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PGS1, a new low cost and low power Portable Geophysical Station "All in One". Design and test

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Abstract

PGS1 is a new compact portable seismic station, designed at INGV OBS and Earth Lab, that is specifically intended for the deployment of dense arrays of seismographs on-shore. With its low cost, compact design, high data-quality and long battery life, PGS1 is a perfect solution for seismic monitoring networks. PGS1 design is based on a solid polypropylene suitcase, containing a complete data acquisition system, two battery packs and a photovoltaic panel. The new Earth Lab 5s medium-period seismic sensor is included. The whole system meets the IP67 standard requirements both in transport and in acquisition configuration. PGS1 is normally equipped with one battery pack, one more pack can be added inside the suitcase achieving 40 days of battery life. The station is equipped with a photovoltaic panel, useful to extend the deployment length. Inside the suitcase, there are compartments where to store the seismic sensor, the photovoltaic panel and all the cables. Therefore, the station is very easy to transport.

Keywords: Portable seismic station; Seismic monitoring network; PGS1; ETL3D/5s; OBS and Earth Lab.

1. Introduction

In the last three decades, the use of mobile digital seismic stations has become increasingly widespread both for active and passive seismological studies. Some manufacturers already offer small-size and low-power portable seismic stations. Being ready-to-use is probably their greatest advantage. With no development time to wait for, the project for a new seismic array can quickly move into the phase of deployment. Of course, this benefit should be weighed against unit price, because portable stations can be quite expensive. In order to reduce costs, researchers often build custom portable stations by assembling off-the-shelf parts, but seldom this approach leads to compact and power efficient solutions; in other cases, some obsolete portable seismic stations were updated introducing new commercial data acquisition systems [Castellano et al., 2007; Cappello et al., 2007]. Here the main benefit comes from reusing components, which helps cut down on cost at the expense of performance. However, portable stations should be suitable for working in forests, snow, deserts and other extreme environments where size, weight and power consumptions considerably matter. The considerations above suggest the existence of a gap between commercial stations, technologically advanced but expensive, and custom stations, cheap but suboptimal. Filling the gap means starting new designs, with low production costs, aimed at maximizing ease of transport and power efficiency. In this regard, some attempts have already been made [Jing et al. 2015; Chiu et al., 1991].

The main purpose of this work is to inform the scientific community of the new low cost and low power Portable Geophysical Station PGS1 "All in One". PGS1 is the result of an effort to develop an effective solution for dense seismic arrays. One of the project goals was to simplify the logistics of deployment, by designing a small size and low weight station. Remarkably, the whole station weighs only 11 kg and occupies a volume of just 28 L. The project, including the production of a first batch of 10 units, was funded by the *Ministero per lo Sviluppo Economico* (MiSE). The development and assembly was carried out by the OBS and Earth Lab (formerly OBS Lab) of the Geophysical Observatory of Gibilmanna.

In order to reduce the development time and production costs, some devices and parts were chosen among products available on the market and customized, some others reused from other projects and others designed from scratch. All new parts were made in outsourcing production. The power supply system consists of a photovoltaic panel, a charge regulator, a battery pack (or two if needed) and a step down switching converter. All these parts were found on the market. The photovoltaic panel was customized so that it can be secured to the station during transport and acquisition. The acquisition system consists of the Earth Lab 5s medium period sensor [Fertitta et al., 2020] and the INGV SeismoLog recorder; both have been entirely designed at the OBS and Earth Lab. The sensor was developed within the MiSE project, integrating low power electronics, designed for marine applications, with a new housing. The recorder, produced with EMSO MedIT funds, was originally intended for Ocean Bottom Seismometers (OBS). In 2014, a fleet of OBS', equipped with SeismoLog recorders, took part to the TOMO-ETNA experiment [Coltelli et al., 2016]. As the electronics was originally intended for marine applications, the station has low power consumptions, 500mW on average. The battery life is 40 days with two battery packs.

All 10 PGS1 units except one reflect the original design, the same described above. The remaining one is reserved for testing new ideas. To give an example, this unit is currently equipped with a Single Board Computer (SBC), a Raspberry Pi3. The SBC allows downloading real time data in miniSEED format, through a SEEDLink server over an Ethernet link. The SBC is powered off when the user interface is inactive, so that its power consumption, which is quite high, does not affect battery life noticeably. Within the EWAS project, the Catania Urban Seismic Observatory (OSU-CT) work group has contributed to this testing by writing and updating the software running on the SBC.

In transport mode, all the parts of the station fit inside a commercial polypropylene suitcase. The suitcase was customized by opening holes for cables and connectors, and adding supports for the photovoltaic panel. A metal box was designed to support the electronics and the sensor inside the suitcase.

PGS1 is specifically intended for the deployment of dense arrays of seismographs. It can perform different monitoring tasks, detecting local and regional earthquakes, either natural or induced by industrial activities [MISE, 2014]. PGS1 produces high quality data and exhibits a long battery life. With its low cost, compact design and high power efficiency, PGS1 is a perfect solution for building seismic monitoring networks. It is intended for harsh natural or artificial environments, including zones damaged by earthquakes.

2. 3D-Modeling

The design of PGS1 is based on a solid polypropylene suitcase, Explorer Cases model 3818, and includes the new Earth Lab 5s medium period sensor, a recorder, one or two rechargeable Li-Ion battery packs, a photovoltaic panel, a battery charge regulator and other power supply circuits.

The whole system meets the IP67 standard requirements, both in transport and in acquisition configuration. On one side of the suitcase, are two bayonet-type connectors, one for the seismic sensor and one for the photovoltaic panel. Each one has a rubber o-ring at the interface with the suitcase. The o-ring guarantees water tightness, in compliance with the IP67 standard.

In the engineering process, the PGS1 was entirely 3D modeled both in transport (figure 1a) and in acquisition configuration (figure 1b); the 3D modeling allowed an easy choice of commercial components, an effective customization of some of them and a correct design of the original parts. The PGS1 was 3D modeled also with the purpose of simplifying the production and the assembly process [Costanza et al., 2017].

