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A Portable Refraction Seismograph PRS1

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1 Introduction

Creation of the LITHOPROBE program in the early 1980's was a turning point for refraction seismology in Canada. Prior to this date, collaboration by associated institutes resulted in experiments deploying no more than 50 refraction seismographs using various recording systems with different frequency responses. Based on past experiences and difficulties in processing recorded traces from unmatched instruments, the LITHOPROBE community decided to standardize field refraction recording in a simple seismograph.

This LITHOPROBE objective had to satisfy a few fundamental requirements. The instrument needed to be light and portable, simple to operate, inexpensive and consume little battery power. Other specifications were driven either by the above fundamental requirements or by practicality of design and implementation and by current technology.

The design, implementation and testing of the prototype simple seismograph was carried out by the Instrumentation Laboratory of the Geophysics Division of the Geological Survey of Canada (GSC) in Ottawa. Based mainly on the fundamental requirements listed above a prototype seismograph was developed and tested successfully in 1985. A technology transfer agreement between the GSC and EDA Instruments of Toronto (now Scintrex Limited) provided the mechanism for Canadian industry to get involved in mass production and marketing of the refraction seismographs.

In 1987 EDA manufactured a batch of 141 seismographs for the Geological Survey of Canada and the LITHOPROBE project. The seismograph which was originally called Single Channel Recorder (SCR) was formally named Portable Refraction Seismograph (PRS1) and is commonly called the Lunchbox seismograph due to its shape and light weight. A new generation of Lunchbox seismographs was later designed and manufactured by EDA mainly to be used for seismicity studies. This instrument, called the PRS4 or Portable Recording Seismograph with four components (3 seismic data and one time channel), departed significantly from the simpler design of the PRS1 instrument. Important new options such as trigger mode recording were included in the PRS4.

Both PRS1 and PRS4 seismographs are now manufactured by Scintrex Limited of Toronto. The PRS1 instrument is exclusively used by GSC and the LITHOPROBE community while the four component PRS4 instrument is used world-wide.

The operation of PRS seismographs requires ancillary hardware such as precision clocks (normally GOES satellite clock) and field computers (IBM- PC work-alike).

The LithoSEIS software is specifically designed to manage the field operation of the Lunchbox seismographs using microcomputers (Field Service Unit or FSU).

The objective of this report is to provide a complete account of the PRS1 seismograph including design specifications and implementation, instrument response and troubleshooting hints. Most of the information for experiment planning and data interpretation is gathered in the appendices for quick reference. Readers not interested in technical details may skip sections three through six.

2 Initial Design Specifications

The initial specifications for the PRS1 seismograph, based on the fundamental design requirements of a light, portable and inexpensive single channel recorder, are given in Table 1 and the basic design layout is shown in Figure 1.

The sensor represents the device which translates the ground motion into some suitable electrical signal to be dealt with by electronic apparatus. It is variously called a transducer, a geophone, or a seismometer by engineers, geologists, and seismologists and typically consists of a large permanent magnet suspended on a precision spring. The field of the magnet threads through a coil of wire called the signal coil which is fixed to the frame of the unit. Ground motion moves the frame and so the signal coil, while the magnet, being spring mounted and having considerable mass, tends to remain at rest. There is thus a net motion between the magnet and the signal coil such that the induction of the magnetic field threading the coil varies with ground motion and generates a voltage in it. It should be noted that the response of the transducer is proportional to ground velocity, not amplitude of the ground motion. The spring and signal coil system acts as a second-order high-pass filter.

A seismometer will generally include some means of calibration. Normally, a second wire coil called the calibration coil is placed in the field of the magnet and attached to the case. Driving a current through the calibration coil exerts a force on the magnet causing it to move, which in turn generates a corresponding voltage in the signal coil. By knowing the motor constant of this force coil, the mass of the magnet, the force current and the resulting output voltage at the signal coil one can obtain the transfer function of the seismometer. Since the seismometer behaves as a high-pass filter, this procedure must be done using an AC current source of adjustable frequency, and the response determined at various frequencies.

Signals emanating from the seismometer are fed to a pre-amplifier which serves a variety of purposes by:

- providing a means of damping for the seismometer,
- amplifying the signal to some minimum level as needed by subsequent circuitry; thus other seismometers of different characteristics may be accommodated with minimal changes,
- providing an electrically balanced input, that is, the impedances to ground are the same at either lead-in wire, and
- providing a low impedance drive for subsequent circuitry.

Great care must be taken in the design and board layout of this circuitry as the overall noise performance of the instrument is largely determined at this point.

The output signal from the pre-amplifier is first low-pass filtered to limit its band width such that the aliasing effects brought about by the finite sampling rate are within

Table 1: Initial design specifications of the PRS1

Feature	Specifications	Status
Input	One analog source	•
	Balanced configuration	•
	Band-pass filters with 40 db rejection at half the sampling frequency	•
	High-pass corner at 0.568 Hz	•
	Provision for slaving several units together	*
Sensitivity	1 nanometer per second ground velocity per bit	•
Accuracy	Less than 1% systematic error	•
System noise	Less than 1 lsb RMS	•
Full scale capacity	2 mm/sec ground motion	•
Dynamic range	132 db pick to pick	•
A/D converter	12 bit resolution	•
Gain-ranging	Selects optimum gain for each measurement	•
Sampling rate	60 or 120 samples per second	*
Time accuracy	Correctable to 5 ms. after a deployment of 48 hours	•
Typical sensor	Light weight 2 Hz geophone	•
Weight	Not to exceed 10 Kg	•
Physical size	About 4 x 20 x 24 cms	•
Operating environs	From -30 deg C to +40 deg C	•
	Reasonably shock resistant	•
	Suitable for deployment in hot, cold, or wet weather	•
Mission duration	Minimum of 200 hours continuous operation preferably 500 hours	•
Internal battery	6 to 14 volts dc, 100 ma peak current	•
Connectors	Geophone	•
	Data I/O, terminal	•
	External battery	○
Data storage	0.5 mbyte solid-state	•
Controls	One push-button switch	•
Display	4 LEDs under processor control	•
Internal program	Bootstrap loader and communications only. Running program with all operating parameters are downloaded from external field computer	•
Field calibration	Manually initiated pulse calibration	•
• = implementd, * =partially implemented, ○ =not implemented.		

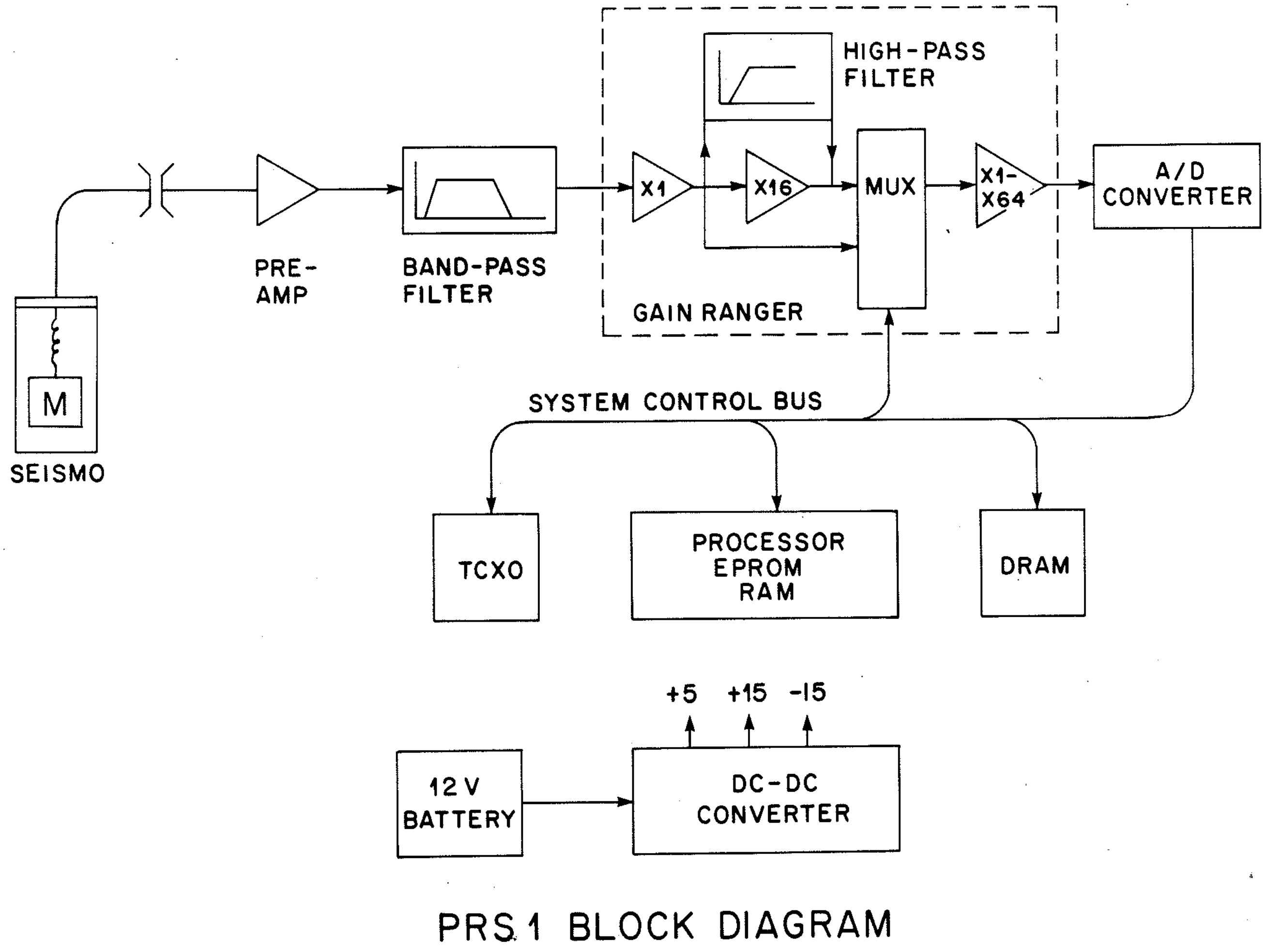

Figure 1: Major design components of the PRS1.

acceptable limits. The initial specifications required that the response of the system to input signals at frequencies above half the sampling rate be at least 40 db below the response at mid-band frequencies. It is convenient to add a high-pass filter after the low-pass section to eliminate the DC offsets and drifts of all circuitry up to this point, since these effects will disturb subsequent circuitry as will be discussed later.

