS-1 sensors. For example, the horizontal sensor does not use the prediction electronics, and its motor control process is different. In order to provide inter-operability between any electronic module and any sensor, an external switch (replacing four internal jumpers) will need to be provided on the exterior of the redesigned electronics module. This switch will select between vertical and horizontal operation.

A crucial point is that the electronics are currently packaged in an essentially non-hermetic enclosure. The connectors and the sensor cable do not provide a fully-sealed interconnection. Because the cable carries low-level electrical signals, moisture-induced electrical leakage phenomena can cause operational errors and difficulties. Within this program, the electronics packaging, the connectors, and the interconnection cable would be upgraded. The electronics box would be replaced by a fully-hermetic enclosure. Upgrade of the interconnection hardware between the sensor and electronics would involve the use of low-cost, oceanographic-grade connectors and cabling. Any required conversions between the new electronics box (pinouts) and the legacy connections used with respect to the “Monitor” and “Remote” connectors would easily be accommodated in a low-cost, custom-made interface cable. Note that hermetic sealing in any existing Remote or Monitor cable is not as critical as in the Sensor connection itself, as the effects of electrical leakage are less severe.

A final point about the electronics is that they utilize a complex set of boards that are inserted into a backplane connection within the box. Almost certainly, an upgraded electronics package can provide component integration with much higher density (using more highly integrated circuits and much smaller, surface mount components), so as to allow a single board solution. This will be an easier-to-manufacture design that will be available at reduced cost. Note that the historical concerns regarding separation of certain power and ground lines, and the separation of sensitive signal lines from higher current ones, is routinely accomplished in highly integrated, single board systems (for example in exploration seismic systems and in a number of very high dynamic range seismic accelerometers). Modern electronic design automation (EDA) tools (for example, the Orcad Unison Suite [Orcad, 2005] that Metrozet uses), allow the efficient design of tightly integrated electronic assemblies, with very high performance.

In many applications, electronics boards, active integrated circuits, passive components, and connectors fail for a number of reasons. After 20+ years of service, the mortality rates of most electronic assemblies rise. Therefore, it is not unexpected that the STS-1 electronics will begin to fail, even in the most benign environments. The most optimistic mean time between failure (MTBF) prediction, for a fairly complex electronic module such as the STS-1, is likely to be under 500,000 hours. In this case, even a small network (with, say 30 STS-1 installed axes) would expect an electronics failure (only one of a larger number of possible failure modes) at least every two years. In addition to lifetime-related failures, extreme environmental conditions (e.g., lightning strikes or excessive humidity) can contribute to sensor failure in some installations. Little imagination is required to understand the problems with lightning. High surge currents damage electronic components. Humidity, however, has been observed to cause both gradual degradation and total failure due to electrical leakage problems.

In addition to electronic failures, a separate set of mechanical problems appears to be afflicting the sensors. Primarily, these involve metallic corrosion to the sensor's hinge assemblies [B. Karavas, 2005, private communication, B. Urhammer, 2005, private communication, and E. Wielandt, 2005, private communication]. The hinge assemblies are fairly simple. They are made from rectangular steel strips (Phynox, a high-strength, austenitic, strain-hardening alloy). The strips are similar in geometry to a mechanical "feeler" gauge. A single hinge consists of two strips, which are rotated by 90^o with respect to one another. The sensor uses two-such hinges, displaced from one another along an axis of rotation. Although the hinges can become highly corroded over time (with a visible, uniform layer of oxidation), significant operational degradation is often associated with far lower levels of corrosion. Symptoms include increased self noise levels (observed in power spectral density data in the frequency range between 0.002Hz and 0.03 Hz) and equivalent-acceleration "steps," observed in the recorded time series [B. Urhammer, 2005, private communication]. Although hinge corrosion/degradation is currently the primary concern, other issues do exist. These include catastrophic failures to other electromechanical components, caused, by environmental corrosion and improper handling during shipping. The DC motor within the sensor has been observed to fail (stick) as it becomes corroded [Erhard Wielandt, 2005, private communication]. Of some concern are the LVDT position sensor module and the coil-magnet actuators. Both can be damaged by improper handling, for example, during shipment of a sensor that has not been properly locked [Valerie Peyton, 2005, private communication]. All are semi-custom components that are no longer available or supported by the manufacturers. Although user experience indicates that mechanical failures are not nearly as common as electronic ones, over the long-term, these failure modes will become significant. A viable maintenance approach needs understand and to address the most significant of these failure modes, as well. Without a qualified repair capability, the result is invariably the same: the permanent removal of the sensor from its installation. Expressed another way, the development of new electronics alone will likely be insufficient to guarantee the long-term health of the STS-1 instrument fleet. The proposed program seeks to identify the most important electro-mechanical failure modes, and to devise and qualify a viable method for their repair.