3D software tools were useful in different ways. One of the project goals was making sure that a user would feel comfortable carrying the suitcase. This would mean walking to a distant place, while holding the station by its handle. In this scenario, the suitcase would be in the so-called transport configuration, with the sensor, photovoltaic panel and cables stored inside, as shown in figure 2. Achieving the goal above not only means keeping weight low but also balancing. In order to balance the suitcase, the center of gravity must be directly below the handle. Otherwise, a neat moment of force would arise. As a result, the suitcase would tend to turn and the user would have to exert an opposite moment to keep the suitcase flat, which could cause premature fatigue in the hand and arm. In figure 2, the green dots represent the projections of the center of gravity on the principal views. figures 2a-c show that the center of gravity is located directly below the suitcase handle. Achieving such an accurate placement is all but a trivial task, because the location of the center of mass depends on the placement of all the components inside the suitcase. In addition, every time a component is moved to a different position, the center of gravity must be updated. The use of 3D tools made it possible to try different configurations, focusing on the solution and letting the software do the hard work.

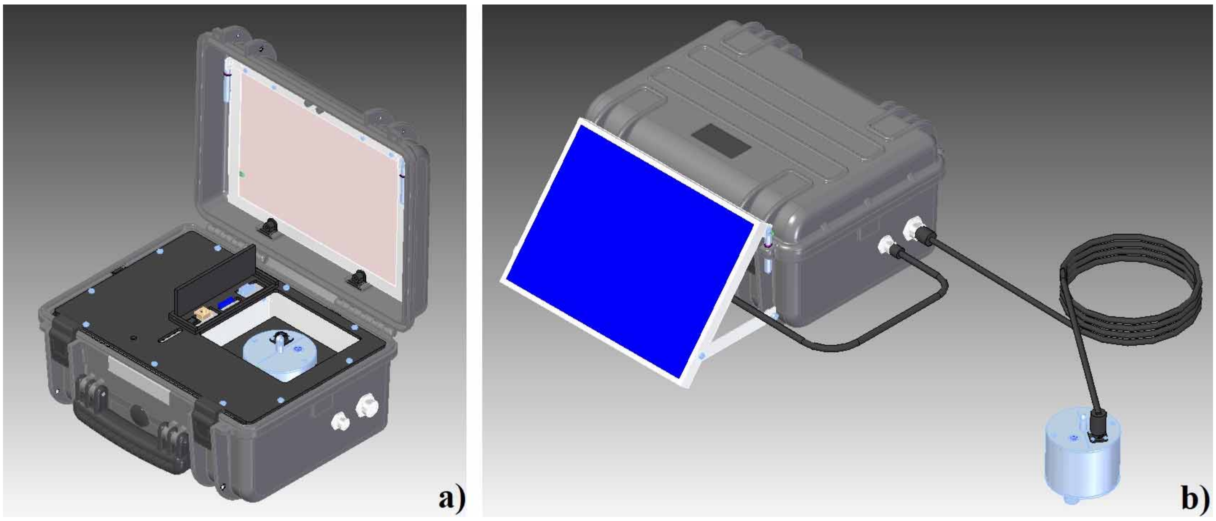

Figure 1. 3D assembly model of PGS1; a) transport configuration (with open suitcase and without pocket), b) acquisition configuration.

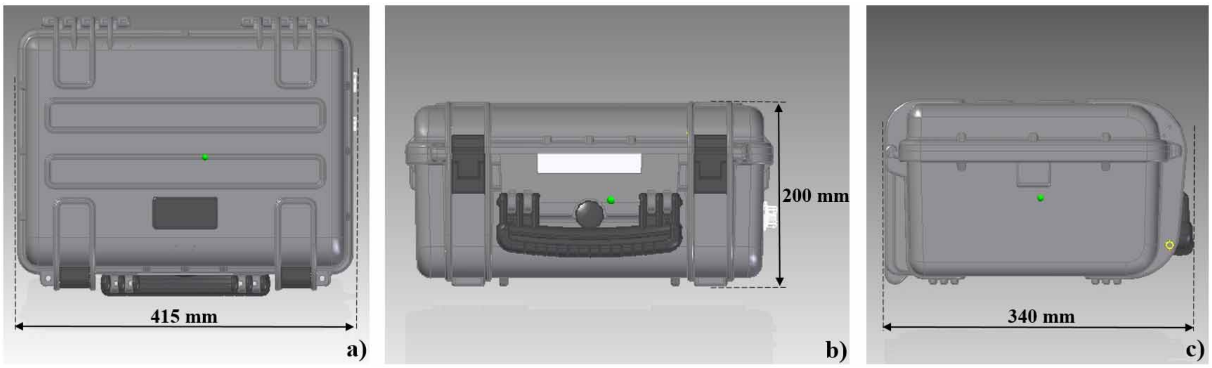

Figure 2. Position of the centre of gravity (green dot) and dimensions in transport configuration; a) top view; b) front view; c) lateral view.

The photovoltaic panel, used to extend the deployment length beyond 40 days, is visible in figure 1a-b (in the two configurations). The 3D-modeling allowed choosing a commercial panel that could be adapted to the two different configurations.

During transport, the panel is stored inside a pocket, attached to the inside of the suitcase lid. During data acquisition, the panel stays outside the suitcase, gathering solar energy. In order to provide a continuous power income, the panel should maintain a stable tilt and orientation, even resisting moderate winds. A custom frame, fixed to the panel's original frame, helps secure the latter to the suitcase. On the suitcase shell, are four anchoring points, where it is possible to fasten the custom frame. This system holds the panel at a 52° angle of inclination to the horizontal. As the custom frame is foldable, the panel and frame can still fit inside the internal pocket. Noteworthy, the panel installation requires no tools (figure 3). The photovoltaic panel (1) is connected, by means of two hinge-screws, to two foldable brackets (2). By means of an auxiliary frame and two hinge-screws, it is also connected to two foldable pegs (3). To assembly the panel on the suitcase, the operator must simply open the pegs (3), insert them in the appropriate holes of the suitcase, open the brackets (2) and fit them into the relative pins fixed to the case. The mechanical constraints ensure a stable connection and a fixed angle of inclination.