The band-pass filtered signal is fed to a gain-ranging device that dynamically adjusts the amplification of the system to suit the incoming signal. While a variety of algorithms may be considered for the gain-ranging procedure, the principle is to measure the incoming signal at the lowest possible value of gain, thus ensuring that overloading of the electronics doesn't occur. Using this information, it is then possible to calculate how large the gain factor could safely be. A second measurement is made using this optimum value of gain, thus affording the highest possible resolution for that sample. Only the data from the second conversion is retained. A selection of amplification factors from 1 to 1024, in binary steps, is available.

The gain-ranged signal is input to the A/D converter and the result recorded in solid-state memory dynamic RAM (DRAM) through the CPU.

A temperature compensated crystal oscillator (TCXO) is used to drive the processor and to provide accurate time-keeping for the system.

The power supply consists of a 12-volt battery and high efficiency DC-DC converters to provide the +5, +15, and -15 volt sources required by the electronics. Under control of the CPU, the supplies to the analog portion of the circuitry are turned off when not needed.

The preceding section shows how the initial design for the PRS1 seismograph was envisaged. It should be noted that almost all of the performance specifications listed in Table 1 were finally realized. The only options not available currently are the sampling rate of 60 Hz and provisions for slaving several units together. The data storage capacity has been increased from the specified 0.5 to 1 mb. The following section describes how some of the main components of the design were selected and finalized.

3 Design Philosophy and Implementation

The fundamental design criteria of low unit cost, weight, bulk and power consumption influenced many of the initial design specifications of the PRS1.

3.1 Band-Pass Filters

The band-pass filter consists of a low-pass anti-alias filter followed by a high- pass filter. Low-pass analog filters have three major design types, each with their own peculiar characteristics. Butterworth filters exhibit maximally flat response over the pass-band. Chebyschev filters have the fastest roll-off at the corner frequency. Bessel filters have a uniform phase delay over the pass-band. The Butterworth filter suffers badly from overshoot with inputs that are impulsive in character. A Chebyschev filter exhibits some ripple in the pass- band, and the Bessel does not have as rapid a roll-off as the others. Settling time is shortest for the Bessel, longer for the Butterworth, and longest for the Chebyschev. A comparison of these characteristics is shown in Figure 2 (from Wong & Ott 1976[1]) .

What is the best choice of analog filter for the PRS1? Since explosively generated seismic waves, at least over distances of a few hundred kilometers, appear at a recorder as impulsive signal, it is imperative that the filter behave reasonably well for such signals. It is also important that the phase response of the instrument be well defined.

Taken together these requirements dictate the use of a Bessel filter. In addition to the performance benefit of the Bessel, there are also practical advantages to the designer; it is easier to construct using reasonable values of resistors and capacitors, and the spread in component values is less. These factors contribute to the stability of filter characteristics with changes in temperature, and reduce component costs as well.

The Bessel low-pass filter was designed using the formulae, and graphs found in Wong and Ott 1976. From the graphs, it was determined that a 6-pole filter would be required. The graphs also indicated that a 6-pole filter would have about 40 db of rejection at a frequency four times the cut-off frequency as defined for Bessel filters. The performance specifications require a rejection of 40 db at one-half of 120 Hz, the sampling frequency. This leads to a cut-off point of 15 Hz, and this figure was used in subsequent calculations.

3.2 Gain Ranger

Gain-ranging has the disadvantage of not affording uniform gain over the whole range of input signal amplitudes. In fact the larger signals must be measured at lower values of gain, thus losing resolution and consequently the ability to recognize small signals in the presence of large ones. However, the cost and power consumption of an A/D converter which could directly span a sufficiently large range of inputs was not affordable for the PRS1 seismograph. The principle of gain-ranging conversion was thus accepted as a necessary but unwelcome compromise. Similarly, the restriction to a converter offering only 12 bits of resolution was dictated by the cost and power consumption criteria.

The performance specifications indicate that a dynamic range of 132 db is needed. A 12-bit converter supplies 72 db, and the remaining 60 db must be provided by the gain-ranging circuitry. Thus the gain-ranger must permit gain selections from 1 to 1000. It proved convenient to design a gain-ranger having ten ranges from 1 to 1024 selectable in binary steps, i.e. 1,2,4,8....etc. To realize these gains, the signal at the input to the gain-ranger is fed to two amplifiers in tandem. The first amplifier has a gain of unity, the second has a gain of 16. The output of one of these two is then selected to be further amplified by another circuit having gains selectable in binary fashion, from 1 to 64. This last circuitry actually has the capacity to amplify by 128, but the noise performance deteriorates at this gain so it is not used in the PRS1.

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[1] Wong, Yue Jen and William. E. Ott (1976). Function Circuits: Design and Applications. New York, McGraw-Hill, 291 p.

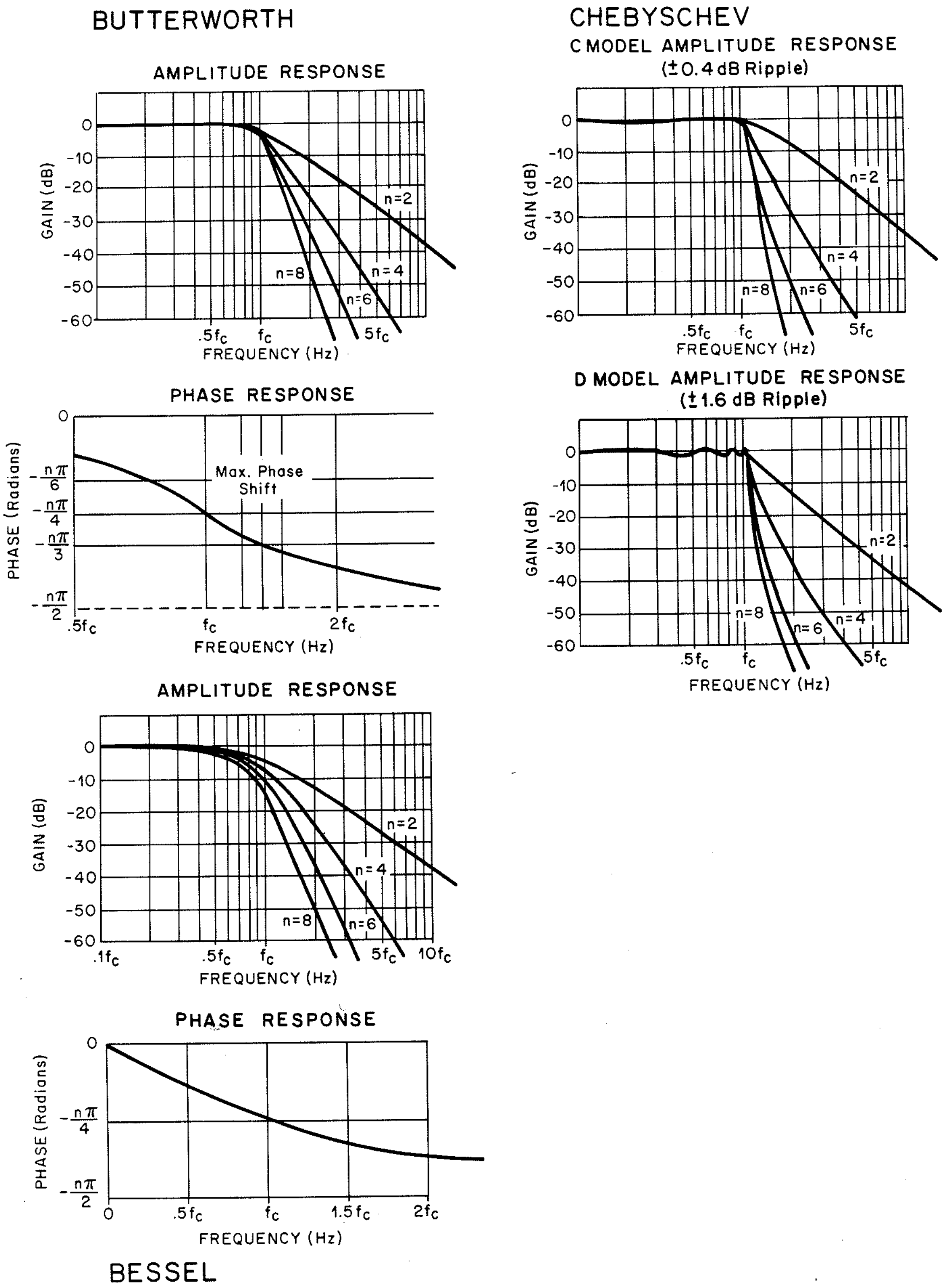

Figure 2: Comparison of various filter characteristics.

