Journal of open hardware

HARDWARE METAPAPER

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Geophysical Open Seismic Hardware: Design of a Vertical Seismic Profiling Instrument

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ABSTRACT

Geophysics can help provide guidance as we adapt to our changing environment. However, with advent of microelectronics, embedded systems and field programmable gate arrays, geophysical instruments have largely become a black box for most users: experiments are limited by the budgets that are available rather than the imagination of the geoscientific community. The solution we propose is to introduce affordable, modular and lightweight multi-component seismic instruments that can be deployed easily by researchers and explorers alike. We have developed a system that allows seismic data acquisition using very sensitive and compact accelerometers. These sensors are coupled to high-speed, multi-channel 24-bit downhole acquisition modules that were developed for this project. The control and synchronization of the system is engineered around microcontrollers that are compatible with the Arduino ecosystem. Communication between the parts of the system is done via a novel frequency modulated RS-485 communication protocol. This protocol makes it possible to send power and data over a wireline with only two conductors. The small diameter and the low cost of this system facilitates the deployment of a large number of channels or in configurations that may not be feasible with commercial equipment. The modular nature of the system makes it easy to adapt to other downhole applications or for draggable sensor arrays on surface. We consider that these efforts will contribute to the democratization of seismic survey in exploration, civil engineering and water prospecting to help reduce the global environmental impacts of human activities.

METADATA OVERVIEW

Main design files: Geophysical Open Seismic Hardware, in *Hardware* and *Firmware* directories.

Target group: Geoscientists and engineers.

Skills required: 3D printing – easy; electronics – intermediate; Programming – intermediate.

Replication: No builds known to the authors so far.

See section "Build Details" for more detail.

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KEYWORDS:

Geophysics; electronics; seismic; arduino

TO CITE THIS ARTICLE:

Mercier, A, Dupuis, JC, Giroux, B. 2023. Geophysical Open Seismic Hardware: Design of a Vertical Seismic Profiling Instrument. *Journal of Open Hardware*, 7(1): 3, pp. 1–14. DOI: https://doi.org/10.5334/joh.50

(1) OVERVIEW

INTRODUCTION

In geoscience, seismic methods are used because they allow to assess several types of information about the subsurface. This information include the geometry of geological units and discontinuities such as faults. Seismic methods have traditionally been used to locate and characterize hydrocarbon reservoirs. In recent years, researchers in other fields such as mineral exploration, geotechnical engineering, CO_2 sequestration, ground water and geothermal research have started to adapt the technologies to their field (Phillips and Bates 2008; Carreras et al. 2017; Costanza et al. 2021; Sirota et al. 2022; Clark and Page 2011).

In most seismic surveys, the seismic source and receivers are deployed at the surface, which allows to cover large areas. On the other hand, in Vertical Seismic Profiling (VSP), the source is at the surface while the receivers are fitted into pressure housings (shuttles) that are deployed in a borehole at regular intervals. The plurality of shuttles record simultaneously the wavefield along the borehole. The shuttles are linked to the surface via a wireline. Figure 1 shows the typical VSP acquisition geometry along with the principal elements of a shuttle. In addition to the acquisition module and sensor module, every shuttle has a pressure housing and a coupling mechanism. This allows the shuttle to be coupled mechanically with the borehole wall and to resist the high pressure environment. VSP is an effective technique to establish accurate time-depth relationships, which is needed to interpret surface seismic data (Hardage 2000). The resolution and scale at which the subsurface can be imaged with VSP cannot be matched by other geophysical imaging techniques.

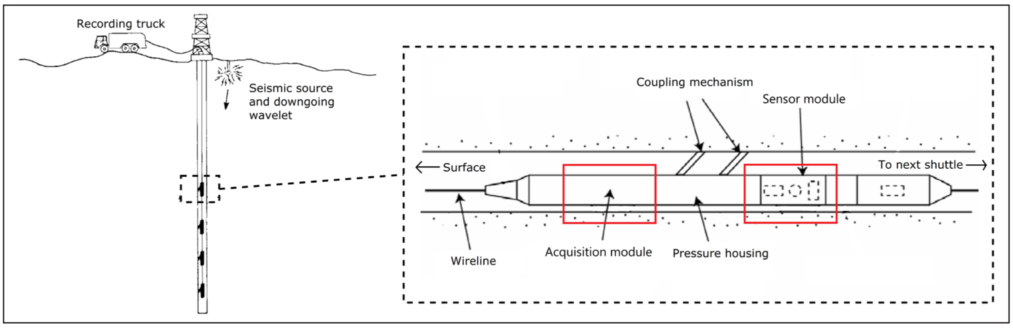

Figure 1 Typical acquisition setup and shuttle elements of a VSP tool. The acquisition module and the sensor module are housed inside of pressure vessels called shuttles.

In practice, however, we have found that the development of VSP imaging is struggling outside of the oil and gas industry. This is because the tools available on the market are not adapted to the needs of the geotechnical, groundwater and mining geoscientists. The oil and gas VSP instruments are destined for larger diameter wells and to operate at considerable pressures and temperatures. These tools are generally impossible to deploy in smaller borehole that are common in other fields of geoscience. At this point, the only solution afforded to geoscientists in other fields are rudimentary analogue VSP instruments tools that are only suitable for the first hundred meters below ground surface. We found that all of the instruments on the market are proprietary and this makes it impossible to modify or adapt existing systems for specific applications. We see this as a major barrier to the development of adapted solutions for geoscientists that are in non-traditional seismic fields.

The design guidelines for our Geophysical Open Seismic Hardware (GOSH) initiative were to design an open source acquisition module and sensor module shown in the red frames in Figure 1, suitable for a VSP instrument. The design constraints and requirements were set by the nature of boreholes encountered in non oil and gas research. Given the modularity of the solution we have designed, we expect that modules of our GOSH initiative will underpin the development of many future geophysical instruments.

OVERALL IMPLEMENTATION AND DESIGN

General requirements

Geoscientists that work outside of the field of oil and gas have access to two different drilling technologies, namely diamond coring and reverse circulation (RC) drill rigs. RC drills are mostly used for shallow boreholes (300 to 600 m (Harlsan 2019)) and thus are not discussed further. The diamond drills allow coring of the rock-mass. Although several different diameters are available, most mineral exploration boreholes are drilled to have a 75 mm internal diameter, according to the (Longyear NQ) standard. In our effort to minimize the size and weight of the tool, we have set our target dimension for the outside diameter of the VSP instrument to be 47.0 mm. This will allow the instrument to engage beyond the diamond bit (NQ) that has a hole in its center (47.6 mm ID). The aluminum pressure housing capable of sustaining the 10 MPa pressure (1000 m with mud of 1100 kg/m^3) provides a 40 mm ID. This imposes the first design constraint on the maximum width of the circuit boards.

The sensors must be able to measure seismic signals with a high-level of fidelity. This is complicated by the significant dynamic range of the seismic signals. There are no documented thresholds for the expected signal amplitudes for all of the different acquisition parameters possible. We chose to focus our specification on sensor sensitivity and noise level instead, as proposed by D'Alessandro, Scudero, and Vitale (2019) and Michael S. Hons (2008) . Their work established that quality data can be acquired if the sensors have a minimum sensitivity of 2 V/g (accelerometer) or 20 V/m/s (geophone). They also established the maximum noise for the sensors to 10 $\mu g/\sqrt{Hz}$ or 20 μV. These values take into account the USGS High Noise Model (Peterson 1993) that was taken into consideration in previous accelerometers development work (Milligan and Ho 2011).