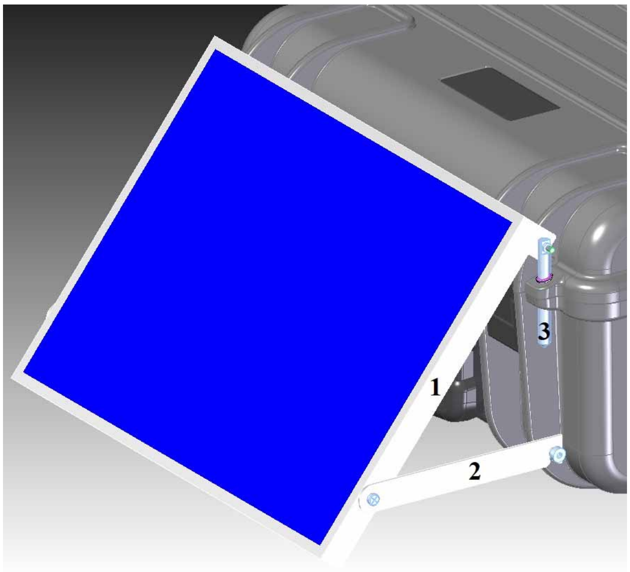

Figure 3. Fixing system of the photovoltaic panel to the suitcase, during the acquisition configuration.

3D-modeling was essential also to define a convenient distribution of the electronic devices inside the suitcase. One of the main goals was to preserve the data-quality, while keeping the assembly procedures as simple as possible. Figure 4 shows a photo of the real PGS1. The plastic panel, that normally hides from view the electronic devices, was removed to show internal elements. An aluminum box (1), open on the top side, provides support for the electronics. The box base is fitted with a set of threaded holes, making it easy to fasten each device with screws. Another set of screws, evenly distributed along the upper edges, fastens the box to the suitcase. The sensor compartment (2) occupies the box upper-right corner, leaving an L-shaped space available inside the box. The recorder (3) is in the upper left corner of the box, and the frequency reference (4) is installed on top of it. The concerns about data-quality came from the analog inputs of the recorder and relative cables, possibly picking-up noise from other electronic sources. The power supply circuits, on the other hand, are perfect candidates to generate ElectroMagnetic Interference (EMI). The recorder is in the upper part of the "L" vertical branch, oriented with the analog inputs facing upwards. The analogue cables run for the most part in between the suitcase and the external walls of the box, except for the short segment that goes to the recorder inputs. The switching regulator (5) is directly below the recorder, followed in counterclockwise order by the charge regulator (6) and batteries (7), the farthest object from the analogue inputs. As the battery voltage is quasi-static in normal use, the process underlying noise generation depends on the applied load. Lithium batteries are close to ideal voltage sources, thanks to an extraordinary low Electronic Series Resistance (ESR). When connected to a switching circuit, they will be able to source very large current pulses. The magnetic fields, associated with the pulses, could be coupled to external circuits producing noise. The considerations above apply to the presented station too, because the charge regulator is actually a switching circuit. However, with the battery and its cables far from the analogue inputs, the risk of picking-up induced noise is very low.

The design of the box posed the problem of providing adequate support for the sensor, the most sensitive part to mechanical shocks, during transport. For this purpose, the sensor compartment features a shockproof padded seat that can hold the sensor securely.

The angle profile (8), constrained to the sensor compartment, holds the serial port connector, SD card slot, Ethernet connector, on/off switch and a set of four LEDs.

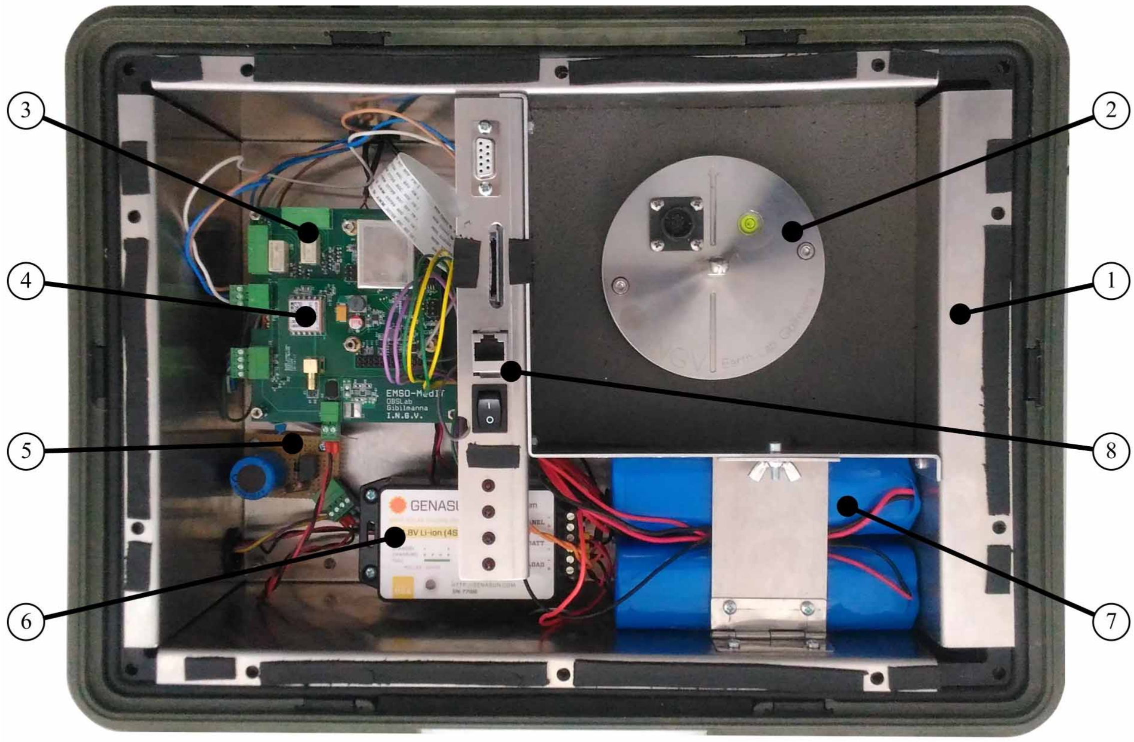

Figure 4. PGS1 without closing panel.