Table 2: PRS1 Binary Gains

using the X1 output	using the X16 output
1	..
4	..
16	16
64	64
	256
	1024

The two amplifiers in tandem are constructed using components accurate to 0.1%. The next amplifier is constructed using an integrated resistor package having a worst-case error of 0.5%, and typically only 0.3%, according to the manufacturer. Furthermore, this maximum error occurs at the maximum gain, and elsewhere is approximately proportional to gain. Hence, by not using the highest gain value of the package, the overall error in amplification should be well within the performance specification.

An eight channel multiplexer (shown as MUX in Figure 1) is interposed between the tandem amplifiers and the programmable gain amplifier. Only three channels are used in the PRS instrument. Channel 0 provides an input for monitoring the battery voltage, and channels one and two serve as inputs for the X1 and X16 amplifiers respectively.

As mentioned above, the principle of gain-ranging is to make a measurement at the lowest possible gain, then using this data, calculate what the maximum gain could be without overloading the converter. If all were ideal one might simply divide the maximum value the converter can accept by the value from the first conversion, then compare this ratio with the list of available gains and select the highest gain just less than the ratio. However a number of factors obstruct this procedure. Evaluating the data from the first conversion and selecting the appropriate value of gain takes a finite amount of time for the processor during which the input signal will have changed somewhat. In addition, the gain-ranging hardware has small errors and offsets associated with each gain and these will drift with temperature. Thus it is necessary to provide some "head room" in the gain selections to prevent possible overload of the converter. This is most easily accommodated by assuming the converter to have a range of about 90% of its actual range. For a 12-bit converter the range is ± 2048 counts, and 90% of this is ± 1843 counts. Using this value as the maximum allowable output of the converter provides the needed margin of safety.

The gain-ranging algorithm must deal with another matter. Referring again to Figure 1, note that the input signal from the filter section is fed to two amplifiers in tandem; one having a gain of unity, the other of 16, and that the output of each is available to subsequent circuitry. Table 2 illustrates the overall gains available.

For overall gains of 16 and 64 there are two possible configurations of the gain-ranger.

The choice is not arbitrary but is governed by the history of the input signal. For small seismic signals the gain can be large. This implies using the X16 output with large values of gain selected for the subsequent circuitry. As the seismic activity increases the gain is adjusted to accommodate the signal first by reducing the gain-ranger setting, while remaining connected to the X16 output, then, when this technique will no longer suffice, switching to the X1 amplifier and adjusting the gain-ranger as before. When the signal is large enough to require the use of the X1 output, the X16 amplifier will be in a saturated condition. While this is not harmful in itself, the hardware can not recover immediately as the input drops to a value which is normally within the limits of the X16 amplifier. Hence, once the signal has reached a value requiring the use of the X1 amplifier, the X16 output must not be used again until the signal has dropped to within its range and has recovered from the saturated condition. In fact once the X1 amplifier is used the X16 can never be used again for that window.

3.3 Analog to Digital (A/D) Converter

The 12-bit analog-to-digital converter was selected from among several offerings chiefly on the basis of price, performance and power consumption. The 12-bit range covers an analog input range of +10.24 to -10.24 volts, corresponding to an input sensitivity of 5.0 millivolts per bit.

3.4 Pre-Amplifier

With the A/D converter and gain-ranger specified, it is possible to establish the gain permitted in the pre-amplifier. For best noise performance of the system this gain must be as large as possible. From the list of performance specifications the required sensitivity is 1 count per nanometer/second.

The Mark Products L-4A seismometer, with a generator coil of 5500 ohms resistance and damped to 0.7 of critical, produces a voltage of 276 volts/meter/sec. The gain-ranger provides a maximum gain of 1024 and with the A/D converter sensitivity of 5 millivolts/bit, the pre-amplifier gain of 17.691 is required to achieve an overall system sensitivity of 1 count per nanometer/sec. For efficiency of manufacture, the nearest standard resistor values were specified in the design of the pre-amplifier and thus the actual gain is 17.24 and is lower than that required (see Appendix A for details). A correction for this discrepancy is provided in the analysis procedures.

3.5 The CPU

The choice of the microprocessor required some additional considerations. Since the development effort of any modern data logger will usually involve about four to five times as much effort in software as in hardware, it was decided to select a processor well supported with software development facilities such as logic analyzers, in- circuit emulators, and various high-level language compilers. Another area of concern was the level of functional integration available in the processor chip. Since the processor and its support circuitry will include RAM, EPROM, and DRAM memories, communications facilities, and a variety of I/O control functions, the most cost effective realization will be obtained with a processor chip containing the largest proportion of these. The choice most consistent with the above considerations was the Hitachi HD6303XP.

The Hitachi HD6303XP is an 8-bit processor with the following functions contained on the chip: Hardware multiply-divide capability, 192 bytes of RAM memory, provision to address as much as 64 kilobytes of off-chip memory, a serial communications interface capable of either asynchronous or synchronous operation at speeds up to 307 kbaud, and several general purpose I/O ports. In addition, a low-power "sleep" mode is available for periods when only a minimum amount of processor activity is needed. This processor is an enhanced version of the popular Motorola 6800 series, and is thus well supported with software development aids.

The entire electronic circuitry is contained on two standard double-width Eurocards of dimension $160 \times 235mm$; one such board is dedicated to the data storage memory, and the other to all the remaining electronics. Each board has provisions for two 64-pin edge connectors. In so far as possible, the signal allocation for the 64 pins follow that defined for the P1000 bus proposed by the IEEE.

Most of the processing and control functions are realized in a straightforward manner. Among these are provision for controlling four Light-Emitting Diodes (LED), conditioning the communications signals to RS-232 standards, two eight-bit system control ports, an eight-input analog multiplexer, and a pulse calibration current source.

A number of functions require some further elaboration. The processor has a 16-bit memory address bus. It is convenient to divide this 64 kb memory space into four quartiles of 16 kb each and allocate them as shown in Figure 3. To minimize the circuitry required, the decoding of these spaces has been carried out only as far as needed, hence some spaces are not uniquely defined and some harmless imaging occurs.

There is provision for controlled start-up such that the processor is held in reset state until the power rails have stabilized and the TCXO has attained a reasonably stable wave-form. These processes typically take only a few milliseconds.

A variety of wire jumpers permit selection of a number of options for supplying the processor clock. A crystal may be mounted on the board, offering a low cost, reasonably stable source, or an external oscillator may be used. The TCXO in the PRS operates at twice the frequency required by the processor and a divide-by-two circuit is incorporated providing a second benefit in that it serves as buffer-driver between the TCXO and the processor, yielding a wave form of better quality. A jumper option allows a measurement of the battery voltage if desired. Another set of jumpers permit automatic reset of the system after a power failure, for those applications where this is desirable.

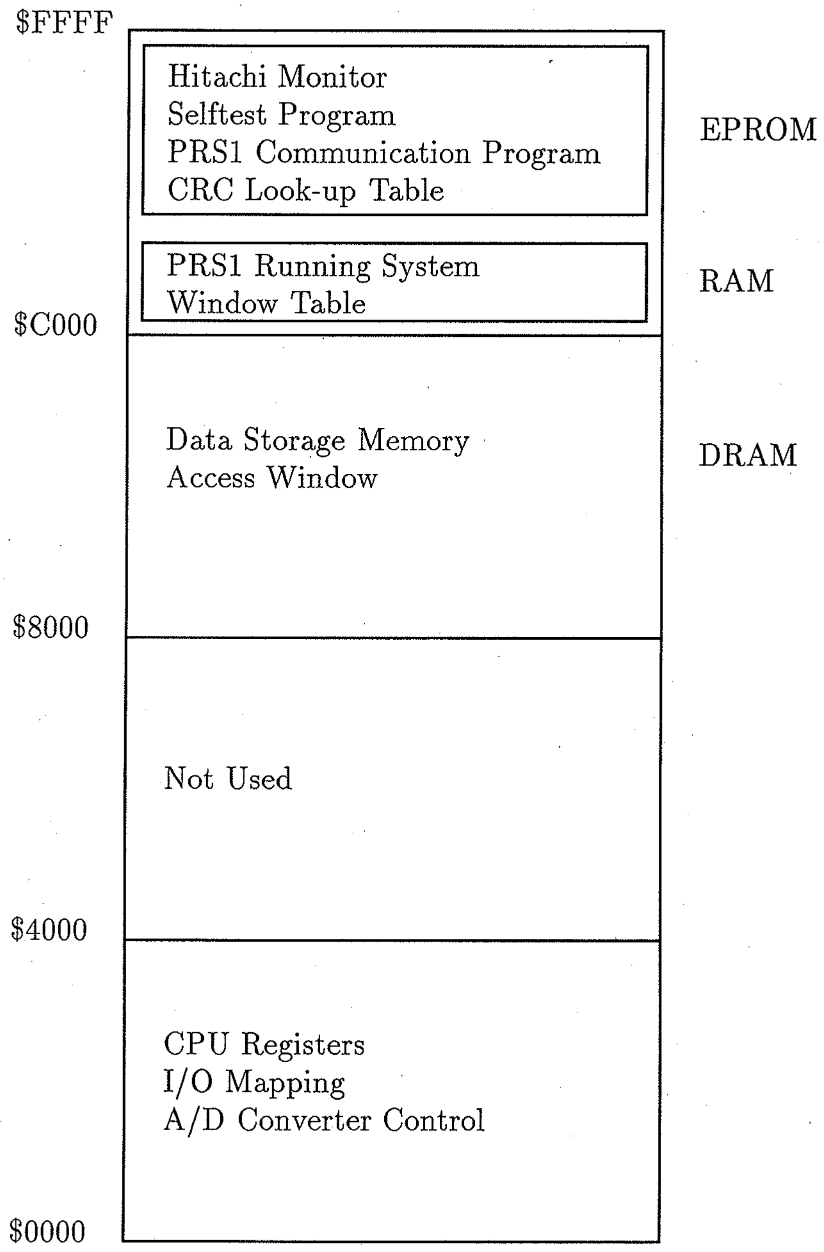

Figure 3: PRS1 Memory Address Space.