The expected bandwidth of seismic signals, according to D'Alessandro, Scudero, and Vitale (2019) and Md Khir, Kumar, and Wan Yusoff (2016), ranges from 10 to 300 Hz. The ideal sensor would have a flat amplitude response over this entire bandwidth.

Seismic waves induce displacements in the three spatial dimensions of the medium in which they propagate. To reconstruct the wavefield, three mutually orthogonal sensors must be synchronized at each measurement station (sensor module). Each acquisition module must also be synchronized with others in the array in order to correctly identify arrival-times and collect quality data.

Survey depths, for the targeted applications, are not expected to exceed 1000 m (Greenwood et al. 2012; Wong et al. 2008; Denis et al. 2013). Even assuming a relatively slow velocity of 4500 m/s (Eaton et al. 2010), the record length is set to 1 second which is sufficient for impulsive sources and most conditions encountered by the targeted users of this system.

The wirelines used in borehole logging equipment have a limited number of conductors. The design of our system is based on the use of a 2 conductor wireline with a maximum length of 1000 m. Winches equipped with this configuration are typical of the equipment available to the targeted audience. Since only two conductors are available, digitization must be done downhole within every shuttle to ensure signal integrity. This also implies that digital data and power must share the same conductors.

For a typical wireline (3.175 mm diameter) the distributed resistance over 1000m is 80 Ohms and the distributed capacitance is 140 μF (A210124). To limit adverse effects, such as ohmic losses, the power delivered to the acquisition modules must be supplied at high voltage and low current. This imposes the requirement of a step-down circuit within every shuttle to transform the voltage (120VDC) into a usable 12VDC.

We also included the requirement that all integrated circuits (IC) of the system must be easily sourced from global suppliers. The firmware was designed to be as small and simple as possible, in order to be used as a building block for future systems.

INTEGRATED CIRCUIT SELECTION

The design of the acquisition and sensor modules housed in individual shuttles is divided into five main elements. These elements and their connections are shown in the conceptual diagram of Figure 2. This approach reinforces the concept of modularity. The following section presents all of the different parts of the modules according to the requirements that were established.

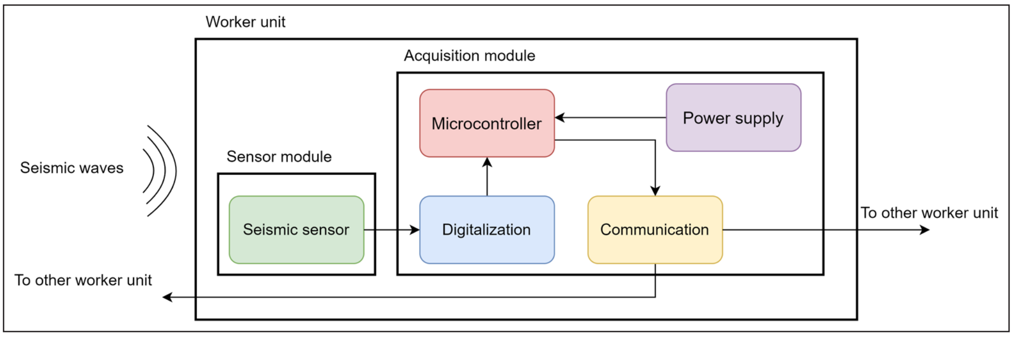

Figure 2 Conceptual diagram showing the main elements of the acquisition and sensor modules.

Seismic sensor

Geophones are well established in the seismic industry and are the standard bearer in this field. They measures particle velocity with great sensitivity, low noise and with a bandwidth meeting the requirements of the design. Orthogonal arrangements, however, are considerably bulky, which makes it difficult to meet the size requirements of the instrument.

MEMS (microelectromechanical systems) accelerometers have been developed for different applications (automobile (Eddy and Sparks 1998), aviation (Dong et al. 2010), medical (Gibbs, Wood, and Asada 2005) and personal electronics). They have found limited use in the seismic industry. The very small form factor of accelerometers makes it possible to assemble orthogonal sensors (sensor module) in a volume that is less than 1 cm^3. In order to identify the best accelerometer for the project, a number of them were tested using an in-house test apparatus. The results and the description of the test apparatus are found in the Sensor test bench section. These tests confirmed the earlier finding of M. S. Hons et al. (2008) who concluded that accelerometers can represent ground motion accurately and may be used to replace geophones in many applications.

In addition to their small-footprint, accelerometers offer a bandwidth that can span from DC to 1kHz. This makes it possible to calculate the orientation of the sensor module while it is in the borehole; a clear advantage for VSP imaging. The sensor module require power (75 mW) in order to measure signals and thus require additional wiring between the sensor module and the acquisition module.

The *Silicon Designs* 1521 MEMS accelerometer was retained for the design (SD 2021). This sensor has a sensitivity of 2 V/g and a noise level of 7 $\mu g/\sqrt{Hz}$. The bandwidth spans from DC to 600 Hz. The output voltage of the accelerometer is a differential analog signal that ranges between +4.0 to –4.0 V. Consequently, the acquisition module was designed to accommodate this voltage swing. In this first version of the acquisition module, a simple unity gain block is used. Later in the development, application specific gain block will be designed to optimize the use of the resolution and the bandwidth of the analog to digital converter (ADC).

Analog to digital converter

ADC transform an analog signal from the sensor to digital data that can be stored and processed by a computer. According to the sensor chosen, the smallest voltage increment to digitize in order to measure its noise level is $7\ \mu g \times \sqrt{300 - 10Hz} \times 2V/g = 238.4\mu V$. Thus, the minimum resolution of the ADC is $8\ V/238.4\mu V = 33556 \approx 2^{15}$ bits. High resolution ADC have limited digitizing speed. Therefore, a balance between resolution and speed must be found.

Given the requirements, we chose to integrate the AD7768 manufactured by *Analog Device* into our design. The specifications of this ADC are found in Figure 3. The resolution of the chosen ADC is higher than the requirements so the acquisition module remains versatile. The use of another sensor type, such as geophone with noise level around 200 nV (calculated from thermal noise), would require resolution up to $\approx 2^{25}$ bits. It is important to note that the AD7768 offers synchronized digitization of four or eight concurrent channels at a sampling frequency that can reach 256 kHz. This added speed is not required at present but it allows extra flexibility for the development of future geophysical instruments.

Channels	Sampling frequency	Resolution	Dynamic range	Programmable sampling frequency
4 or 8	256 kHz	24 bits	108 dB	Yes

Figure 3 Important specifications of the chosen AD7768 ADC.

Microcontroller

The microcontroller (MCU) is the brain of the system. It is used to configure the ADC and manages the communication between each IC of the acquisition module. The design includes an MCU in each shuttle. Given the digitization of three channels with a bit depth of 24 bits and a sampling rate of 4 kHz, the MCU must be able to address at least 1 MB of on-board memory in order to store a 1 second shot record.

The Teensy 4.0 manufactured by PJRC meets all of the specifications for inclusion in the design, including a compact footprint of (35 × 18 mm) (Teensy 2022). Engineered around NXP's MIMXRT1062DVL6A microcontroller (ARM Cortex-M7 at 600 MHz) the relatively high clock rate and the 32 bits architecture means that the MCU consumes more power than 8-bits MCU, but can easily cope with the tasks required. It supports the required SPI interface along with two USB interface and eight universal asynchronous receiver-transmitter (UARTs) that are used for external communication. The compatibility of the Teensy 4.0 with the popular Arduino ecosystem is also an important benefit. Custom libraries for this MCU and support are abundant and easily found on the internet.