3. The electronics

The following sections will briefly describe the PGS1 subsets and the user interface.

3.1 SeismoLog recorder

PGS1 is equipped with SeismoLog, a geophysical recorder developed by the OBS and Earth Lab, INGV. Before SeismoLog, INGV had already produced two recorders, GAIA [Cardinale et al., 2010] and GILDA [Giudicepietro et al., 2015; Orazi et al., 2006; Orazi et al., 2008]. Both projects met their goals, releasing reliable instruments, which served and are still serving INGV's needs in different fields. However, more than a decade ago, the OBS and Earth Lab, undertaken the construction of a new class of marine instruments for geophysical monitoring, the Ocean Bottom Seismometers (OBS). These instruments, with the potential to bring a sensible improvement in the study of marine geophysics, were battery powered and had to work autonomously for long time. The new requirements on power consumption led to rule out both GAIA and GILDA as viable solutions.

From the beginning, the OBS and Earth Lab has acquired different off-the-shelf solutions. While this strategy worked well in most cases, some limitations, related to the use of commercial instruments, became also evident. Often, data acquisition systems are required to implement custom functions, which seldom the manufacturer can provide for an affordable price. In 2014, the OBS and Earth Lab released the first version of SeismoLog. The new recorder consumed only 120 mW and was intended for passive geophones. In the subsequent years, a new version followed, whose analogue inputs were suitable for active sensors, including broadband seismometers. However, the overall consumption increased to 200 mW. Therefore, the two versions coexisted for different applications. A simplified diagram of SeismoLog, broadband version, is shown in figure 5.

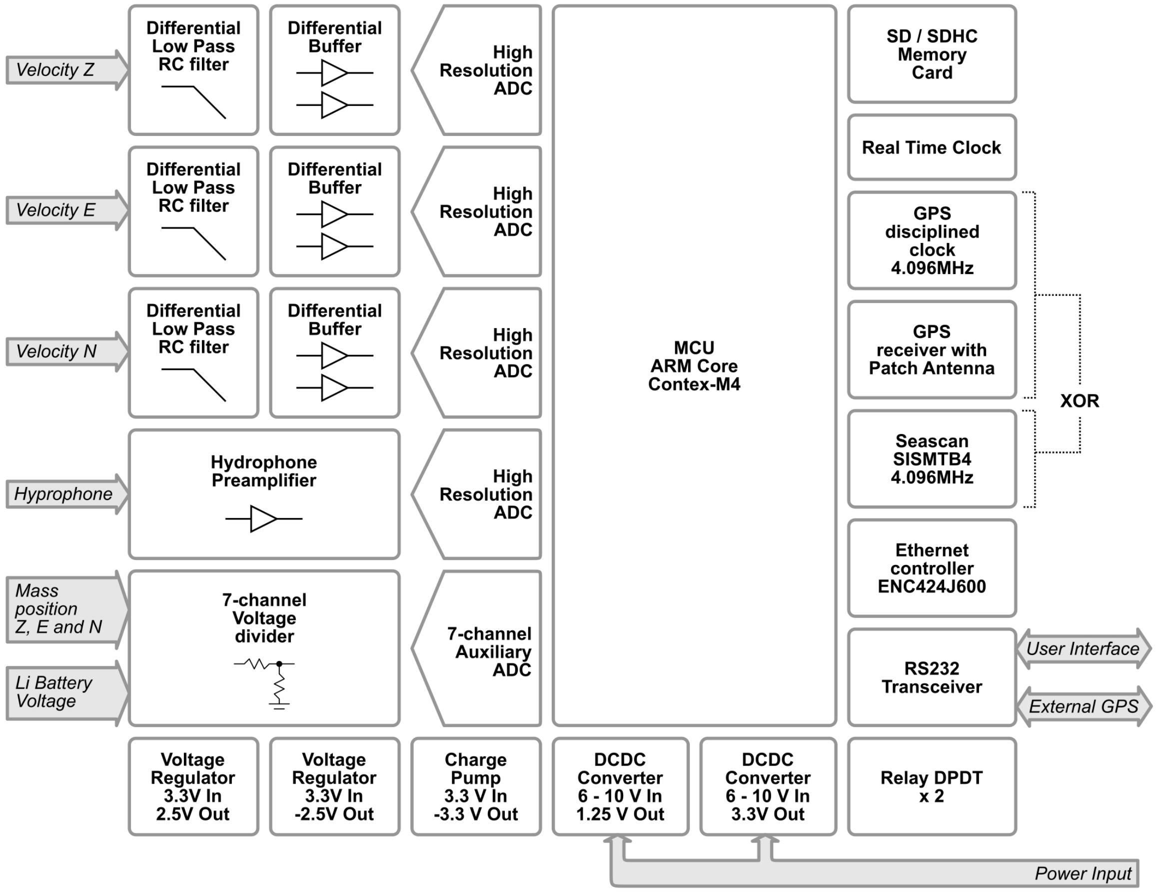

Figure 5. Simplified system diagram for the SeismoLog recorder.