At present, in the case of some electronic failures, experienced instrumentation technicians may be able to identify the faulty part or parts. If these are still available, then they may be replaced, provided that the user has the required equipment and competence for solder re-work. If this is not the case, or if the damage is very widespread, then the electronics module (and hence the entire instrument) must be retired. Note that the normal economic considerations relating to self-repair (buying new, qualified components is normally a much superior option to self-diagnosis and repair) do not currently apply as there are no legitimate replacement options. User-repair of the mechanical sensor has normally not been attempted. Ultimately, this is not due to any fundamental impediment, rather the lack of readily-available replacement components and of a fully-tested repair methodology [Erhard Wielandt, 2005, private communication]. Specifically, it must be stressed that a widespread misconception that the STS-1 mechanical hinges are formed out of a critical, exotic, metallic alloy, which is no longer commercially available, is not supported by Professor Wielandt, or by the BSL/Metrozet team. As such, this should not be used as a rationalization to discourage the careful development of approaches for mechanical repair. Our pre-proposal investigations indicate that the hinges' Phynox alloy (or its equivalent) is readily available, at US suppliers.

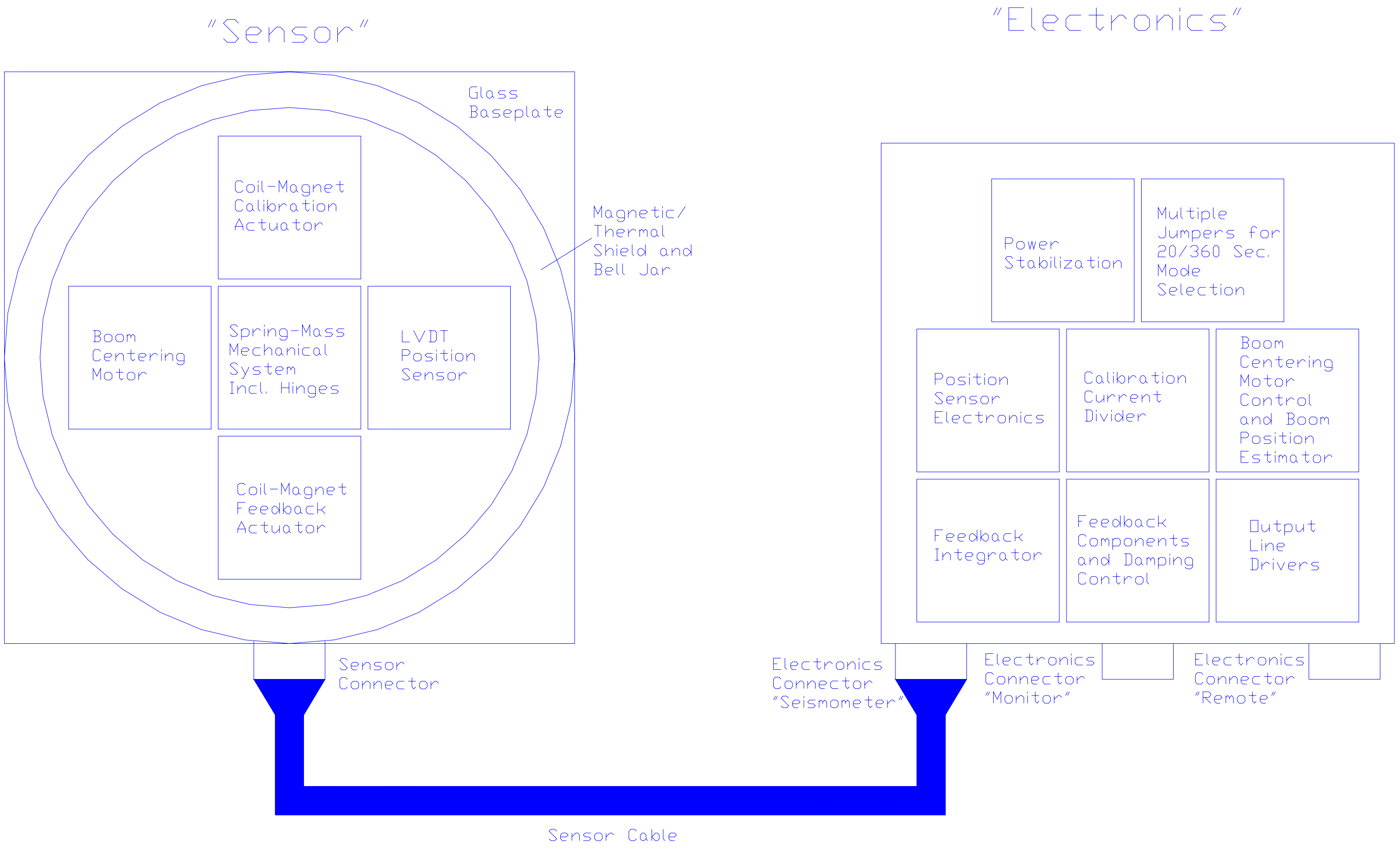


Figure 3. Block diagram of STS-1 VBB Instrument. The STS-1 consists of a sensor, an electronics module, and an interconnecting cable. While the sensor is often operated within a (dry) evacuated housing, it may be exposed to moisture during shipment and storage. As a result, there are some long-term corrosion issues, particularly with respect to its hinges. The electronics are currently packaged in an essentially non-hermetic enclosure. The connectors and the cable are, strictly speaking, non-hermetic as well.

3. Proposed Work Plan

The proposed program will involve four subtasks:

- **a. Development of Replacement Electronics Module.**
  This subtask will develop a fully-tested, economically-viable, replacement electronics module for the STS-1 VBB. This will be a drop-in replacement that maintains the operational performance of the present electronics, while adding a number of the enhancements discussed above. The product will be a complete design (electrical schematic, netlist, bill-of-materials, printed circuit board layout, and hermetic enclosure design) for the module.