Communication

The wireline used in the mineral industry was optimized to offer a light, rugged and cost effective means to deploy borehole instruments. These optimization parameters have negatively impacted the quality of the telemetry link that can be established. The RS-485 communication protocol can cope with the conditions imposed by this telemetry link and was retained for the design. It allows reasonable telemetry speeds (100 kbps at 1200 m) with good common-mode noise immunity. DC power distribution to the downhole acquisition modules over the same wire pair is achieved by implementing the frequency modulated variant (THVD8000) of the RS-485 protocol.

Power supply

As noted previously in the General requirements section, power must be sent at high DC voltages to limit ohmic losses along the wireline. We implemented power supply modules with switch mode converters to step-down the wireline voltage from 120VDC to 12 VDC. The LT7101 DC-DC converter manufactured by *Analog Device* was chosen as the core of the design. This part can source a maximum of 1 A (@Vin 13 to 120 V). This is current is 4 times higher then the peak consumption of an acquisition module. Thanks to its integrated switches, the LT7101 limits the electromagnetic interferences (CISPR 25 Compliant).

DESIGN OF PRINTED CIRCUIT BOARDS

The acquisition module elements were divided into three functional subgroups. Each subgroup was implemented on its own printed circuit board (PCB). The board of the acquisition module hosts the ADC and the communication elements. This board is a 4 layer design that aims to reduce the overall size of the PCB and provide the best decoupling between digital and analog signals and the transients that could be present on the power supply. The dimensions of this PCB is 40 by 160 mm which respects the objective (OD < 46 mm). Figure 4 shows the acquisition and sensor modules elements in a dummy pressure housing used for illustration. The second PCB is for the MCU which is mounted onto the acquisition module board as shown in Figure 4.

The third PCB hosts the power supply and all of the associated IC (40 × 85 mm). This gives flexibility to modify the power supply as required for a given application. These three PCBs constitute the acquisition module.

In addition, a PCB was designed as a breakout board for the accelerometers. These miniature PCBs (20 × 11 mm) route the pins from the accelerometers to suitable headers such that the power and signal can be routed from the acquisition module board to the sensor module. These PCBs are mounted into a 3D printed Galperin mount to maintain the geometry of the

DOI: 10.5334/joh.50

accelerometers within the pressure housing. This mount allows to fit 3 orthogonal sensors and their hardware symmetrically in a compact form factor (Galperin 1985). This geometry also allows the cables to go through the center of the sensor module. This greatly facilitates the assembly into a cylindrical pressure housing. The three populated PCBs and the mount constitute the sensor module.

Once fully assembled, the whole system fits into a 40 mm diameter tube that is 500 mm long.

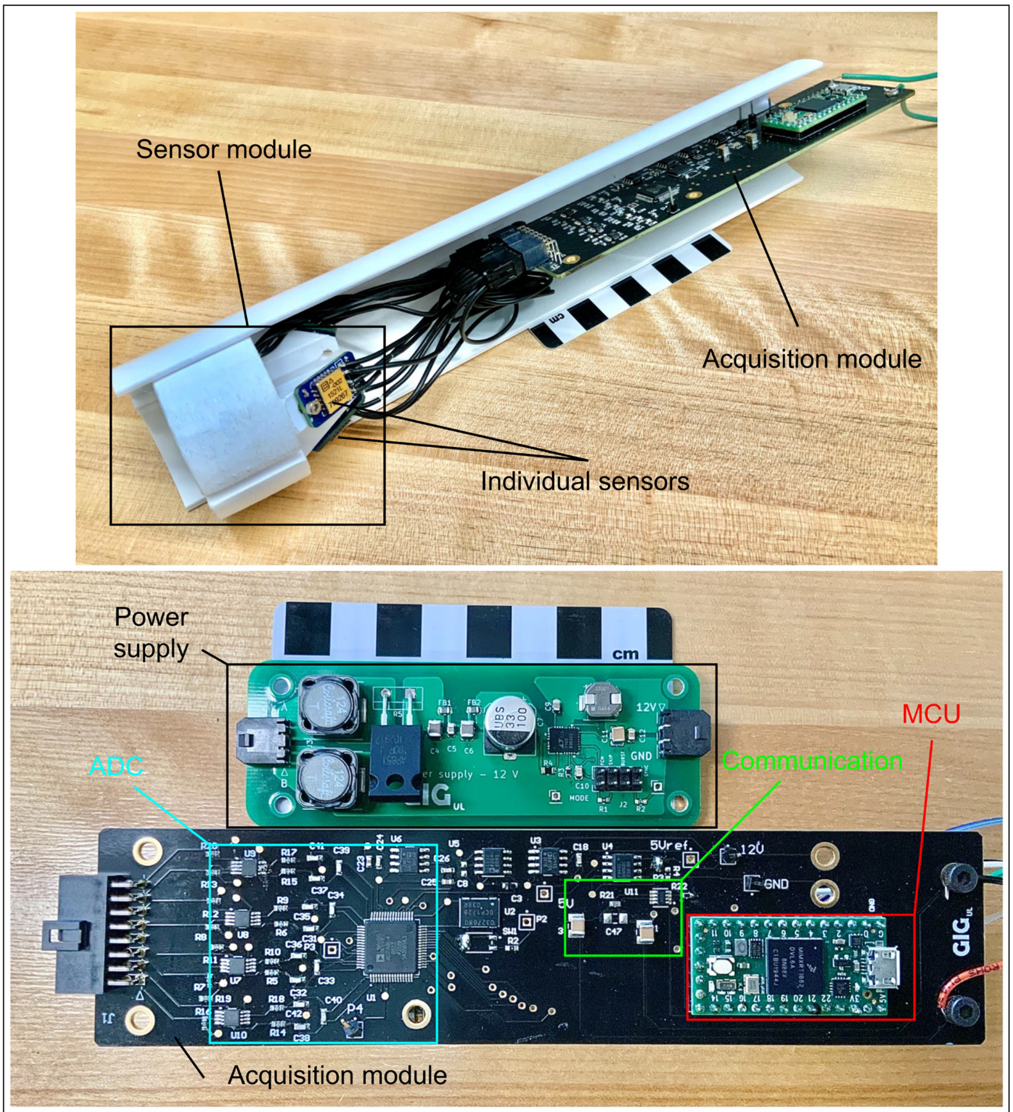

Figure 4 Demonstration of the integration of the acquisition module and sensor module PCBs in a dummy pressure housing. The acquisition module board (ADC, MCU and the communication) is slid into the rail as well as the sensor module with the accelerometers. Below, the elements of the acquisition module board are shown with the power supply PCB. Each black square on the rule is 1 cm.

FIRMWARE

The acquisition modules are arranged along the array that uses a parallel bus for power and communication. The first acquisition module of the array, which is at surface, is termed the leader unit. The subsequent units are worker units. The leader and worker units are essentially the same physical hardware, differing only in the firmware that is loaded and their position in the array.