The input noise level is one of the most important parameters for seismic recorders. Broadband sensors exhibit excellent dynamic range values, over outstandingly large frequency bands, extending to periods higher than 100 s. However, low frequencies are especially problematic for most electronic devices. Both active (transistors, operational amplifiers, ADCs) and passive electronic devices (resistors) produce higher noise densities at lower frequency. The physical phenomena involved are different for each device, but the effects are similar for most of them: at low frequency the noise power spectral density is proportional to the inverse of frequency, tending to infinity when frequency approaches zero. This kind of noise density is commonly referred as 1/f noise.

An effective way to reduce 1/f noise is to use a special family of amplifiers, designed to cancel their own 1/f noise, commonly referred as chopper amplifiers. Some ADCs implement this technology too. The analogue inputs of SeismoLog broadband version are designed with chopper amplifiers and chopping-input ADCs. As the PGS1 does not include a broadband sensor, the use of SeismoLog broadband version would not be strictly necessary. However, the electrical characteristics of the 5s sensor, in particular the output-voltage swing, would not be compatible with the geophone version. Therefore, PGS1 is equipped with SeismoLog broadband version. For this version, the dynamic range, i.e. the ratio of maximum input signal to short-circuit noise power, is greater than 122 dB when the sampling rate is 200 Hz. This dynamic range translates to an equivalent resolution of 20-bit.

SeismoLog uses a high stability frequency reference to generate the sampling frequency. The reference can be either a state-of-the-art Temperature Compensated Crystal Oscillator (TCXO) or a Global Positioning System (GPS) disciplined clock. The latter is the preferred choice for terrestrial use, because achieves the same long-term stability as the GPS system. The diagram in figure 6 shows how the recorder synchronizes the data samples with the GPS signal. The GPS disciplined clock produces two reference frequencies, 1 Hz and 4.096 MHz respectively. The latter is an integer multiple of the former, and both are phase-locked to the 1 PPS coming from the GPS receiver. The residual phase error is about ± 200 ns, when the GPS antenna has a clear view of the sky. The 4.096 MHz signal is routed to both the ADCs and the MicroController Unit (MCU) inside the recorder. The MCU uses this signal to run the system clock, which exhibits a resolution of 2^{-16} sec (about 15 µs). Clocking the ADCs through the reference frequency ensures that the number of samples per second is a constant integer value. The method used to assign a time stamp to each sample is to read time from the system clock, as soon as a sample arrives. This process occurs inside an Interrupt Service Routine (ISR), with a latency of a few microseconds. Storing the time stamp for every sample would waste memory, because the sampling interval is constant. In fact, the recorder uses the system clock only once in a recording session, when it reads the time of the very first sample. When sample time is to be determined, it is calculated, based on the time of the first sample and the number of samples acquired from start. This is just a conceptual description though, leaving out implementation details and optimizations. For marine

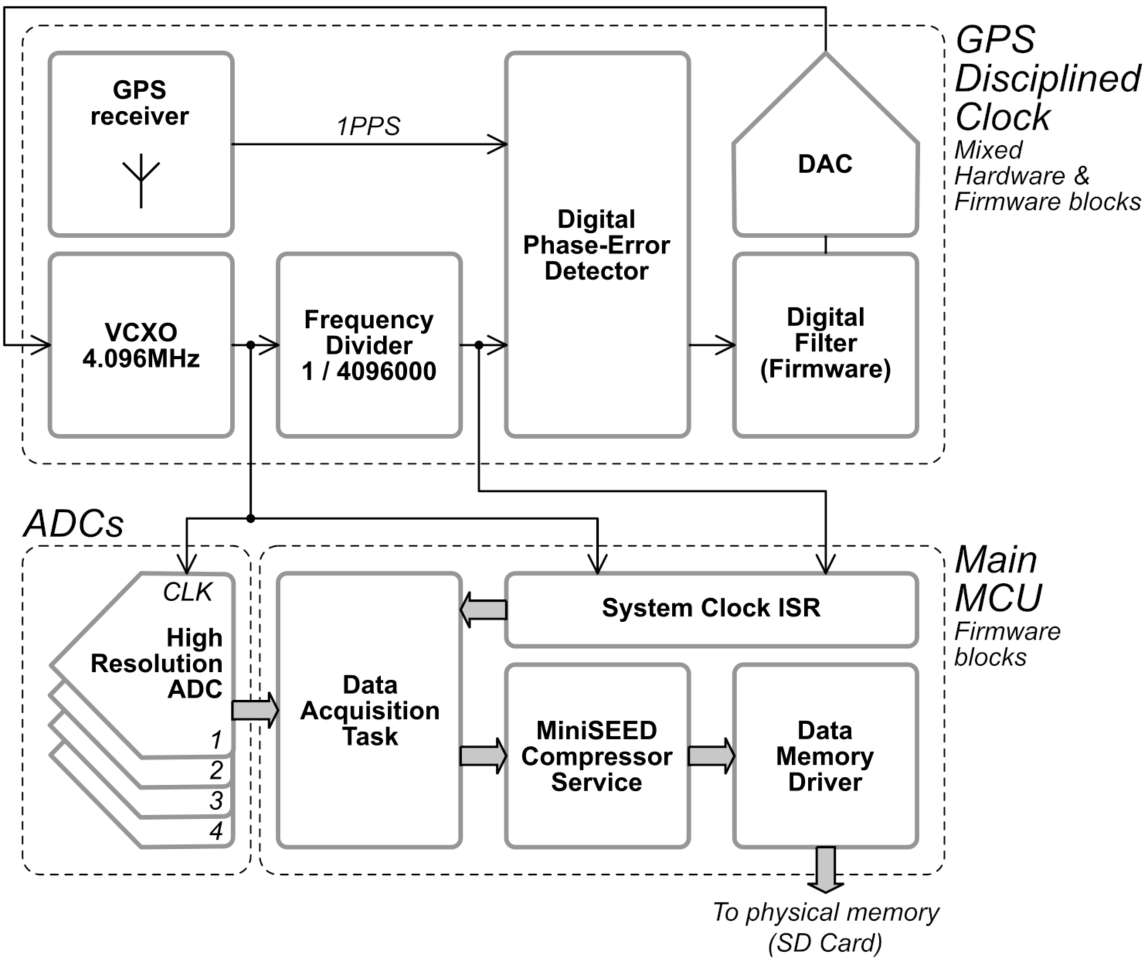

Figure 6. Clock distribution network of the SeismoLog Recorder.

applications, the recorder works in a similar way. The TCXO generates the same reference frequencies as the GPS disciplined clock. However, the lesser stability of the TCXO affects sample times, limiting accuracy in the long term.