3.6 Dynamic RAM

The concept of using volatile solid-state memory for the data storage medium was carefully examined. Experience with non-volatile media such as magnetic tape recorders indicated that they were unreliable and had significantly higher power consumption. A new CMOS memory element became available that featured a low power-mode when not actually being accessed by the computer. Implementing the data storage memory with this very low power, solid-state device provided many advantages for the PRS. The danger of data loss because of power failure was reduced by having the processor monitor the battery condition and, when necessary, establishing a configuration which minimized power consumption while maintaining data retention.

The data storage module is designed using the CMOS dynamic memory (DRAM) integrated circuit manufactured by Intel and identified by the number 51HC256L. This package is organized as a 1 × 256 kb array. Eight packages must be used in parallel to achieve a word width of 8-bits as required by the processor. It was possible to mount 32 of these packages along with the required support circuitry on one double-width Eurocard, thus providing 1 megabyte of data storage.

The 1 mb capacity of the module requires a 20-line address bus. This was accomplished by arranging to access the module in 64 banks of 16 kb through a window in the processor address space. In this way the processor can provide 13 of the needed address lines. The remainder are provided through a 7-bit I/O port managed by the processor. Hence within a bank the processor has direct access at full speed. At the bank boundaries the processor must first select the appropriate bank through the I/O port, then access again proceeds at full speed.

A characteristic of all DRAM memories is the need for regular refreshing of the memory cells to retain data. Most of the power consumption of the device is used in the refresh operations. A significant advantage of the CMOS chip is the ability to retain data with infrequent refresh cycles during times when the computer is not actually accessing the chip. By carefully controlling the refresh rate, a significant reduction in power consumption is realized. To make best use of this feature, the computer must make the least possible demands on the DRAM, and must also adjust the refresh rate such that all cells are refreshed at the full speed just before reading or writing to and again immediately afterwards before resorting to the power-saving rate.

3.7 The TCXO

The TCXO was selected as the lowest priced and most efficient offering from among several manufacturers. The drift specification of ± 0.2 ppm over the temperature range of -25 to +35 degrees C seems to be state-of-the-art performance for the technique of compensation for temperature variation. A reduction in power consumption was made possible by selecting an oscillator frequency at twice that required, and performing the frequency division by our own circuitry.

Some comments are in order concerning the anticipated performance. An uncompensated crystal exhibits a drift characteristic which is approximated by a third order curve. Compensation techniques are able to modify this curve to contain it within an error band of ± 0.2 ppm over the specified temperature range. However, the resulting curve is now much more complicated, and may have several maxima and minima within the temperature range of interest. Therefore it is not correct to assume lower drift rates with reduced temperature fluctuations, nor is it helpful to insulate the TCXO. The only recourse is to thermostat the crystal, but the added power consumption cannot be afforded for the PRS.

3.8 Power Supply

The PRS is supplied with power from a 12 volt source. This voltage was chosen to allow a common automotive battery to be used for missions of long duration. For refraction studies with durations of a few days a battery pack of 16 D size dry cells is sufficient. Since the power rails within the unit are +5, and ± 15 volts, two high-efficiency DC-DC converters are used to generate these from the 12 volt source. In order to conserve energy, the power to the analog portions of the unit are switched off (by the CPU) unless recording is actually in progress. Current consumption is less than 20 ma when the PRS is least active and rises to about 80 ma or so when it is most active.

4 Initial Field Tests

Fourteen prototype units were constructed according to the design just described. Following extensive laboratory tests, the fourteen units were deployed in a short field experiment in November 1985. Results were most encouraging, and no significant problems were revealed. The ease of deployment was appreciated by field personnel, and the reliability and resolution appreciated by seismologists. At this time the high speed upload facility had not been developed, but its importance to a large experiment was readily apparent; uploading 1 megabyte of data, using conventional means at 9600 baud, took about 40 minutes per unit!

A comparison of the achieved specifications with those proposed at the outset reveals a few minor differences. Only one sampling rate is available, 120 s/sec. The prototype case size and shape are different but not significantly so. Subsequent commercialization by a geophysical company resulted in a still larger case, with room for some additional features. The cost of DRAM memory had dropped so significantly at the time of manufacture that a 1 mb capacity was practicable. All other specifications were met without compromise. The system noise corresponds to about 0.5 nm/sec RMS.

5 The High Speed Link (HSL)

Development of a high speed communications device involved effort in four areas. While the hardware in the PRS was largely complete and compatible with this development, quite a number of software enhancements were required to take advantage of the higher speeds built in to the serial communications interface of the processor. A more significant effort was expended in developing special hard disk utilities for the FSU computer. These were needed since the utilities resident in the then current version of DOS could neither receive data nor store to disk at the rates required. In addition, the proposed high speed facility would involve a hardware module to be resident in the host processor, and software was needed for this also. Finally, the hardware module had to be designed.

Since all the software efforts are described elsewhere, this section is concerned with the hardware only. It contains a Hitachi HD6303XP microprocessor similar to the one in the PRS , two 8 kb data buffers so arranged that they can be resident in the memory space of either the Hitachi processor or the FSU computer, and interprocessor control circuitry. The data buffers can be used together as one buffer of 16 kb or separately, in "ping-pong" fashion. Interprocessor handshaking is a byte-at-a-time operation.

As now implemented, the high speed capability is only used for upload transfers. Download operations are made using the same hardware but at the slow asynchronous speed of 4800 baud. While the high speed capability is as great as 307 kbaud, the real throughput is about one third of this, since extensive error detection procedures are employed to ensure faithful transfers. Even so, the upload of one megabyte of data was reduced to about 100 seconds typically. This improvement in the speed of data recovery has contributed very significantly to the efficiency with which a refraction survey can be carried out. The High Speed Link uses PC memory addresses 0xAC000 to 0xAFFFF which is in conflict with the memory allocated to the VGA adaptor (0xA0000 to 0xBFFFF). This implies that the High Speed Link will not operate on an FSU with VGA display adaptor. Most VGA adaptors support an optional EGA simulation that could be used to avoid the conflict.

6 Technology Transfer to Industry

As the development of the refraction system neared completion, and every consideration indicated a satisfactory system had been realized, the possibility of transferring this technology to some private corporation for commercial development was investigated. First, an application for patent rights was filed with Canada Patents and Developments Ltd. Then discussions with the NRC officers administering the Industrial Research Assistance Program (IRAP) indicated that submissions from suitable corporations for such a project would be favorably received. Proposals for this development were invited from a number of firms in the geophysical instrumentation field. Selection of a suitable firm included consideration of the following qualifications:

Table 3: PRS1 Inventory

PRS1 Serial Number	No	Origin
A001-A141	141	EDA
A142-A155	14	Prototype
A160-A189[2]	30	Scintrex

Note 1. Serial numbers A156-A159 not used.

- experience of the firm in geophysical techniques, particularly using seismic methods,
- financial stability and resources,
- engineering and manufacturing resources,
- marketing experience world-wide,
- past performance in similar development projects, and
- compatibility with present company products and plans.

Chiefly on these criteria, EDA Instruments Ltd. of Scarborough, Ontario was granted a license through Canada Patents and Developments Ltd. to carry out the commercial development of the system and to market it world-wide. EDA Ltd immediately submitted a request to NRC for funding under the IRAP program, and this was approved.

The company undertook to redesign certain aspects of the system to improve the sales appeal and to reduce manufacturing costs. The case of the PRS was redesigned to house a bank of 16 size D dry cells in place of the 12 volt lantern battery used in the prototype, since it was felt that these would be more readily available in some parts of the world. EDA also preferred to make the battery compartment accessible without exposing the electronics. The case dimensions were altered to accommodate a number of expansions envisaged by EDA, and the DC-DC converters were designed and built in-house, in preference to the commercial units used in the prototypes. Some alternate components were selected for the high speed link to improve the reliability of this module.

After approving these design changes, EMR placed an order with EDA Ltd. for 141 PRS1's and 10 HSL's. The equipment was delivered early in 1987. In 1989, Scintrex Inc. of Toronto purchased the license to manufacture the PRS instruments and replaced EDA Ltd. A batch of 30 PRS1's were manufactured in 1989. The total inventory now is shown in Table 3.

A The PRS1 Seismograph Response

The design goals of the PRS1 seismograph were to obtain a high gain unit with an overall sensitivity of 1 count/nanometer/sec, an amplitude response of -40 db at the Nyquist frequency, no overshoot in the bandpass and low long period amplitude response. The response will be fully described by defining the static magnification and the frequency response of these instruments.

A.1 The PRS1 Static Magnification

The static magnification is the overall gain of the seismograph at mid-band frequencies as the seismic signal is amplified and digitized using an A/D converter. The input is a unit of ground motion and the output is a number of computer units; the static magnification will be represented here as counts/m/sec.

L4-A Seismometer The generator constant of the seismometer is 276 volts/m/sec as shown in Table 4. The input signal is impedance matched to provide an initial voltage gain of 17.24 and an electrical damping factor of 0.418 critical (pre-amplifier stage; U27, Figure 4). The gain of the input stage is:

$$\frac{R38}{R34 + RS/2} = 125/7.25 = 17.24$$

The natural mechanical damping (or open circuit damping) of the seismometer is 0.280 critical. The total seismometer damping is 0.698 critical which very closely approaches the Butterworth "maximally flat" characteristic (where damping =0.707 critical). A unit ground motion of 1 nanometer/sec will produce a signal (at mid-band) of

$$(276\ volts/m/sec) \bullet (1 \times 10^{-9}\ m/sec) \bullet (17.24) = 4.758\ micro-volts.$$

Band-Pass filter The 6-pole Bessel anti-alias and single-pole high-pass filters both have unity gain.