In order to configure the worker units and retrieve data from them, we have written custom libraries for the ADC (AD7768). These libraries are compatible with the Arduino ecosystem. The high level functions required to perform a survey with the workers are:

1. *configure*
2. *arm*
3. *retrieve* data
4. *save* data to local file on the PC

Those functions were implemented in the main.py python script that runs on a portable computer (PC) that is connected to the leader unit at the top of the borehole in the recording truck (Figure 1). *Configure* allows the user to modify the acquisition rate, setup averaging windows, record length, and adjust the type of digital filter to use with the ADC. The main.py script sends these high-level commands to the leader unit which can transmit specific configurations instructions to the worker units via the 2 conductor wireline.

Two other programs are part of the software and are intended to run on either the leader or worker units. They both use custom Command and AD7768 library. The important functions of each program are detailed in Figure 5. The mainWorker.cpp lives on the MCU of the worker unit and is based on a real-time interrupt driven scheme to ensure minimal delay when a triggering event is received and when data is received from the ADC. The mainLeader.cpp lives on the MCU of the leader unit and receives the commands from the PC and transmits them to the worker unit.

Only the basic functions have been implemented thus far to make the system simple to use and yet highly configurable.

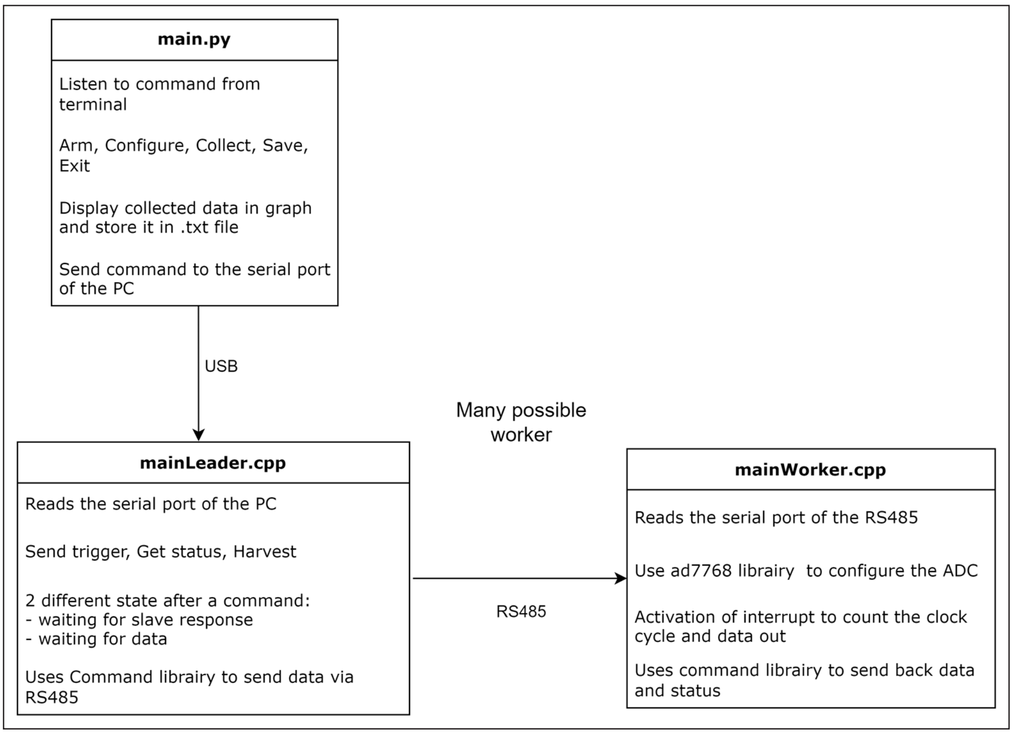

Figure 5 Firmware architecture of the GOSH. The firmware is divided in three main scripts. The main functions of every scripts are detailed in the boxes as well as the library used.

(2) QUALITY CONTROL

CALIBRATION AND TESTING

Sensor test bench

The use of accelerometers in consumer electronics have ushered in a plethora of models and makes of accelerometers. These sensors are available at a multitude of price points and different degrees of integration.

In order to compare some of the offerings, three low-cost, fully integrated digital accelerometers were retained for evaluation. These sensors were mounted onto a test bench along with a purpose built accelerometer (1521) manufactured by the *Silicon Designs* (D) (SD 2021). A geophone (HG-6HS, natural frequency of 4.5 Hz, sensitivity of 79 V/m/s) was also included on the test bench. The three generic low-cost digital devices under test were KX (A) (Kionix 2019), MMA (B) (NXP 2017) and LS (C) (STM 2017). The seismic source used was a sledgehammer on a steel plate. The signal acquired are compared to the reference geophone (GEO) in Figure 6. Geophones and accelerometers have intrinsic differences and thus cannot be compared directly against each other. It is possible to compare, however, the relative amplitudes and the signal-to-noise ratio of each signal acquired.

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DOI: 10.5334/joh.50

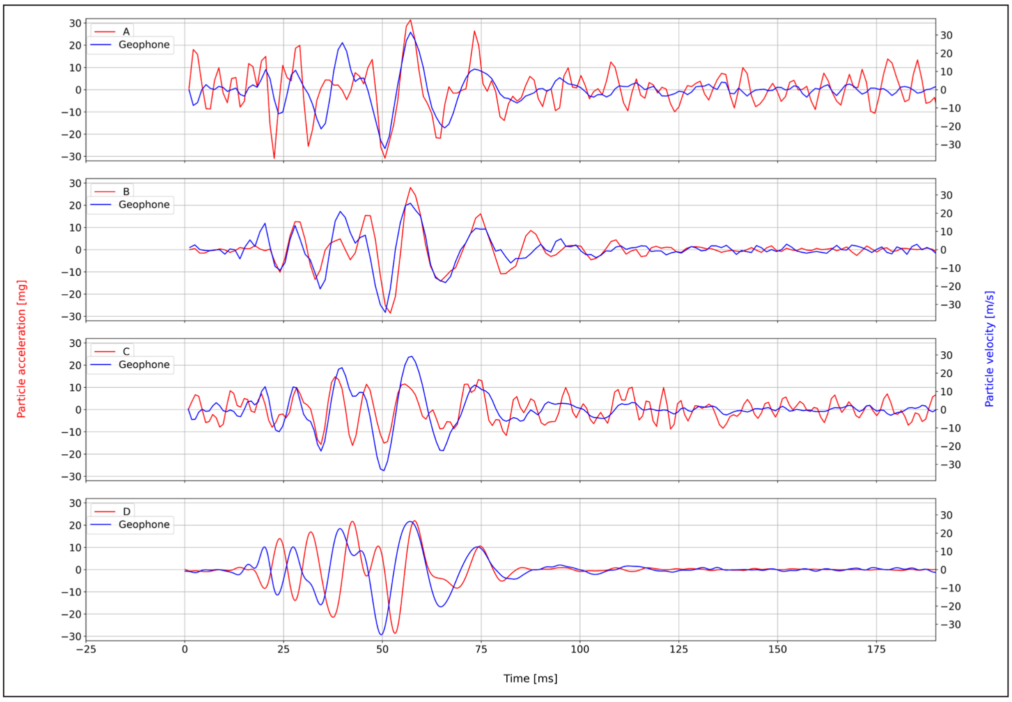

Figure 6 Seismic traces recorded from different accelerometers compared to a geophone. Seismic source is a sledgehammer and sensors where laid out at the surface and coupled with a 3D printed spike at 4 m from the source. Each sensor has a gain of 1 and a low pass filter with cut-off frequency of 300 Hz.