3.2 Earth Lab 5s (ETL3D/5s) seismic sensor

PGS1 includes the new Earth Lab 5s (ETL3D/5s) seismic sensor [Fertitta et al., 2020], a three-component velocimeter with 5 second period and 100 Hz high cut-off frequency. This sensor was designed for monitoring of medium-range earthquakes and can be used in areas where industrial activities may induce seismicity. The sensor has very small size (97 mm diameter, 117 mm height) and low weight (1.7 kg). Its low power electronics consumes only 75 mW of quiescent power. The housing, made of AISI 316L stainless steel, is resistant to atmospheric agents and is IP67 waterproof. The sensor is based on a set of three geophones, combined with a low power and low noise amplifier. A revised version of Lippmann's method [Romeo and Braun, 2007] is used to extend geophone natural period up to 5 seconds.

The transfer function of the Lippmann's circuit depends on the geophone's coil resistance. Temperature affects the resistance value, making the transfer function vary over time [Mikhail and Boulaenko, 2002]. The Earth Lab 5s implements a temperature compensation scheme that mitigates the effect of temperature variations, keeping period and gain stable.

3.3 Power supply system

PGS1 uses 14.8 V-17.5 Ah lithium battery packs. One or two packs can be housed in the suitcase depending on user needs.

If the installation site offers some clear view of the sky, the photovoltaic panel can be used to further extend the acquisition length. The incoming solar energy is transferred to the battery packs by a Genasun GV5 charge regulator, a high efficiency controller with Maximum Power Point Tracking (MPPT) function [Xiao et al., 2011]. The GV5 provides also over discharge protection, disconnecting the load when the battery State Of Charge (SOC) drops below a fixed threshold. Northern Italy average insolation data were used to design the power supply system, whose theoretical energy production exceeds the station's needs over the entire year. These data can be downloaded from *Atlante italiano della radiazione solare*, a website provided by *Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile* (formerly *Ente per le Nuove tecnologie, l'Energia e l'Ambiente*, ENEA). The site uses a mathematical model that takes into account the orientation of the panel, which is defined by a couple of quantities, the tilt and azimuth angles. As already said, the panel tilt is fixed at 52°. The azimuth was assumed 0°, which is the orientation of a panel facing south. With these input values, the model yielded satisfactory insolation values, which guarantee continuous operation throughout the year. In January, for example, it is estimated that the energy production will exceed energy consumption by 20%. Remarkably, even if the energy balance were negative, for example by -20%, it would take more than 3 months for one battery pack to be completely depleted.

A DCDC switching converter supplies power to the recorder at 9 VDC. The DCDC input is connected to the GV5 power output. When the battery voltage becomes too low, the GV5 suddenly disconnects the load from the battery. In order to prevent data losses, the DCDC switching converter is designed to hold the output voltage for a few seconds after the disconnection. During this time, the DCDC output voltage is not perfectly stable, but decreases slowly. When the voltage drops below a certain threshold, the recorder closes the acquisition files and enters the sleep-mode. As a result, the battery disconnection, operated by the GV5, does not produce any data losses.

PGS1 schematic diagram, in figure 7, shows how PGS1 holds the recorder supply voltage when the charge regulator shuts the battery load off. A 10 mF capacitor, connected to the recorder power input, stores electric charge during normal operations. This charge can be delivered to the recorder, as a supply current, when the DCDC is switched off. At the same time, the diode across the DCDC prevents the DCDC output from being at higher voltage than the DCDC input, a destructive condition known as voltage inversion.

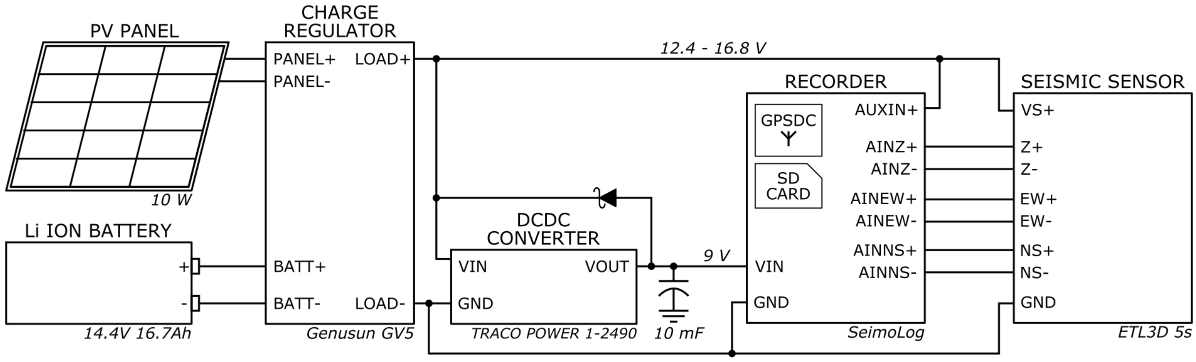

Figure 7. PGS1 schematic diagram.