Low-Pass filter The additional single-pole low-pass filter has a fixed gain of 16.

Gain Ranger The gain ranger has a variable gain from 2^0 to 2^7 (1 to 128). The highest gain setting has large errors when compared to the gain settings of 64 and below and so is not used; the useful range is limited to 1 to 64. A unit ground motion of 1 nanometer/sec will produce a signal (at midband) of

$$(4.758\ micro-volts) \bullet (16) \bullet (64) = 4872.4\ micro-volts$$

(or 4.872 millivolts) at the highest gain setting.

Table 4: L-4A, 2 Hz, 5500 ohm Geophone

Coil Resistance	$R_c = 5500$ ohms
Trunsduction (generator constant)	276 volts/meter/sec
Coil Inductance (henries)	6.0 henries
Analog Capacity Equivalent (microfarads)	6.65 microfarads
Analog Inductance Equivalent (henries)	950 henries
Shunt for 0.83 Critical Damping	5500 ohm
Shunt for 0.70 Critical Damping	8900 ohms
Shunt for 0.60 Critical Damping	11800 ohms
Type	Moving dual coil, humbuck wound
Frequency	2.0 ±0.25 Hz measured on 200 pound weight at 0.09 inches/second
Frequency change with tilt	Less than 0.10 Hz at 10 degrees from vertical
Frequency change with excitation	Less than 0.10 Hz from 0 to 0.18 inches/second
Suspended mass	500 grams
Linkage to case	100 megohm minimum at 500 volts
Trunsduction Power	13.6 watts/meter/second
Opern Circuit Damping	$b_0 = 0.28$ critical
Current Damping	$b_c = \frac{1.1R_c}{R_s+R_c} = 0.420$ (for $R_c = 5500, R_s = 8900$)
Total Damping	$b_t = b_0 + b_c = 0.70$
Coil Inductance	$L_c = 0.0011R_c = 6.05$ henries
Electric Analog of Capacity	$C_c = \frac{36500}{R_c} = 66.36$ microfarads
Electric Analog of Inductance	$L_m = 0.17R_c = 935.0$ henries
Case Height	13 cm
Case Diameter	7.6 cm
Total Density	2.9 grams/cm3
Total Weight	1.7 kg
Operating Temperature	-29 to 60 centigrades
Operating Pressure	500 psi

A/D Converter The A/D converter is a 12 bit unit (11 bit mantissa and one sign bit) with a reference voltage of ± 10.24 volts DC. The operand of the unit is thus

$$(2^{12}\ counts)/(20.48\ volts) = 200\ counts/volt.$$

A unit ground motion of 1 nanometer/sec will produce a signal (at midband) of

$$(4.872\ millivolts) \bullet (200\ counts/volt) = 0.9744\ counts.$$

The static magnification of the PRS1 seismograph, G, is 0.9744 counts/nanometer/sec or $9.744 \times 10^8 counts/m/sec$.

A.2 The PRS1 Bandpass and the System Transfer Function

The PRS1 bandpass is determined by its four elements: the L4A 2 Hz seismometer; a 6-pole Bessel anti-alias filter; a single-pole high pass filter to further attenuate the long period signal; and, a further bandpass shaping single-pole low-pass filter.

A.3 L4-A Seismometer

The electromagnetic seismometer acts as a second-order high-pass filter with a transfer function (from Wong and Ott, 1976, p 216; setting the gain factor to unity) of the form:

$$H(s) = \frac{s^2}{s^2 + s\omega_0/Q + \omega_0^2} \tag{1}$$

in which ω_0 is the natural frequency of the seismometer in rad/s, the damping constant $Q = 1/2\zeta$ where ζ is the seismometer damping, and s is the complex frequency ($s = i\omega$, $i = \sqrt{-1}$). For the L-4A seismometer $\omega_0 = 2\pi f_0$ where $f_0 = 2$ Hz ($\omega_0 = 12.5664$ rad/s) and $Q = 0.716$ (for $\zeta = 0.698$).
Substituting ω_0 and Q in (1), we get

$$H_1(s) = \frac{s^2}{s^2 + 17.5427s + 157.9137} \tag{2}$$

There is a complex conjugate set of poles and there are two zeroes for this transfer function, which are:

$$8.771 \pm 8.999i; \quad 0.0, 0.0 \tag{3}$$

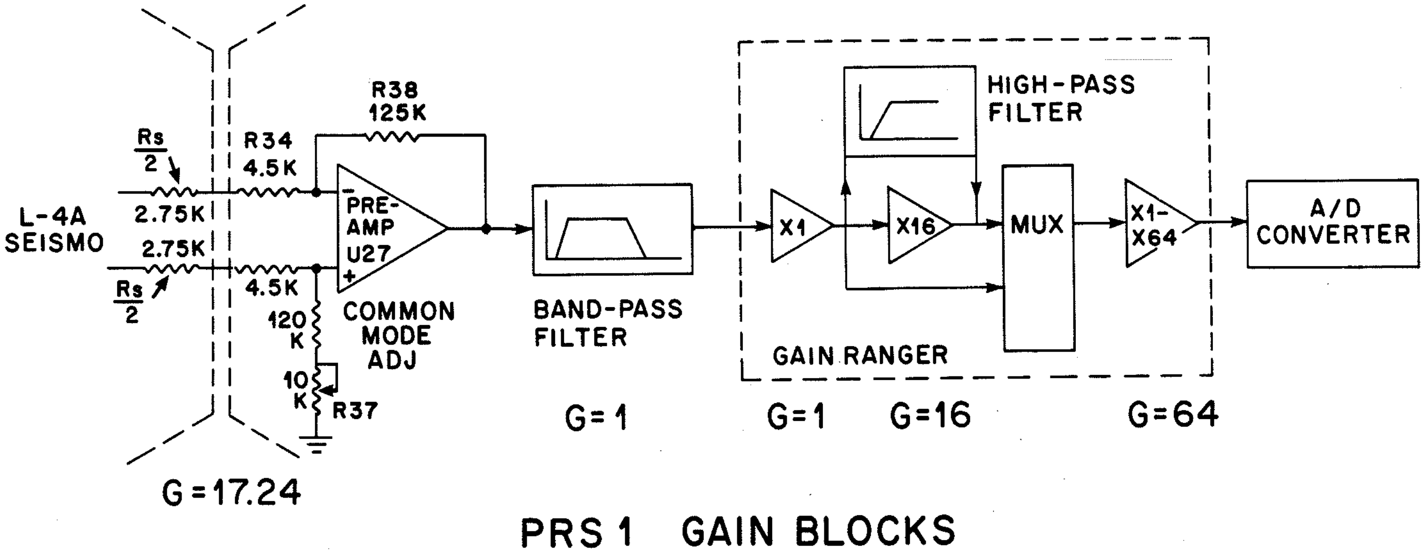

Figure 4: PRS1 gain blocks.

A.3.1 Anti-Alias Filter

The 6-pole Bessel anti-alias filter attenuates the amplitude response 40 db at the Nyquist frequency (60 Hz) while maintaining excellent phase shift linearity and no overshoot in the bandpass. The corner frequency is at 30 Hz for the fixed sampling rate of 120 samples/sec. The filter is constructed as 3 cascaded second-order low-pass filters, each with a transfer function (from Wong and Ott, 1976, p 214; setting the gain factor to unity) of the form:

$$H(s) = \frac{\omega_0^2}{s^2 + s\omega_0/Q + \omega_0^2} \tag{4}$$

The overall transfer function for the 6-pole filter is of the form:

$$\begin{aligned} H(s) = & \frac{\omega_1^2}{s^2 + s\omega_1/Q_1 + \omega_1^2} * \\ & \frac{\omega_2^2}{s^2 + s\omega_2/Q_2 + \omega_2^2} * \\ & \frac{\omega_3^2}{s^2 + s\omega_3/Q_3 + \omega_3^2} \end{aligned} \tag{5}$$

The normalized filter parameters for Bessel filters (taken from Wong and Ott, 1976, p 240) are:

$$\begin{aligned} \omega_1 &= 1.092700 & Q1 &= 1.023310 \\ \omega_2 &= 0.969010 & Q2 &= 0.611195 \\ \omega_3 &= 0.920141 & Q3 &= 0.510318 \end{aligned}$$

For a corner frequency of $f_0 = 30$ Hz, $\omega_0 = 188.4956$ and ω_1, ω_2 and ω_3 become:

$$\begin{aligned} \omega_1 &= 205.9691 \\ \omega_2 &= 182.6541 \\ \omega_3 &= 173.4425 \end{aligned}$$

Substituting in (5), we get the transfer function for the Bessel anti- alias filter:

$$\begin{aligned} H_2(s) = & \frac{42423.31}{s^2 + 201.277s + 42423.31} * \\ & \frac{33362.48}{s^2 + 298.847s + 33362.48} * \\ & \frac{30082.30}{s^2 + 339.871s + 30082.30} \end{aligned} \tag{6}$$

There are no zeroes, the poles of this equation are:

$$\begin{array}{rcr} -100.639 & \pm & 170.708i \\ -149.424 & \pm & 105.048i \\ -169.936 & \pm & 34.701i \end{array} \tag{7}$$

and the scale factor for the filter is $\omega_1^2 \bullet \omega_2^2 \bullet \omega_3^2 = 4.2576 \times 10^{13}$.