The results of the test show that all sensors have a similar sensitivity. Signal amplitudes for the seismic event that occurs between 0 and 100 ms are all comparable. The major difference is observed in the section between 100 and 250 ms, where there is no seismic signal arrivals. The noise amplitude of accelerometers A and C are considerably greater than that of accelerometers B and D. While the B accelerometer is a good performer out of the box, the low resolution (14-bit) of the integrated ADC and the fixed signal conditioning circuit cannot be modified. Further, the integrated ADC is limited to an acquisition frequency of 800 Hz which limits the signal acquisition bandwidth. The results of these tests lead us to conclude that the 1521 manufactured by *Silicon Designs* (D) is the best accelerometer for the design since it has a signal-to-noise ratio comparable with the geophone.

Acquisition module validation

The next step was to compare the performance of the GOSH acquisition module to a popular engineering seismograph. This particular 24 channel 24 bit seismograph is widespread amongst engineering consulting companies and academic institutions alike. We connected an arbitrary function generator (Agilent 33500B) to the input of each system. The impedance of the channels on the arbitrary function generator were set to match the impedance of the sensors. The first signals used as input to the acquisition module were a series of square waves with different repetition frequencies. We also programmed a representative Ricker wavelet that was used as the input signal to both systems. Figure 7 shows the result of these tests.

The signals digitized by the engineering seismograph are well captured, but the amplitudes were 12% greater than anticipated from the settings chosen. More importantly under-damped responses were present on the transitions of the square wave excitation. Our hypothesis is that, the cable and the geophone usually provides extra damping to the system which reduces this ringing. Through filtering of the signal we conclude that the ringing observed before the rising edge of a square wave and the slope between edges are likely due to the anti-aliasing filter that is present on the front-end of the engineering seismograph. The GOSH acquisition module has no such filter, which make it suitable for application with higher frequencies if aliasing signals are not present in the sensing environment. Given the confined environment of a borehole where a VSP array is deployed, this is a reasonable assumption.

The GOSH acquisition module shows an accurate measurement with no ringing or filtering artifact. The amplitudes are true with respect to the generator. However, an offset between 10 and 25 % of the reference signal can be seen in every waveform. This constant offset can be removed and would not affect the stacking operation nor the interpretation of the data.

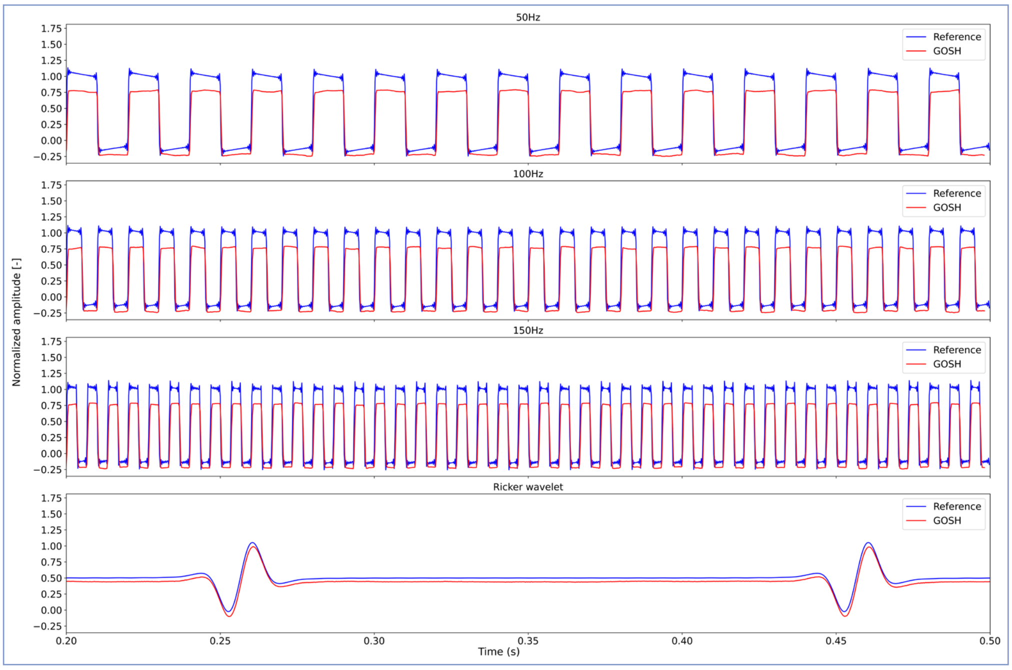

Figure 7 Comparison of the digitization between the reference system and the GOSH acquisition module. Amplitudes are normalized with respect to the function generator amplitude of 50 mVpp. Both systems were sampling at 4 kHz. The reference system has a low pass filter with cut-off frequency of 1600 Hz, while the GOSH acquisition module has no filter.

The Ricker wavelet data is used to determine the signal-to-noise ratio (SNR) for both systems. The noise can be measured by considering a portion of the traces where there is no signal. The engineering seismograph has a SNR of 60 dB over a bandwidth of 200 Hz. The GOSH acquisition module has a SNR of 48dB over a bandwidth of 2kHz. Reducing the bandwidth of the GOSH acquisition module to one comparable to the engineering seismograph would yield an SNR on the order of 68 dB. Thus it is possible to conclude that the GOSH acquisition module meets the state of the art in terms of accuracy and SNR. It can also accommodate higher frequency in an environment that is free of aliasing signals.

(3) APPLICATION

REFRACTION SEISMIC SURVEY

The pressure housing and coupling mechanism for the shuttles of the VSP tool are still in active development and were not finalized at the time of this writing. In order to test the performance of the system under field conditions, a small seismic refraction survey was acquired with the GOSH acquisition and sensors module along with the reference engineering seismograph. The goals of this field test were to record seismograms from both systems and compare the signals. These tests also validated the functionality of the 3-axis sensor module of the GOSH system via hodogram analysis.

The seismic source used for this survey was , once again, a sledgehammer. Sensor modules (3 axes) for each system were positioned side by side at 2 m station intervals. The custom 3-axis sensor module of the GOSH system were mounted onto spikes, similar to geophones. Multiple shots were acquired at 6 source offsets as shown in Figure 8.

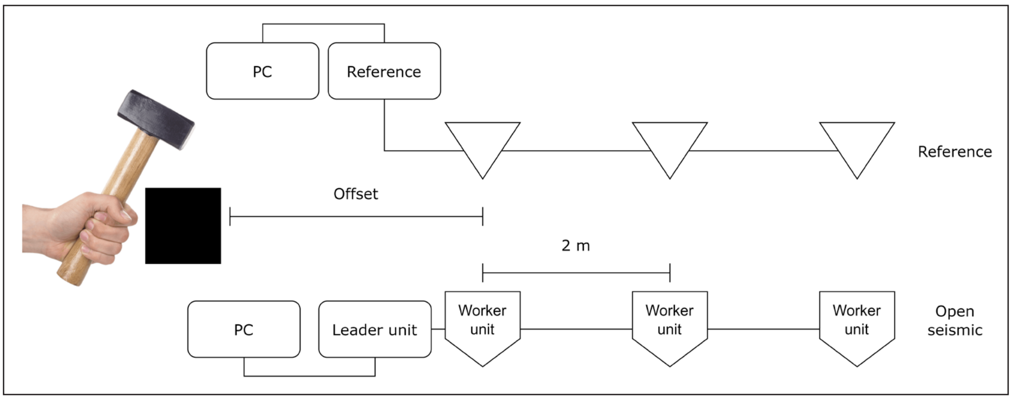

Figure 8 Refraction survey geometry. Sensor modules from both system are paired at 3 position with a 2 m interval. The Source is moved away to create multiple offsets and enhance spatial coverage. Eight shots are stacked for every position to increase SNR.