3.4 User interface

PGS1 can be controlled through a computer, connected to the RS232 port. Any terminal-type software can be used to send commands and monitor acquisition parameters. The command set can be divided into a few categories: channel-configuration, acquisition-control, synchronization, interface control, special commands. Channel-configuration commands let user set up the analog inputs. For example, these functions include turning inputs on and off, or assigning a sampling frequency to each input. The recorder has more inputs than PGS1 requires. Actually, the ETL3D/5s seismometer is the only sensor connected to the recorder, and the unused inputs are free for future developments. Therefore, turning inputs on and off is generally not necessary, as the default configuration enables the seismometer inputs only. For these inputs, selectable frequencies are 1, 10, 20, 25, 50, 100 and 200 Hz. Acquisition-control commands allow starting and stopping data recording. The recorder responds to each command in this class with a message containing the current configuration and status of input channels, storage memory, and battery voltage. Synchronization commands affect the system clock and Real Time Clock (RTC). The former is a mixed hardware and software unit that produces a stable sampling frequency during data acquisition; the latter is a hardware module, which runs on a back-up battery when the recorder is powered off. At boot, the system clock is set to RTC time. Upon reception of a specific command, the recorder will try to align both clocks with the UTC time, provided by the GPS disciplined clock. After a successful synchronization, the time error is very low, actually negligible. The system clock will be continuously aligned with the disciplined clock, even without user's intervention. Therefore, as long as there is a clear view of the sky and the disciplined clock tracks an adequate number of satellites, the time error will stay low. Among the synchronization commands is the *delay* command, which can be used for measuring the time error without altering the system clock. The interface-control commands determine how the user interface work. One of the most important function is to make the interface switch to data-dump mode. In this mode, the recorder sends data over the serial link, in MiniSEED or in a proprietary format. However, the recorder keeps listening to user commands, so that it can switch back to user mode, upon reception of a specific request. The special commands let the user perform different actions, not required by ordinary operations, such as formatting the data storage memory or updating the firmware of the recorder.

A new user interface, based on an embedded web server is currently under development. In the meanwhile, with the help of OSU-CT team, a prototype has been developed which can be accessed over an Ethernet link, thanks to the introduction of a Single Board Computer (SBC). The PGS1 can now be configured via Secure Shell (SSH) and can run a SEEDLink server. However, the SBC cannot operate continuously because of its high power consumption. To overcome this problem, PGS1 powers on the SBC only when a device is connected to the Ethernet port. Once the Ethernet device is disconnected, the SBC is turned off immediately, thus saving energy. Once the SSH connection to the SBC is established, the user launches a Phyton script stored in the SBC memory. The logic of the script makes the SBC transparent to the user, allowing direct communication with the recorder.

3.5 Reading data

PGS1 stores its data to an SD or SDHC card. Binary data, like analog input samples, are written to miniSEED files, organized in monthly created folders. Data can be easily copied to a computer by means of a flash card reader. Table 1 summarizes the most important technical specifications.

Sensor	
Type	Three-component velocimeter
Bandwidth	- 3dB points at 5 s and 100 Hz
Sensitivity	360 V/(m/s) +/- 5% after calibration
Clip level	12.5 mm/s
Dimensions	diam. 97 mm, height 117 mm
Cable length	5 m
Recorder	
Sampling rate	1, 5, 10, 20, 50 ,100 and 200 Hz
Dynamic range	122 dB
Equivalent resolution	20 bit
Conversion factor	$3.32258 \bullet 10^7$ (counts / V)
Time accuracy	15 µs (with GPS)
Interface	
Control port type	RS232
Control port connector	DB9 female
Data memory	SD or SDHC
File format	MiniSEED
Memory usage	Up to 4 months with a 16 GB SDHC, three channels at 200 Hz
Synchronization	Internal GPS receiver
Battery	
Configuration	20 cells, Lithium INR18650-35E, 4 series 5 parallel
Nominal voltage	14.4 V
Capacity	16.7 Ah
Protection	Low voltage disconnection (without data loss)
Battery life	20 days with 1 battery pack 40 days with 2 battery packs endless with photovoltaic panel
PV Panel	
Peak power	10 W
Open circuit voltage	21.96 V
Short Circuit current	0.63 A
Power	
Average consumption	500 mW
Physical	
Suitcase	Explorer Cases model 3818
Transport dimensions	415 x 340 x 200 mm
Operative dimensions	415 x 480 x 200 mm
Weight	11 kg (with two battery packs)
Environmental	
Operating temperature	-10 to 50 °C (by design, not tested)
IP degree	IP67

Table 1. Electrical and physical specifications.

4. Testing

This paragraph describes different tests conducted on PGS1. The first is a power consumption test aimed at measuring battery life without solar energy. Battery life is defined as the time difference between two events. The first is acquisition start. The second is the disconnection of any load from battery, operated by the charge regulator when the low voltage condition (voltage < 12.4 V) results true. This time value is available in a log file, automatically stored to data memory by PGS1. The same file contains battery voltage samples as swell, taken at least once a day. Figure 8 shows the test results, with just one battery pack installed. The graph on the left is the battery discharge curve. This goes from the initial 16.7 V to 12.8 V, in about 20 days. The log file tells that battery voltage dropped to 12.4 V a few hours later, triggering a shutdown, as expected.

The test did not end at that point, in fact the photovoltaic panel was connected. The goal was to verify if PGS1 could restart with solar energy only, from the state of having a completely depleted battery. The graph on the right of figure 8 shows what happened. The charge regulator kept the acquisition system off until the battery voltage rose above 14 V, which occurred after about two days. Then battery voltage increased slowly from this point on, because the acquisition system started to consume power. The plot on the right of figure 8 shows a steady increase in battery voltage over time. This is a desirable result, but the operating conditions needs to be described in more detail, because the test took place in Sicily, thus at a relatively low latitude, and in August. In addition, the sky was mostly clear throughout the test. With all the favorable conditions above, PGS1 would have exhibited a very high and optimistic charge rate, if solar energy had not been artificially limited. This was accomplished by placing PGS1 in a site hit by sunlight between 08:30 and 10:30 a.m. only (a few large buildings surrounds the spot, shading it the rest of the day).