A.3.2 High-Pass Filter

The single-pole high-pass filter has a corner frequency of $f_0 = 0.568$ Hz, $\omega_0 = 3.5714$ rad/s, and its transfer function is:

$$H(s) = \frac{s}{s + \omega_0} \tag{8}$$

or

$$H_3(s) = \frac{s}{s + 3.5714} \tag{9}$$

The single pole and single zero of this transfer function are:

$$-3.5714; \quad 0.0 \tag{10}$$

A.3.3 Low-Pass Filter

The single-pole low-pass filter has a corner frequency of $f_0 = 30.14$ Hz, $\omega_0 = 189.375$ rad/s, and its transfer function is:

$$H(s) = \frac{\omega_0}{s + \omega_0} \tag{11}$$

or

$$H_4(s) = \frac{189.375}{s + 189.375} \tag{12}$$

There is no zero, the single pole of this transfer function is:

$$-189.375 \tag{13}$$

and the scale factor is $\omega_0 = 189.375$.

A.3.4 Overall System Transfer Function

The overall system transfer function for the seismograph is constructed as follows:

$$H(s) = G * H_1(s) * H_2(s) * H_3(s) * H_4(s) \tag{14}$$

where G is the static magnification of the seismograph as described in the previous section ($G = 9.744 \times 10^8 counts/m/sec$ and $H_1(s), H_2(s), H_3(s)$ and $H_4(s)$ are given in (2), (6), (9) and (12) above.

The overall system transfer function of the seismograph can be more compactly expressed in terms of G and the poles and zeroes and scaling factors; the transfer function takes the form:

$$H(s) = G * K * \frac{\prod_{i=1}^{n}(s - zero_i)}{\prod_{i=1}^{m}(s - pole_i)} \tag{15}$$

where K is the product of all of the individual filters' scale factors ($K = 8.06283 \times 10^{15}$).

The poles and zeroes, the scale factors and the static magnification are given in Table 5.

Table 5: Poles, zeroes & scaling factor

Component	Poles	Zeroes	Scalar
L-4A seismometer, 2 Hz	-8.771 $\pm$8.999i	0.0,0.0	1
Anti-Alias filter: Six–pole Bessel with $f_0 = 30$ Hz	-100.639 $\pm$170.708i -149.424 $\pm$105.048i -169.936 $\pm$ 34.701i		4.2577×10^{15}
High-pass, f_0=0.568 Hz	-3.571	0.0	1
Low-pass, f_0=30.14 Hz	-189.375		189.375
Static magnification, $G = 9.744 \times 10^8$			

A.4 The PRS1 Response

The PRS1 phase and amplitude responses computed from the poles and zeroes given above are given in Figures 5a and 5b.

A.5 PRS1 group delay

The phase response of the Bessel Anti-Alias filter (Figure 5b) shows a fairly smooth slope for the frequency range around the corner frequency. The group delay introduced by the filter is more pronounced near the lower frequencies. For the frequency range of 10-20 Hz, the group delay changes little from 35 to 30 ms (see table 6).

Table 6: Digital response of PRS1 with a 2 Hz L-4A Geophone

Frequency *Hz*	Period *sec*	Velocity Sensitivity *counts/m/sec*	Group Delay *sec*
100.00	0.01	0.185817E+06	0.00270
50.00	0.02	0.174316E+08	0.01132
33.33	0.03	0.143362E+09	0.02313
25.00	0.04	0.343744E+09	0.02835
20.00	0.05	0.503936E+09	0.02990
16.67	0.06	0.616509E+09	0.03098
14.29	0.07	0.695536E+09	0.03197
12.50	0.08	0.752078E+09	0.03301
11.11	0.09	0.793448E+09	0.03411
10.00	0.10	0.824355E+09	0.03529
6.67	0.15	0.900049E+09	0.04292
5.00	0.20	0.920644E+09	0.05397
3.33	0.30	0.894467E+09	0.08708
2.50	0.40	0.801339E+09	0.12870
2.00	0.50	0.666934E+09	0.16518
1.67	0.60	0.530001E+09	0.18956
1.43	0.70	0.414378E+09	0.20447
1.25	0.80	0.324724E+09	0.21465
1.11	0.90	0.257167E+09	0.22301
1.00	1.00	0.206360E+09	0.23094
0.67	1.50	0.820529E+08	0.27076
0.50	2.00	0.401925E+08	0.30608
0.33	3.00	0.136941E+08	0.35289
0.25	4.00	0.613078E+07	0.37779
0.20	5.00	0.323465E+07	0.39169
0.17	6.00	0.190417E+07	0.40001
0.14	7.00	0.121189E+07	0.40532
0.12	8.00	0.817572E+06	0.40890
0.11	9.00	0.577000E+06	0.41142
0.10	10.00	0.422107E+06	0.41326

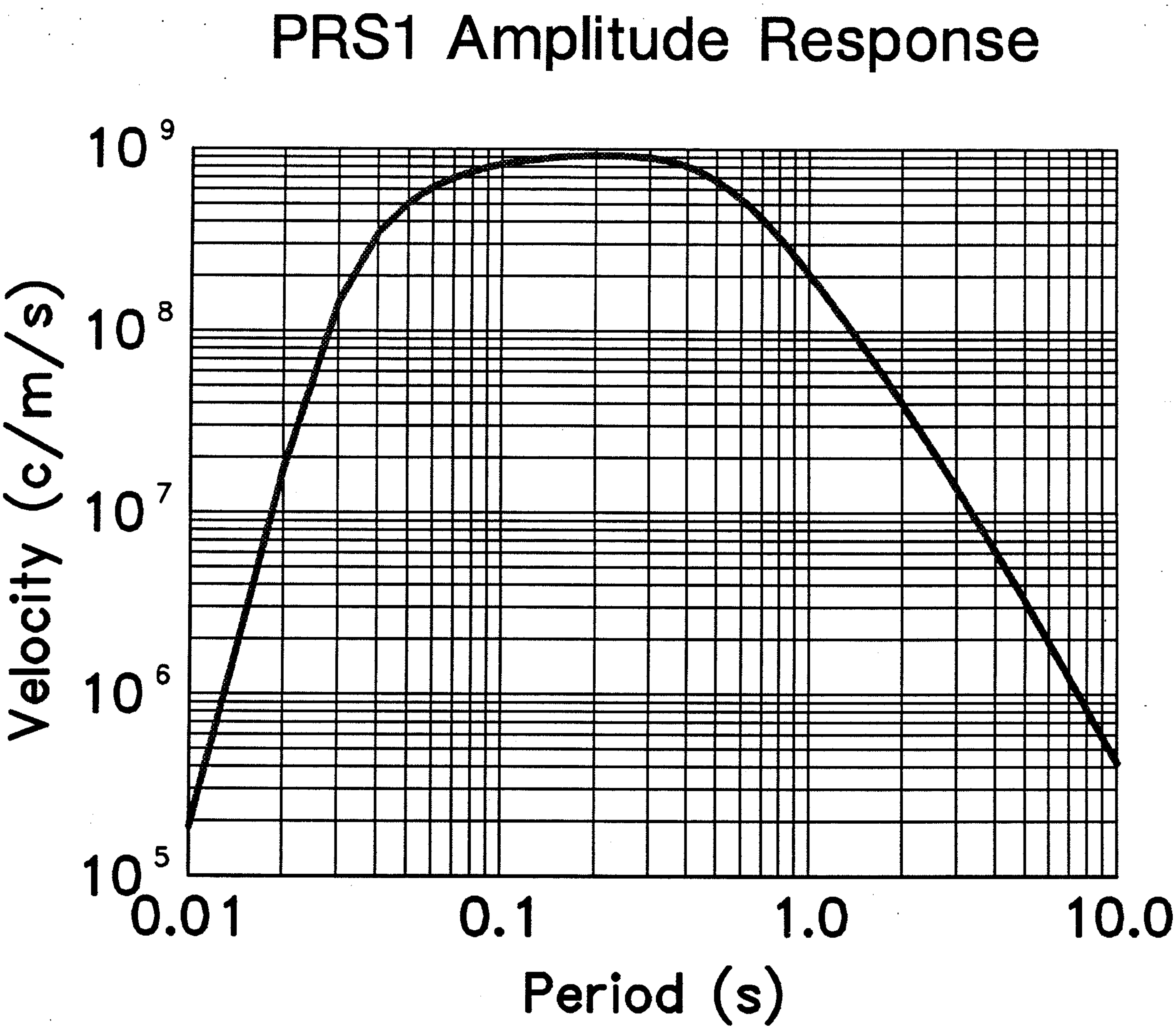

Figure 5: a - PRS1 Amplitude Response.