- **b. Development of Mechanical Repair Hardware and Methods.**
  This subtask will develop a set of fully-tested repair methodologies, and designs for selected replacement components, that will enable repair of chronic (e.g., long-term corrosion) and acute (e.g., inadvertent mechanical damage) problems that affect the STS-1's electro-mechanical sensor assembly. The product will be a complete design (mechanical drawings and materials specification) and a published repair process (essentially a step-by-step process flow) for repairing the STS-1 VBB's mechanical sensor.
- **c. Development of Calibration Methodology.**
  This subtask will develop a fully-tested calibration methodology, and all required hardware, that will allow users to more easily calibrate a repaired or upgraded instrument, *in situ*, using a conventional seismic data reorder (e.g., Quanterra Q4120 or Q330). The main goal is to provide a method that provides highly automated determination of sensor response factors (poles/zeros and absolute scalar response factor), in a time-efficient manner. It will provide greater operational flexibility (e.g., the ability to swap electronics modules without the loss of instrument calibration) for the STS-1 users. The basic products will be an electrical design (detailing all separate cabling and connectors, as well as any other required electronic components), a published algorithm for data acquisition and analysis, and any required software (both source code and compiled code) for implementing the calibration algorithms.
- **d. Determination of Costs and Commercial Availability.**
  This subtask will determine the raw cost-of-goods associated with the replacement hardware and labor for all of the upgrade products that are developed during this program. This will provide the user community with firm estimates of the upgrade costs, should they wish to manufacture and upgrade their instruments internally. In addition, a detailed estimate of the expected commercial retail costs will be developed, under the assumption that manufacturing and long-term support are to be provided by a typical commercial entity, such as Metrozet. By the end of the program, the team expects to be able to determine the commercial viability of each of the upgrade products. This will help the user community to understand those solutions that are likely to be available commercially, and those that may have to be implemented in-house.