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The DC offsets were removed from the raw traces and the amplitudes were normalized for each trace. Data were then filtered using a 2 stage low pass filter. The first filter with a cutoff frequency of 0.5 times the Nyquist frequency (1600 Hz) was applied to the data of the GOSH system. This filter mimics the anti-alias filter of the reference system. The second low pass filter (250 Hz cut-off) was applied to the GOSH data to mimic the bandwidth of the signal acquired with the reference engineering seismograph. The results are shown in Figure 9.

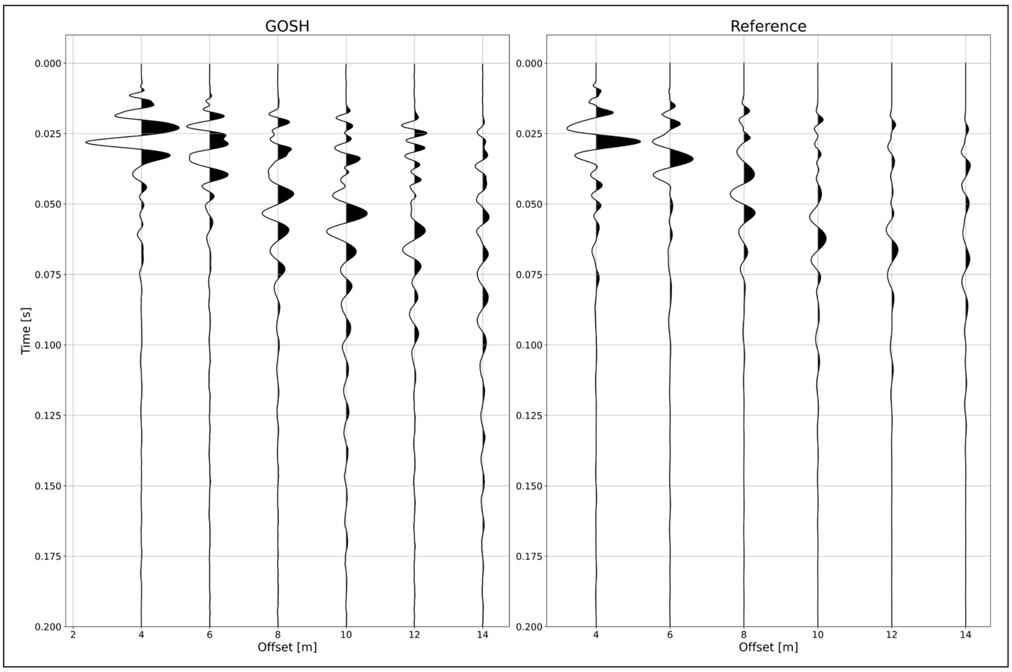

Figure 9 Seismogram of the reference and the GOSH system with multiple offset. Data acquisition frequency is 4 kHz for both system.

Both systems show clear first breaks and good SNR. From the analysis of the first-breaks of the direct arrival, the velocity of the uppermost layer can be determined. The velocity calculated for the GOSH system is 450 ± 10 ms while the reference system one is 430 ± 10 ms. These values are in agreement with velocity values of the observed unconsolidated weathered layer in that area (Dion 1986). The limited number of sensor modules is the principal cause of uncertainty for the velocity calculation.

Although the acquisition and sensor modules of the GOSH system meet expectations, we can see that the mechanical coupling mechanism that was 3D printed for the tests is likely the weak point in the design. This is visible from a low frequency oscillation at the GOSH sensor module that was placed at an offset of 10 m. We expect that an improved mechanical coupling mechanism will largely resolve this issue.

The tests used to determine the quality of the 3-axis sensor module relied on the same distribution of sensor modules than in the first tests, however the source was placed orthogonally to the acquisition line approximately 2 m off-line from the middle of the spread. The same 2 stage filtering procedure was applied to the raw data and only the data of the first 0.1 s were used to compute the hodogram in Figure 10.

The results from this validation test show that the custom 3-axis sensor module allows the identification of the direction of propagation of the seismic wave. It shows great potential for VSP survey, helping identify the origin of a seismic wave (direct, reflected or refracted). Even if great care was taken in the positioning of the individual sensors in the custom 3-axis sensor module, it is possible that slight misalignments may be responsible for the asymmetry in the propagation direction estimation observable between each hodogram. We consider that this uncertainty may be reduced by implementing the orientation algorithm from the DC component of the accelerometers.

The results of these tests show that the data acquired with the GOSH system are comparable to the reference engineering seismograph in terms of SNR and provide a greater bandwidth with faster digitization. This means that the GOSH system is a reasonable choice for users that cannot use the engineering seismograph because it does not fit within the constraints of their experiments. In the case of a VSP system, for instance, the engineering seismograph would not

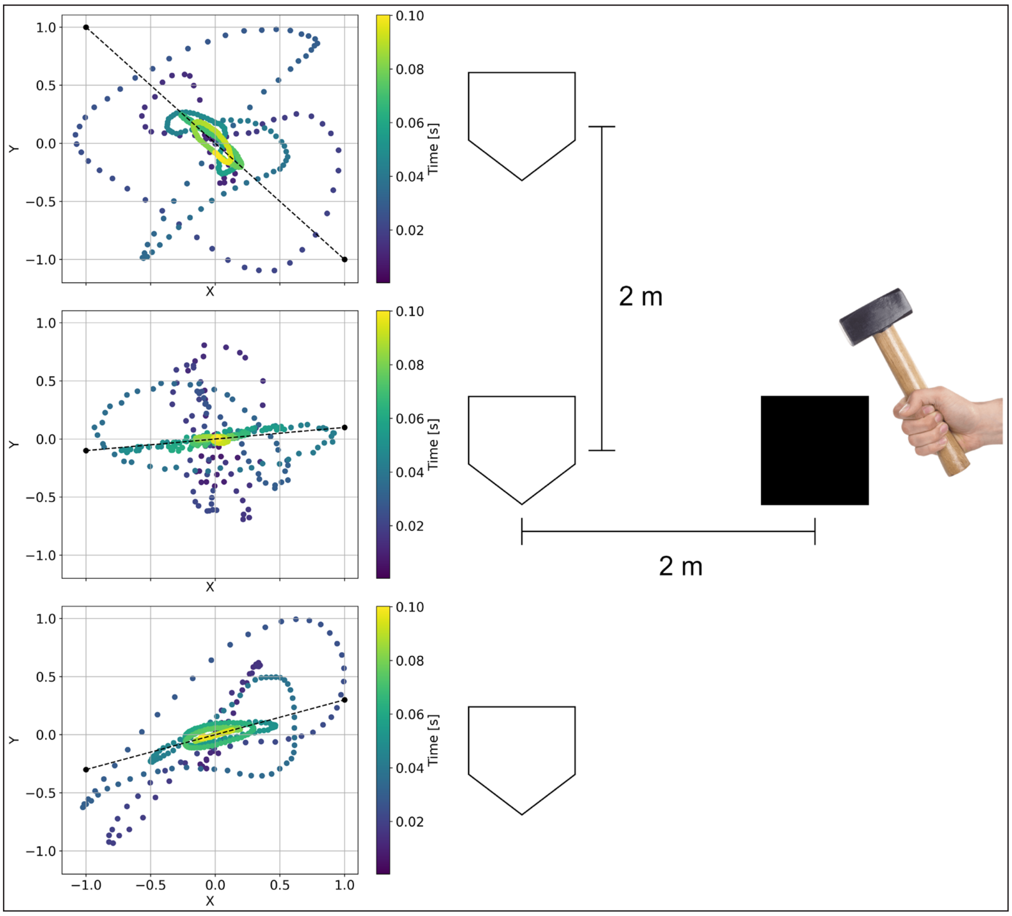

Figure 10 Hodogram of three sensor modules with an orthogonal source shot. Black dashed line represent estimation of the direction of propagation based on red dots. Multiple shots where performed to increase signal amplitude.