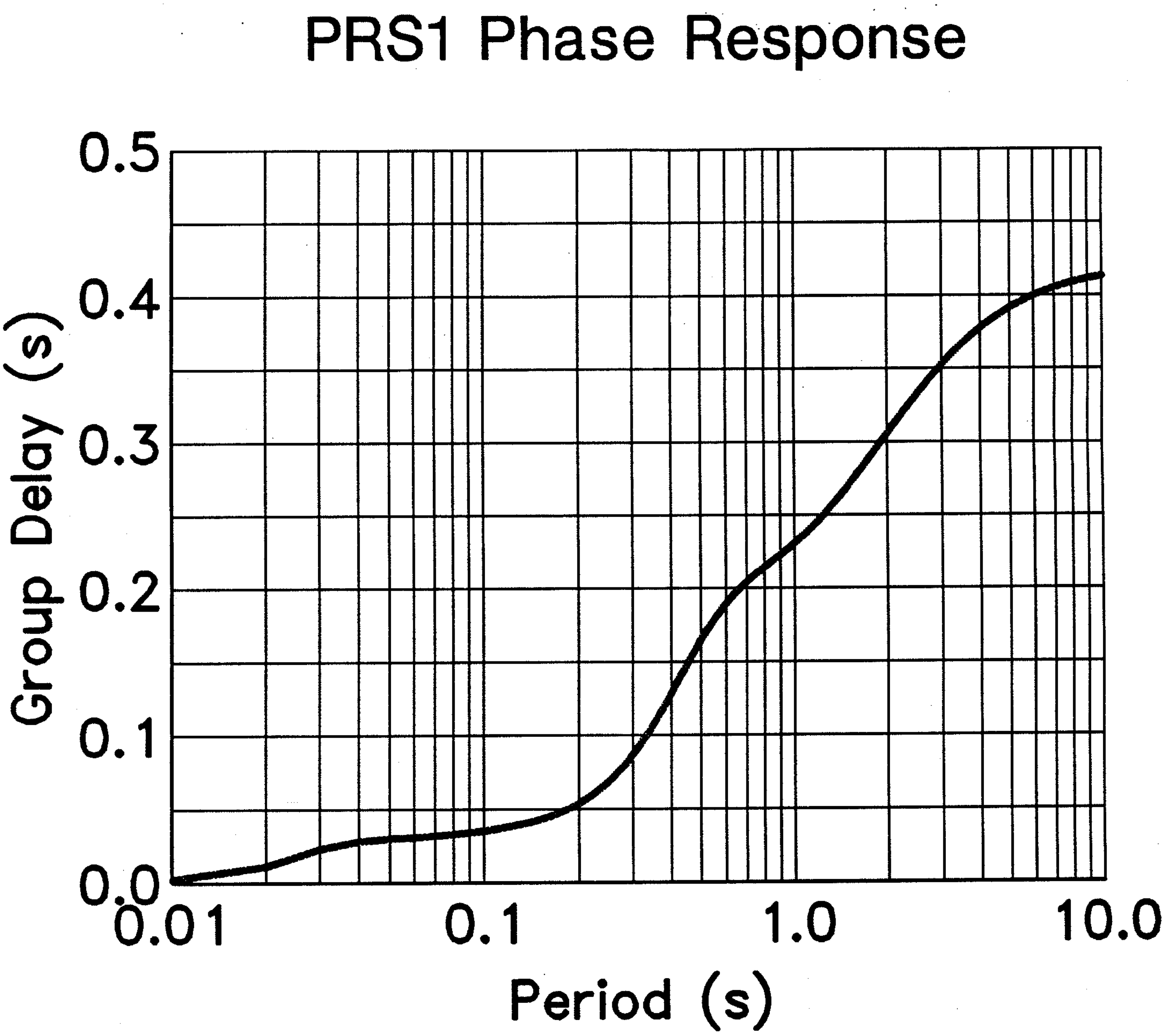

Figure 5: b - PRS1 Phase Response.

B PRS1 Emergency Restart Procedure

If a PRS1 stopped functioning prior to Data UPLOAD with LED B flashing (clock ticking and PRS1 keeping time) and LED C turned on (PRS1 = hung) then to get the PRS1 out of this "HUNG UP" state try Procedure A below.

If the PRS1 stopped functioning prior to Data UPLOAD with the LED lights neither flashing nor on (but PRS1 still powered up) then to get the PRS1 out of this "HUNG UP" state try Procedure B.

B.1 Procedure A

1. Disconnect the PRS1 from the Field Service Unit (FSU) computer.
2. Connect the RESET BOX to the PRS1 with the Bendix connector.
3. Plug the RESET BOX into the POWER SOURCE (wall outlet) and turn it ON. At this point if the LED C were to turn itself off (which implies that it is no longer hung up!), then skip step 4 and continue from step 5.
4. Press "ETN" button on the BOX a few times firmly.
5. Reconnect the PRS1 to the FSU.
6. Attempt to recover data again by running the UPLOAD option in LithoSEIS. There are no side effects to this procedure.
7. If one still can not recover data then try procedure B.

B.2 Procedure B

1. Disconnect the PRS1 from the FSU.
2. Connect the RESET BOX to the PRS1 with the Bendix connector.
3. Plug the RESET BOX into the POWER SOURCE (wall outlet) and turn it ON.
4. Press the "RESET" button on the BOX and hold it down for several seconds.
5. Reconnect the PRS1 to the FSU.
6. Run any communication program such as PROCOMM PLUS. Set active port to COM1 and port speed to 4800. Connect a FSU-COM cable between COM1 and the PRS1. If everything is done correctly so far, the PRS1 MONITOR prompt "*" should appear on the screen.
7. At the MONITOR prompt "*", type **C415G** followed by a carriage RETURN. Remember to use UPPER CASE letters only; also any other wrong address can mess up the PRS1 Running System with the possible result of never being able to recover the data from that PRS). At this point LED B should start flashing.

8. Exit from the communication program.
9. Attempt to recover the data again by running the UPLOAD option of LithoSEIS. Note that as a side effect to this procedure the clock correction is lost.

C PRS1 Startup Procedure

The PRS1 seismograph stores only 8 kb of information in its EPROM memory. The EPROM contains the Hitachi Monitor Program, the Self-test Program and tables, the CRC look-up table and the PRS1 communication program. The Hitachi Monitor Program is used to bootstrap the PRS1 and to establish communication with the FSU. All other instructions including the PRS1 running system that controls the operation of the instrument and the window table must be downloaded into the PRS1 from a FSU. Once the running system is started, the PRS1 communication program controls all communication with the FSU.

When the PRS1 seismograph is first turned on for programming, the front-panel LED lights show the self-test procedure and cycle through a sequence of binary counts for 8 seconds. If all tests pass, all LED lights will be turned off and the PRS1 is ready for programming. If any of tests fail, some of the lights remain lit and indicate the type of failure by their binary pattern. The most common failure is due to low battery voltage. A new set of batteries normally cures this problem. Table 7 shows the self-test LED pattern for the PRS1. Note that System Voltage and the Gain Select tests are not implemented.

Table 7: PRS1 Self-Tests

Test	Type	Comments
0	LED	All LED's are turned on and then off
1	System Voltage	Spare channels of the multiplexer are checked
2	CPU	CPU Branch Instructions Test
3	On Chip RAM	Read and write to testable address space
4	External Static RAM	Read and write to 2 kb of static RAM address
5	Dynamic RAM	Test the available banks of memory
6	EPROM	A checksum is computed and compared to a known one
7	Timer 1	Check with various program loops
8	Timer 2	Check with various program loops
9	Gain Select	Use a 50 mV voltage on channel 3 of multiplexer

After the self-test procedure is complete, the PRS1 system is ready and waiting for instruction from the FSU computer. Initially, it will report its serial number and await downloading of its running system and window table. After this, the PRS1 clock is synchronized to an external clock and the unit is ready for field deployment. For a live PRS1, the front panel LED's indicate operational status as shown in Table 8.

Table 8: PRS1 LED Indicators

LED A	Input polarity indicator
	+ ve on – ve off
LED B	Internal clock indicator
	Turns on for 100 ms on even seconds
LED C	Processor activity indicator
	Turns on during PRS1-FSU communication Turns on when recording Turns on during calibration
LED D	Error and calibration indicator
	Flash at 10 Hz to indicate memory overflow error Flash at 10 Hz to indicate clock overflow error Turns on during calibration on a master PRS1 Will flash during calibration on slave PRS1

D PRS1 Recording Parameters

Although the PRS1's were originally envisaged to access a maximum of 3 mb of RAM, they are only populated with 1 mb. There are a number of software restrictions on how this 1 mb can be utilized for recording a window table. The PRS1 recording parameters are shown in Table 9.

Table 9: Recording Window Limitations for PRS1 with 1 mb RAM

Parameter	Minimum	Maximum
Window Duration Limits (s)	1	540
Gap Between Windows (s)	10	32000000[1]
Number of Windows	1	130
Recording Capacity (s)	–	4320
Number of Channels	1	1
Recording Sample Rate (sps)	120	120
Recorded Window Size[2] (byte)	$1 * 120 * 2 + 240 = 480$	$540 * 120 * 2 + 240 = 129840$

1- Maximum Gap must be such that successive windows do not overlap.
2- Based on 2 bytes per sample, 120 sps and 240 bytes trace header.

D.1 PRS1 Trace Header

The recorded data in the PRS1's DRAM is stored in binary segments. When a unit is UPLOADED in LithoSEIS, a binary trace file is created for each recorded window. Each binary trace file consist of a 240 byte header and a number of data samples in packed binary format. The binary trace header is given in Table 10.

Table 10: LithoSEIS Binary Trace Header (240 bytes)

Type	Length bytes	Name	Comments
char	64	file_name[64]	Left justified with no path information
char	4	fsu_id[4]	Field Service Unit Id
long	4	window_start_time	Julian seconds counting from January 1
float	4	prs_t_correction	PRS time correction in seconds
long	4	maxval	Maximum sample value of this trace
long	4	minval	Minimum sample value of this trace
char	6	site_id[6]	Left justified, space filled
char	4	line_id[4]	Left justified, space filled
int	2	sample_rate	
long	4	number_of_samples	
char	1	channel	ASCII format: '1', '2', '3' or '4'
char	1	event_type	ASCII format: 'Z', 'T', 'C' or 'R'
long	4	shot_time	Julian seconds counting from January 1
char	4	shot1[4]	Only this 'primary' shot name filled in
char	4	shot2[4]	
char	4	shot3[4]	
char	4	shot4[4]	
char	4	shot5[4]	
float	4	trigger_time	Time in seconds past trace start time
char	1	chans_triggered	Bit map of channels triggered
char	1	junk	Unused field
float	4	detrigger_time	Not filled in for now
char	1	chans_detriggered	Not filled in for now
char	1	junk	Unused field
char	1	triggerable_chans	Bit map of channels checked for trigger
char	1	junk	Unused field
char	2	sensor_type[2]	Not filled in for now
char	4	sensor_azmth[4]	Not filled in for now
char	4	sensor_incln[4]	Not filled in for now
char	88	junk[88]	Unused field
char	2	endmarker[2]	
int=integer*2, long=integer*4, float=real*4, char=character data.			