Of these, subtask **a.** is expected to be the largest and most critical. The overall program will be a joint task between BSL and Metrozet, LLC, and our technical consultant, Professor Erhard Wielandt. As a general breakdown, Metrozet will take the lead on new hardware development. This includes electronic module design, modeling, integration, and test, and electro-mechanical design, fabrication and test. BSL will provide sensor testing facilities and expertise, as well as assistance to Metrozet regarding the determination of all key operational issues relating to the STS-1. BSL will also provide STS-1 "candidate" instruments that will be used during this development. Together, Metrozet and BSL will develop, test, and refine complete methodologies for implementing the new hardware and repair methods that could be implemented within a standard seismic laboratory (i.e., field-compatible methods). In his consulting role, Professor Wielandt will provide specific, non-proprietary information regarding all aspects of the instrument design, and he will develop an appropriate set of field-compatible sensor test and calibration methods that will support this development work. Metrozet will assume the responsibility of organizing, maintaining, and publishing (*via* its web site) all of the designs, methods, software, test data, etc. that comes from this work. This is consistent with the company's aim to be a non-exclusive manufacturer and supplier of replacement components and services for the sensor. Metrozet will also assume responsibility for developing and managing all of the required documentation that is related to the NSF program (including any final reports). We provide some additional details regarding each of the development subtasks.

a. Development of Replacement Electronic Module

Metrozet will essentially reverse engineer the existing STS-1 VBB electronics using a combination of the published schematics [Streckeisen, 1987] and the non-proprietary knowledge of its co-inventor, Professor Wielandt. The company will develop a comprehensive electronic model of the complete system, using both nodal circuit simulation tools [PSPICE, 2005] and *ad hoc* mathematical models, written in LabVIEW [LabVIEW, 2005]. PSPICE simulations are often used to model the performance of a complete closed-loop feedback sensor (including its mechanical system, through LRC circuit analogues), while LabVIEW can often provide more flexible, interactive modeling of both noise sources and closed loop sensor response, given the open-loop parameters of the mechanical sensor and the electronics. Both types of models will allow predictive simulation of existing and new circuit designs. This greatly accelerates the process of evaluating the effects of new circuit components on the sensor's performance. Metrozet will develop new schematic designs and board layouts using Orcad EDA tools [Orcad, 2005]. As mentioned above, it is expected that the entire electronics design will be integrated within a single board. Metrozet will utilize its existing, PC-based data acquisition (DAQ) systems to thoroughly characterize the open-loop performance of existing and new electronics designs. These systems provide multi-channel, low-noise preamplifiers and anti-alias filters, with simultaneous, 24-bit digital-to-analog/analog-to-digital converters (DAC/ADC). Control and analysis software is written in LabVIEW. This has been used successfully by Metrozet during the development of its very high dynamic range (>160 dB) seismic accelerometers. The same test systems would likely be adapted by Metrozet for use in pre-shipment testing of commercial electronic modules.