fit within the borehole and thus analogue signals would have to be transmitted up-hole over a specialized multi-pair cable. Long cable lengths to the surface would degrade the analog signal and compromise the quality of the signal that is acquired. The GOSH system makes it possible to acquire data with the same quality that someone could expect if the sensor array were deployed on surface. This is a significant step towards quality VSP data for the mineral and geotechnical industry.

REUSE POTENTIAL AND ADAPTABILITY

The GOSH system is a compact rugged multi-channel 24-bit acquisition and sensor module. Since many other geophysical tools are built around the same type of modules, we believe that the system can be adapted to a plurality of geoscientific acquisition scenarios (seismoelectric (Dupuis, Butler, and Kepic 2007), magnetometric resistivity (Jessop et al. 2018), electric resistivity, borehole electromagnetics, passive seismics). Originally designed as an acquisition module for a vertical seismic profiling equipment, it can easily be reconfigured to digitize analog signals from other sources. The ADC sampling rate could go as high as 256 kHz, which will satisfy most applications. The use of a sampling rate higher than 32 kHz, however, will require a more powerful MCU with more memory.

The principal modifications needed to adapt the current system to other applications are the firmware and the communication protocol. The use of an Arduino based MCU allows the user to easily modify the firmware, with great community support. It could be possible, for instance for someone to replace the RS-485 communication protocol with a wireless variant of Arduino (e.g. Arduino Portenta H7).

(4) BUILD DETAILS

AVAILABILITY OF MATERIALS AND METHODS

Integrated circuits of the modules can easily be sourced from usual electronic component distributor. The accelerometers must be purchased directly from the manufacturer. They are available for export but may be considered as controlled export outside of the United-States of

DOI: 10.5334/joh.50

America. The PCBs for acquisition and sensor modules, can be built at a common manufacturing facility that can produce 4 layer boards. A 3D printer can be used to print the Galperin mount used in the sensor module. Screws and miscellaneous hardware were purchased at a local hardware store and should be readily available anywhere in the world.

EASE OF BUILD

The assembly of the PCBs can take up to 5 to 6 hours for users familiar with soldering. The assembly requires surface mount as well as through-hole soldering.

OPERATING SOFTWARE AND PERIPHERALS

As detailed in the Firmware section, the software is based on the Arduino ecosystem. The MCU was programmed using the PlatformIO extension in Visual Studio Code. The PCB was designed using the KiCAD 6.0, which is released under the GNU General Public License(GPL) version 3.

DEPENDENCIES

- Main script uses Python 3.8 with standard libraries and the added pyserial V3.4.
- The Arduino code uses the Vector 1.2.2 library.
- The Teensy 4.15.0 framework is used to program the MCU from PlatformIO 6.1.3.
- The MCU firmware is uploaded to the Teensy with the Teensy Loader 1.55 from PJRC.

HARDWARE DOCUMENTATION AND FILES LOCATION

The development of the electrical circuit design (hardware folder) as well as the operating software (firmware folder) are documented in a single GitHub repository. The documentation about the assembly instructions and the main software function are also found in the repository (*doc* folder).

Name: Geophysical Open Seismic Hardware

Identifier: https://github.com/Geophysical-Instrumentation-Group-UL/Geophysical-Open-Seismic-Hardware

Persistent identifier: DOI. 10.5281.6977117

License: TAPR Open Hardware License for hardware and GNU General Public License v3.0 for software

Publisher: Arnaud Mercier

Date published: 24/07/22

(5) DISCUSSION

CONCLUSIONS

Compact and modular seismic sensor and acquisition modules were designed for the GOSH system. The GOSH system uses sensitive accelerometers that can be used to position the VSP instrument in space and acquire quality VSP data. The acquisition module designed for the project meets or exceeds the capabilities of the commercial engineering seismograph that was used for comparison. The Teensy microcontroller provides a familiar development environment for students and provides performance and flexibility. The frequency modulated RS-485 communication protocol allows to send power and signal on the same 2 conductor wire. All the ICs used in our design are available on the market and are inexpensive. The small size of the tool is a great step towards easier deployment at sites without elaborate rigging arrangements. We expect that the GOSH system will help democratize the use of VSP and other seismic survey in the mining industry but also for geotechnical, groundwater, and environmental projects that could also benefit from cost-effective VSP data. We hope that the GOSH system will be part of a broader initiative to promote open-hardware modular geophysical tools.

FUTURE WORK

As demonstrated here, the GOSH system can be used as a building block for many geophysical measurements. In the future, many updates and modifications are planned to make the system accessible to other groups. The following points are the development priority:

- New version of the acquisition module board to allow the user to use different Arduino or Teensy microcontroller. A generic connector will replace the specific microcontroller used on the actual acquisition module board, so that a microcontroller with built-in SD card for example, could be used within each worker unit. The size of the acquisition module board will also be reduced for an easier integration in a compact pressure housing.
- Implementation of a selectable communication speed to allow greater speed when the wireline allows it.
- Adjustable gain block to comply with other sensor modules (i.e geophone, flux-gate magnetometers).
- Development of the coupling mechanism and the pressure housing to host the acquisition and sensor modules described here.

FUNDING INFORMATION

The Geophysical Open Seismic Hardware initiative is brought to you by the Geophysical Instrumentation Group at Université Laval (GIGul) and is funded by the Fonds de Recherche du Québec- Nature et technologies (FRQNT), grant FT126607.

COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Carreras, Normandino, David Moure, Spartacus Gomáriz, Daniel Mihai, Antoni Mànuel, and **Ramón Ortiz.** 2017. "Design of a Smart and Wireless Seismometer for Volcanology Monitoring." *Measurement* 97 (February): 174–85. DOI: https://doi.org/10.1016/j.measurement.2016.11.013

Clark, James A, and **Richard Page.** 2011. "Inexpensive Geophysical Instruments Supporting Groundwater Exploration in Developing Nations." *J. Water Resource Prot*. 03 (10): 768–80. DOI: https://doi.org/10.4236/jwarp.2011.310087

Costanza, Antonio, Gioacchino Fertitta, William Yang, Giuseppe D'Anna, and **Claudio Chiarabba.** 2021. "PGS1, a New Low Cost and Low Power Portable Geophysical Station 'All in One.' Design and Test." *Ann. Geophys*. 64 (1): SE105–5. DOI: https://doi.org/10.4401/ag-8544

D'Alessandro, Antonino, Salvatore Scudero, and **Giovanni Vitale.** 2019. "A Review of the Capacitive MEMS for Seismology." *Sensors* 19 (14). DOI: https://doi.org/10.3390/s19143093

Denis, Michel, Charles Naville, Jean Claude Lecomte, Laurence Nicolettis, Eric Suaudeau, and **Quartus Snyman.** 2013. "3D VSP: A Mine of Information for Mining Exploration." *ASEG Extended Abstracts* 2013 (1): 1–4. DOI: https://doi.org/10.1071/ASEG2013ab044

Dion, Denis-Jacques. 1986. "La Méthode Sismique Réfraction Appliquée Au Génie Géologique." DV 85-06. Québec, QC: Gouvernement du Québec Ministère de l'Énergie et des Ressources Direction générale de l'Exploration géologique et minérale.