E PRS1 statistics

The PRS1 instruments have been used in about a dozen seismic refraction surveys with remarkable success. In almost all of these surveys, the data recovery rate has been better than 99%. Some useful statistics are now available on battery performance and clock drifts for the PRS1 instruments.

E.1 PRS1 Battery Consumption

The PRS1 seismographs are powered either by a 12 volt lantern battery (prototypes) or 16 standard 1.5 volts D cells (EDA and Scintrex units). They draw a maximum current of 80 ma during recording and a modest current of 20 ma in 'sleep' mode. In a standard refraction experiment, the PRS1 seismographs operate for the duration of an entire experiment (normally 4 to 5 deployments in one month) with a set of fresh batteries. It is possible to extend the battery life to more than one experiment but this option is not practiced for data safety. Figure 6 shows typical battery voltage decay curves for 10 PRS1 units during the Southern Cordillera experiments of 1989. As this figure shows, after nearly 300 hours of usage, the battery volts dropped to about 11.5 volts which is well above the safe margins.

E.2 PRS1 Clock Drift

The TCXO clocks inside the PRS1 seismographs are synchronized to an external clock at the time of DOWNLOAD and are rated at the time of UPLOAD. The clock drift during the recording is assumed to be linear. Most of the clock drifts are well within design specifications and do not exceed $\pm 20ms$ during a standard 24 hours deployment. Occasionally, extreme weather conditions may cause erratic clock drifts. Figure 7 shows clock drifts for 10 PRS1 units during the Ice Island 1990 survey.

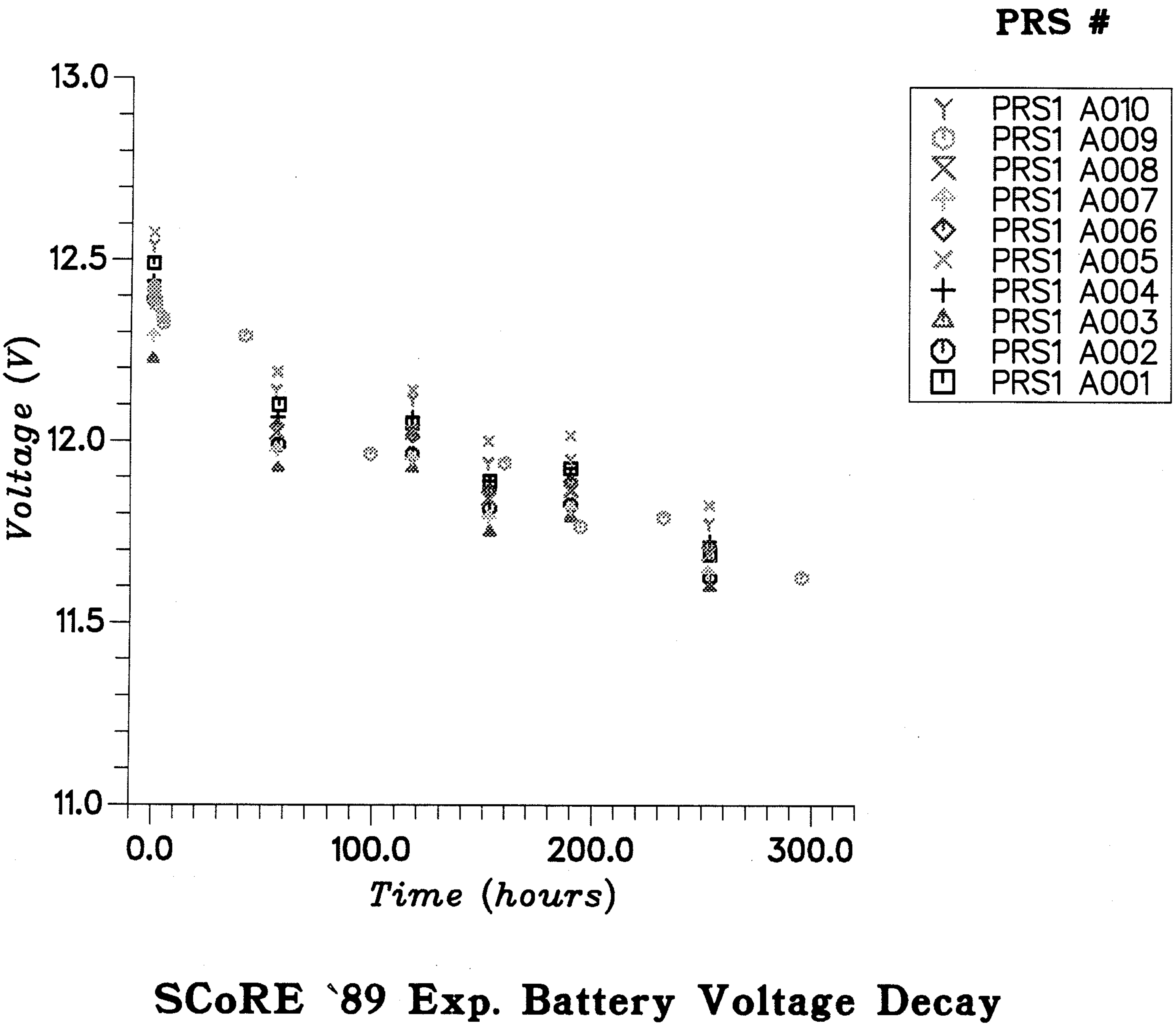

Figure 6: PRS1 Battery Voltage Decay.

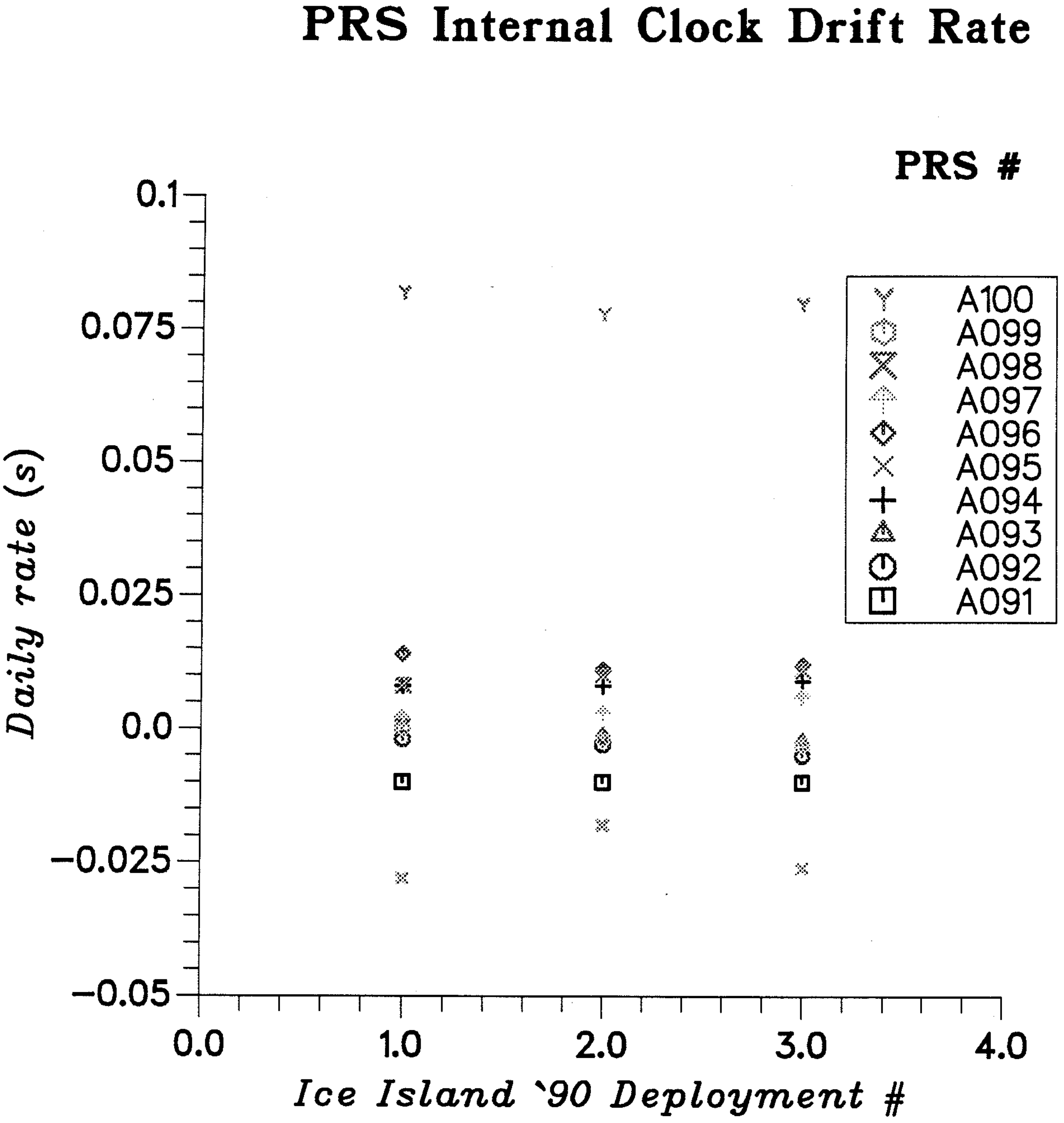

Figure 7: PRS1 Internal Clock Drift Rates.