The aforementioned DC motor circuitry will be upgraded significantly through the use of low-cost microcontroller technology (specifically Texas Instruments MSP430) along with a small number of monolithic power driver circuits. This will provide control of the boom-centering motor and it will implement the "look-ahead" position estimation in software.

Fully-hermetic packaging of the electronics and its cabling will likely utilize low-cost oceanographic connectors [Seacon, 2005] to implement a fully-sealed connection between the sensor electronics and the mechanical sensor. This will eliminate electrical-leakage-induced effects in the instrument. Oceanographic bulkhead connectors will provide improved sealing to a fully-hermetic electronics enclosure, relative to the existing circular connectors. The three hermetic connectors (Sensor, Monitor, and Remote) will ultimately need to match the geometry and pin-connections of the existing modules (and any legacy equipment attached to it). That is, any new cabling would be developed during the program in order to allow users to attach the new electronics to an existing installation, with little or no modification required by the user. This may involve the use of a short, waterproof, hybrid cable (one end matching the existing connector on the existing cabling) between the new bulkhead connectors and this legacy equipment. Metrozet personnel have significant experience in the development of hermetic packaging for ocean bottom seismic instruments. A separate issue is related to the hermetic packaging of the sensor itself. Some users have found the conventional glass plate and hermetic enclosure to be unsatisfactory for ultra-low noise installations of the instruments. In certain cases, the manufacturer-recommended glass baseplate, which is an integral part of the evacuated chamber, is subject to temperature and pressure induced tilts. These tilts can cause a large, aseismic (noise) signal on a horizontal STS-1 instrument. In response to this problem, some users will abandon the hermetic enclosure and will run the sensor in the ambient environment [Wielandt, 2005, private communication]. This is known to accelerate corrosion of the sensor's hinges and its motor. Note also that the standard baseplate-bell jar assembly is prone to leakage in environments (often in humid, tropical locations) in which there are significant diurnal temperature variations [Valerie Peyton, 2005, private communication]. An improved, "warpless" baseplate has been developed in response to these problems [Holcomb and Hutt, 1992 and Hanka, 2001]. This is a rigid metal (steel or aluminum) plate that replaces the standard glass baseplate. While this has shown considerable promise, it has not yet been widely adopted. Development of a qualified, manufacturable design for this component might have significant benefits: it could provide a larger set of users with a higher performance option for installing the STS-1 sensor, while ensuring the environmental isolation that would reduce long-term corrosion in the sensor. The BSL/Metrozet team will consider the technical and commercial feasibility of the warpless baseplate, and they will also consider its application to other sensors (e.g., the STS-2).

This subtask will involve two iterations. Metrozet will develop and test an initial version of the electronics. This will be connected with an existing STS-1 sensor (perfectly functioning) at BSL's Byerly Vault. Calibration and testing will be performed by the BSL/Metrozet team. The design will be refined based upon results of this testing. A second version will be designed and manufactured by Metrozet, and the testing will be repeated at BSL. Any required modifications will be incorporated into a final, published version of the electronics design. The work breakdown, and schedule, for these activities are provided in Figure 4, below.

b. Development of Mechanical Repair Hardware and Methods

Metrozet will work with the BSL to identify the major mechanical failure modes for the STS-1 sensor. This will involve communication with a number of the operators of the largest STS-1 networks. This will help the team to prioritize the importance of the known or anticipated failure modes (presently believed to be hinge corrosion, corrosion of the DC motor, and damage to LVDT sensor and coil-magnet actuator assemblies), based upon actual field experience. It may also identify other problems that require attention within this program. Metrozet will work with Professor Erhard Wielandt to understand the critical issues related to the design, fabrication, and installation of mechanical hinges within the STS-1. These will be done using a perfectly functioning STS-1 sensor and its electronics. The efficacy of any repair techniques will be demonstrated by replacing the original hinges in the sensor (a single variable experiment) in a way that maintains the instrument's performance. Due to the mechanical simplicity of the hinge design, it is not expected that any significant simulation (e.g., finite element modeling) will be required. As with the electronics, Metrozet expects that the development of a hinge replacement will involve two separate design and test iterations.