Dong, Y., P. Zwahlen, A.-M. Nguyen, F. Rudolf, and **J.-M. Stauffer.** 2010. "High Performance Inertial Navigation Grade Sigma-Delta MEMS Accelerometer." In *IEEE/ION Position, Location and Navigation Symposium*, 32–36. DOI: https://doi.org/10.1109/PLANS.2010.5507135

Dupuis, J. Christian, Karl E. Butler, and **Anton W. Kepic.** 2007. "Seismoelectric Imaging of the Vadose Zone of a Sand aquiferSeismoelectric Imaging." *Geophysics* 72 (6): A81–85. DOI: https://doi.org/10.1190/1.2773780

Eaton, David, Erick Adam, Bernd Milkereit, Matthew Salisbury, Brian Roberts, Don White, and **James Wright.** 2010. "Enhancing Base-Metal Exploration with Seismic Imaging." *Canadian Journal of Earth Sciences* 47 (May): 741–60. DOI: https://doi.org/10.1139/E09-047

Eddy, D. S., and **D. R. Sparks.** 1998. "Application of MEMS Technology in Automotive Sensors and Actuators." *Proceedings of the IEEE* 86 (8): 1747–55. DOI: https://doi.org/10.1109/5.704280

Galperin, E. I. 1985. "The Exploration Potential of VSP and the Prospects for Its Progressive Development." In *Vertical Seismic Profiling and Its Exploration Potential*, 373–427. Springer Netherlands. DOI: https://doi.org/10.1007/978-94-009-5195-2_13

Gibbs, Peter T., Levi B. Wood, and **H. Harry Asada.** 2005. "Active motion artifact cancellation for wearable health monitoring sensors using collocated MEMS accelerometers." In *Smart Structures and Materials 2005: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, 5765: 811–19. International Society for Optics; Photonics; SPIE. DOI: https://doi.org/10.1117/12.600781

Greenwood, Andrew, Christian J. Dupuis, Milovan Urosevic, and **Anton Kepic.** 2012. "Hydrophone VSP Surveys in Hard Rock." *Geophysics* 77 (5): WC223–34. DOI: https://doi.org/10.1190/geo2011-0490.1

Hardage, B. A. 2000. *Vertical Seismic Profiling: Principles*. Handbook of Geophysical Exploration, v. 14. Pergamon. https://books.google.ca/books?id=MpoZAQAAIAAJ.

Harlsan. 2019. "What Is Reverse Circulation Drilling?" Harlsan. https://www.harlsan.com.au/what-is-rc-drilling/.

Hons, M. S., R. R. Stewart, D. C. Lawton, M. B. Bertram, and **G. Hauer.** 2008. "Field Data Comparisons of MEMS Accelerometers and Analog Geophones." *The Leading Edge*. DOI: https://doi.org/10.1190/1.2954030

Hons, Michael S. 2008. "Seismic Sensing: Comparison of Geophones and Accelerometers Using Laboratory and Field Data." PhD thesis, University of Calgary. DOI: https://doi.org/10.11575/PRISM/2190.

Jessop, M., A. Jardani, A. Revil, and **V. Kofoed.** 2018. "Magnetometric Resistivity: A New Approach and Its Application to the Detection of Preferential Flow Paths in Mine Waste Rock Dumps." *Geophys. J. Int.* 215 (1): 222–39. DOI: https://doi.org/10.1093/gji/ggy275

Kionix. 2019. "KX132-1211." https://www.digikey.ca/en/products/detail/rohm-semiconductor/KX132-1211/10488054. https://www.digikey.ca/en/products/detail/rohm-semiconductor/KX132-1211/10488054.

Md Khir, M. H., Atul Kumar, Wan Ismail, and **Wan Yusoff.** 2016. "Accelerometer Sensor Specifications to Predict Hydrocarbon Using Passive Seismic Technique." *Journal of Sensors* 2016 (September). DOI: https://doi.org/10.1155/2016/4378540

Milligan, Donald J., and **Brian D. Ho.** 2011. "An Ultra-Low N Noise MEMS Accelerom Meter For." In *SENSORS, 2011 IEEE*, 1281–84. DOI: https://doi.org/10.1109/ICSENS.2011.6127185

NXP. 2017. "± 2g/4g/8g, Low g, 14-Bit 3-Axis Accelerometer." https://www.nxp.com/products/sensors/pressure-sensors/lpg-and-cng-gas-20-to-550-kpa/2g-4g-8g-low-g-14-bit-digital-accelerometer:MMA8451Q. https://www.nxp.com/products/sensors/pressure-sensors/lpg-and-cng-gas-20-to-550-kpa/2g-4g-8g-low-g-14-bit-digital-accelerometer:MMA8451Q.

Peterson, Jon R. 1993. "Observations and Modeling of Seismic Background Noise." Edited by U. S. Geological Survey. Open-File Report. DOI: https://doi.org/10.3133/ofr93322

Phillips, Dave, and **C. Richard Bates.** 2008. "Geophysics and Climate Research: High Resolution 2D Seismic Surveys Recorded at Lake Tana, Ethiopia — the Source of the Blue Nile." In *SEG Technical Program Expanded Abstracts 2008*, 1328–31. DOI: https://doi.org/10.1190/1.3059160

SD. 2021. "Compare Silicon Designs Surface Mount Accelerometers." https://www.silicondesigns.com/1521.

Sirota, Dana, Jeffrey Shragge, Richard Krahenbuhl, Andrei Swidinsky, Nicaise Yalo, and **John Bradford.** 2022. "Development and Validation of a Low-Cost Direct Current Resistivity Meter for Humanitarian Geophysics Applications." *Geophysics* 87 (1): WA1–14. DOI: https://doi.org/10.1190/geo2021-0058.1

STM. 2017. "LIS3DSH – STMicroelectronics." https://www.st.com/en/mems-and-sensors/lis3dsh.html. https://www.st.com/en/mems-and-sensors/lis3dsh.html.

Teensy. 2022. "Teensy 4.0." https://www.pjrc.com/store/teensy40.html. https://www.pjrc.com/store/teensy40.html.

Wong, Joe, Soo K. Miong, Laurence R. Bentley, and **Robert R. Stewart.** 2008. "VSP and Well Logs from a Shallow Test Well." In *21st EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*. Philadelphia, USA: European Association of Geoscientists & Engineers. DOI: https://doi.org/10.3997/2214-4609-pdb.177.53

TO CITE THIS ARTICLE:
Mercier, A, Dupuis, JC, Giroux, B. 2023. Geophysical Open Seismic Hardware: Design of a Vertical Seismic Profiling Instrument. *Journal of Open Hardware*, 7(1): 3, pp. 1–14. DOI: https://doi.org/10.5334/joh.50

Published: 15 February 2023

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