With assistance from Professor Wielandt, Metrozet will procure and test latest-generation DC motors and they will develop a specific mechanical adapter that simplifies its installation within in the STS-1. The team will also develop and test designs for identical replacements for the LVDT position sensor and for feedback and calibration actuators used within the STS-1. The team feels that this is a very manageable task, given their considerable experience in the development of a number of high performance coils and magnetic assemblies. Note that Metrozet designs coil-magnet assemblies for its sensor products for exploration seismology, ocean bottom seismology, and strong motion earthquake recording. These replacement components will be tested using the same single variable test described above. Because the replication of these electromechanical components is a strictly deterministic process (all of the dimensions and specifications can be accurately matched), we expect the technical risk to be very low. A single design and test iteration should be sufficient. All of the mechanical designs will be developed and documented using standard mechanical drafting tools [AutoCAD, 2005].

c. Development of Calibration Methodology

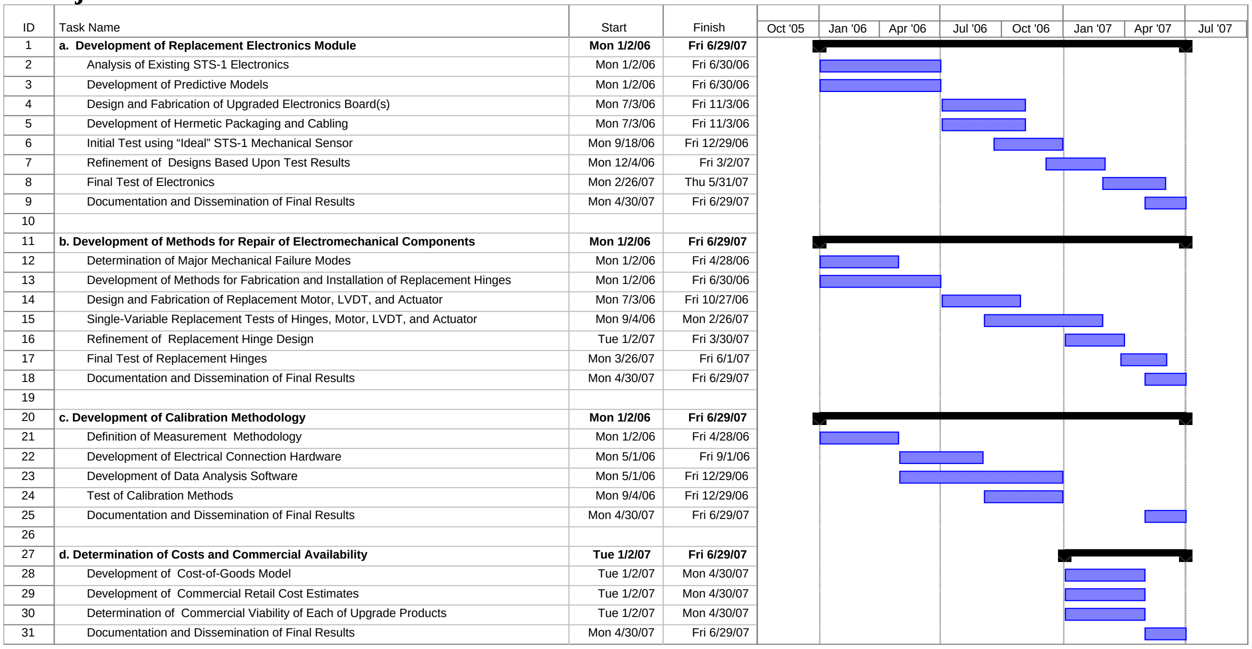
Professor Wielandt will provide a comprehensive calibration methodology (measurement and analysis algorithms) for the STS-1 instrument. For the most part, this will not require a great deal of new development, but rather the collection and organization of a number of existing processes that he has previously used for broadband sensor test. While the test methods will relate mainly to the *in situ* determination of the sensor's response, it is expected that some will address broad band noise measurements as well. The sensor calibration methods are a critical deliverable for this program. They are needed to enable the upgraded sensors to provide data with sufficient accuracy. Although both BSL and Metrozet have a good deal of understanding regarding sensor testing, Professor Wielandt's specific knowledge regarding the STS-1 instrument and its characterization is important. One key emphasis will likely be the use of "step-test" techniques for absolute calibration of sensor response [Wielandt, 2005]. This is in addition to the relative transfer function measurements made via the sensor's calibration coil.

Metrozet and the BSL will implement these test methodologies within the standard seismic recording systems that are normally used to record the STS-1 VBB output. It is expected that this will involve the design of a small amount of specialized cabling to provide the required connectivity. For example, a switchable connection may be needed to allow simultaneous recording of both stimulus and response data within the existing digitizers. This cabling will be developed in a manner that will allow its widespread application in the field. Note that the program will acquire a dedicated system (Quanterra Q330, six-channel recorder) for all calibration and test of the complete sensors. The PC-based DAQ system described above will be used solely for electronic testing. Analysis software will be developed to allow automated determination of sensor response parameters from the raw data. The details regarding its implementation (programming language and computer platform) will be determined during this task. Most of the development and test of these routines can be accomplished using an existing (perfect) STS-1 VBB reference sensor.

d. Determination of Costs and Commercial Availability

Utilizing its experience in development and fabrication of commercial seismic instrumentation, Metrozet will develop accurate cost-of-goods models for all of the upgrade products that are developed during this program. These will accurately reflect the materials and labor that will be required to manufacture, test, and support the products in a commercial setting. This will also provide guidance to STS-1 users that contemplate manufacturing their own upgrade packages, using the published products of this work. Initial estimates dictate that a replacement electronics module would have a commercial retail cost of between $2,500.00 and $3,500.00. This would include all packaging and any new cabling that is necessary. This is consistent with the goal to provide a life enhancement option for the STS-1, at a fraction of the current cost of a number of putative replacement sensors. Repair of electro-mechanical components within the sensor will involve both materials and labor costs. The unit costs of the replacement parts currently envisioned (e.g., hinges, motors, LVDTs, actuators), would be small, typically under $500. The program endeavors to develop repair methods that can be carried out on a reasonably short timeframe (approximately two hours per repair), so as to minimize repair labor costs. Following a successful development and test program, Metrozet intends to become a non-exclusive supplier of the hardware. The company would expect to manufacture and sell replacement electronic modules, and to provide mechanical repair services, to the STS-1 user community. Non-exclusivity implies that other commercial or non-profit entities would also be free to offer these products and services.

4. Project Schedule and Milestone Chart



ID	Task Name	Start	Finish
1	**a. Development of Replacement Electronics Module**	**Mon 1/2/06**	**Fri 6/29/07**
2	Analysis of Existing STS-1 Electronics	Mon 1/2/06	Fri 6/30/06
3	Development of Predictive Models	Mon 1/2/06	Fri 6/30/06
4	Design and Fabrication of Upgraded Electronics Board(s)	Mon 7/3/06	Fri 11/3/06
5	Development of Hermetic Packaging and Cabling	Mon 7/3/06	Fri 11/3/06
6	Initial Test using "Ideal" STS-1 Mechanical Sensor	Mon 9/18/06	Fri 12/29/06
7	Refinement of Designs Based Upon Test Results	Mon 12/4/06	Fri 3/2/07
8	Final Test of Electronics	Mon 2/26/07	Thu 5/31/07
9	Documentation and Dissemination of Final Results	Mon 4/30/07	Fri 6/29/07
10			
11	**b. Development of Methods for Repair of Electromechanical Components**	**Mon 1/2/06**	**Fri 6/29/07**
12	Determination of Major Mechanical Failure Modes	Mon 1/2/06	Fri 4/28/06
13	Development of Methods for Fabrication and Installation of Replacement Hinges	Mon 1/2/06	Fri 6/30/06
14	Design and Fabrication of Replacement Motor, LVDT, and Actuator	Mon 7/3/06	Fri 10/27/06
15	Single-Variable Replacement Tests of Hinges, Motor, LVDT, and Actuator	Mon 9/4/06	Mon 2/26/07
16	Refinement of Replacement Hinge Design	Tue 1/2/07	Fri 3/30/07
17	Final Test of Replacement Hinges	Mon 3/26/07	Fri 6/1/07
18	Documentation and Dissemination of Final Results	Mon 4/30/07	Fri 6/29/07
19			
20	**c. Development of Calibration Methodology**	**Mon 1/2/06**	**Fri 6/29/07**
21	Definition of Measurement Methodology	Mon 1/2/06	Fri 4/28/06
22	Development of Electrical Connection Hardware	Mon 5/1/06	Fri 9/1/06
23	Development of Data Analysis Software	Mon 5/1/06	Fri 12/29/06
24	Test of Calibration Methods	Mon 9/4/06	Fri 12/29/06
25	Documentation and Dissemination of Final Results	Mon 4/30/07	Fri 6/29/07
26			
27	**d. Determination of Costs and Commercial Availability**	**Tue 1/2/07**	**Fri 6/29/07**
28	Development of Cost-of-Goods Model	Tue 1/2/07	Mon 4/30/07
29	Development of Commercial Retail Cost Estimates	Tue 1/2/07	Mon 4/30/07
30	Determination of Commercial Viability of Each of Upgrade Products	Tue 1/2/07	Mon 4/30/07
31	Documentation and Dissemination of Final Results	Mon 4/30/07	Fri 6/29/07

Figure 4. Project Schedule and Milestone Chart. The proposed program will have a duration of eighteen (18) months. (Use zoom control to view chart with greater detail.)

5. Results from Prior NSF Support

Barbara Romanowicz (PI) of BSL:
Program Number: EAR-0308750
Amount of Award: $296,624.00
Period of Support: 07/01/03-06/30/05
Title: "Investigation of Global Scale Seismic Mantle Structure"

This active grant is supporting several studies of global earth structure, using both tomographic waveform approaches and forward modeling of seismic waveforms. It has supported the work of 3 graduate students and 1 post-doc. A global anisotropic model of the whole mantle has been developed as well as a global model of attenuation in the upper mantle. Also, several studies have focused on the structure at the top of the inner core. Already, numerous publications have resulted from this work [Cao and Romanowicz, 2004a,b, Cao and Romanowicz, 2005, Gung and Romanowicz, 2004, Panning and Romanowicz, 2004, Panning and Romanowicz, 2005, and Capdeville et al (2005)].

Thomas VanZandt (PI) and Stephen Manion, of Metrozet, LLC,
are receiving support under an NSF Small Business Innovative Research (SBIR) Phase II grant. This grant has been awarded to Metrozet's parent company, GEOSense, LLC:
NSF Award Number: 0450461
Amount of Award: $495,716.00
Period of Support: 01/01/05 to 12/31/06
Title: "Advanced Unified Oceanographic Data Logger"

This ongoing task is supporting the commercial development of a universal sensor recording system that will allow long-duration, unattended oceanographic recording, with very low operating costs. The recording system will reduce the cost of batteries by a factor of 50X for standard, ocean bottom seismic recording applications. This task is supporting the full-time equivalent of one senior and one junior electromechanical engineer, for a period of two years. As this is a strictly commercial development program, no publications are expected. The task will provide up to five (5) pre-production prototype recording systems that will be delivered to informal partners (at academic and non-profit oceanographic institutions), for field evaluation, in late 2006.