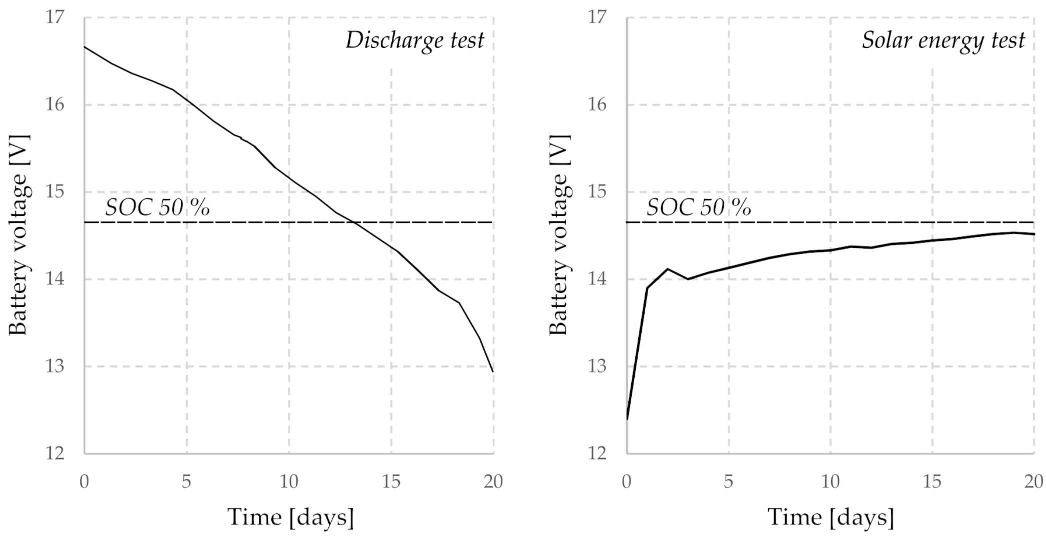

Figure 8. The graph on the left shows the voltage across the Lithium battery pack during a 20-days uninterrupted recording, with one battery pack and without photovoltaic panel. The graph on the right shows what happened when the photovoltaic panel was connected. The horizontal line labeled SOC 50% shows the point where the battery charge (State Of Charge, or SOC) is 50%.

The second test presented was conducted in 2017. Six PGS1s, installed a few kilometers away from one another, acquired about three days of seismological data. The location chosen for this test was the Sulcis, a large area in the southwestern part of Sardinia, Italy. Figure 9 shows two pictures from this test, taken during data acquisition (a) and setup (b) respectively. The recordings contain ambient noise and no seismic events, which is consistent with INGV official data for the same dates. Data show a strong microseismic activity, probably generated by the nearby sea. This phenomenon produced large peaks of power spectral density, in a frequency range between 0.35 and 0.40 Hz for the three components, see figure 10. All the spectra compare well at low frequency, which is a predictable result considering the mutual distances between the stations. At high frequency, the spectra diverge instead, but this too is in line with the scale of the experiment, and is ascribable to natural differences in local ambient noise among the sites. Despite these differences, for each component all the traces look similar in the time domain. This is because the microseismic peak, which is common to all, represents the most part of the total noise power. The microseismic activity manifests itself as a slow fluctuation, with a series of maxima (and minima) spaced by 2.5 to 2.8 s. As an example, figure 11 shows a comparison among the E/W time series. The two other components are not included because they look similar.

In an attempt to measure the self-noise of PGS1, one of the stations was brought to a low noise environment, where it recorded 30 minutes of ambient noise. In the same area is the station of Castelbuono, a node of the Italian Seismic Network, run by Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy.

Figure 12 shows the spectra from this recording. The dotted curve is the sensor's self-noise, as resulted from simulations; the dashed curves are the Peterson models, high and low; the continuous curve are the measured spectra. The curves stay within Peterson model high and low and above theoretical self-noise. Below 0.2 Hz, self-noise becomes higher than ambient noise. As the three components share the same hardware architecture, they also show comparable self-noise levels. This is the reason why the spectra almost coincide at very low frequencies.

Figure 9. a) PGS1 in acquisition; b) in configuration mode.

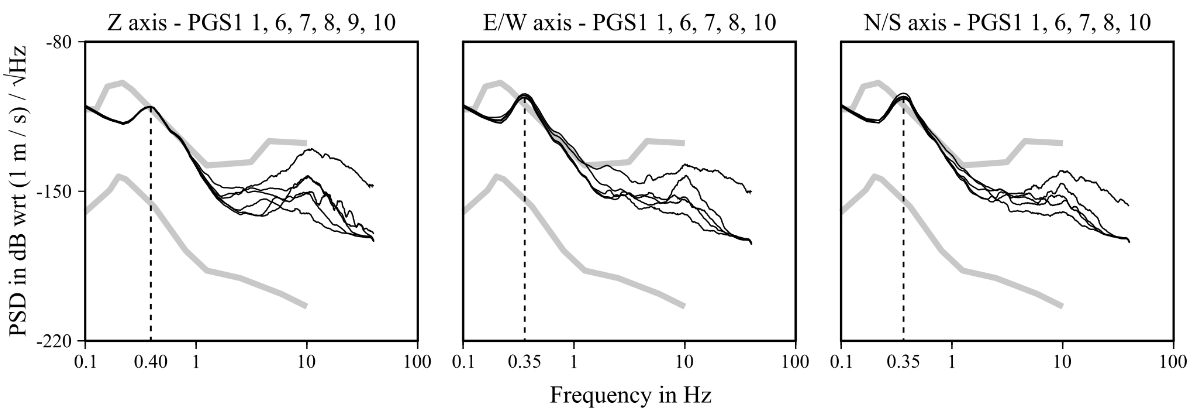

Figure 10. Power Spectral Densities from the recordings made in the Sulcis, in 2017. The horizontal components from station PGS1 9 are not included, because the corresponding time series are affected by strong noise, in the form of a train of periodic pulses, which prevents the correct evaluation of the spectra. The cause of this noise was a faulty electrical connection, inside PGS1 9.

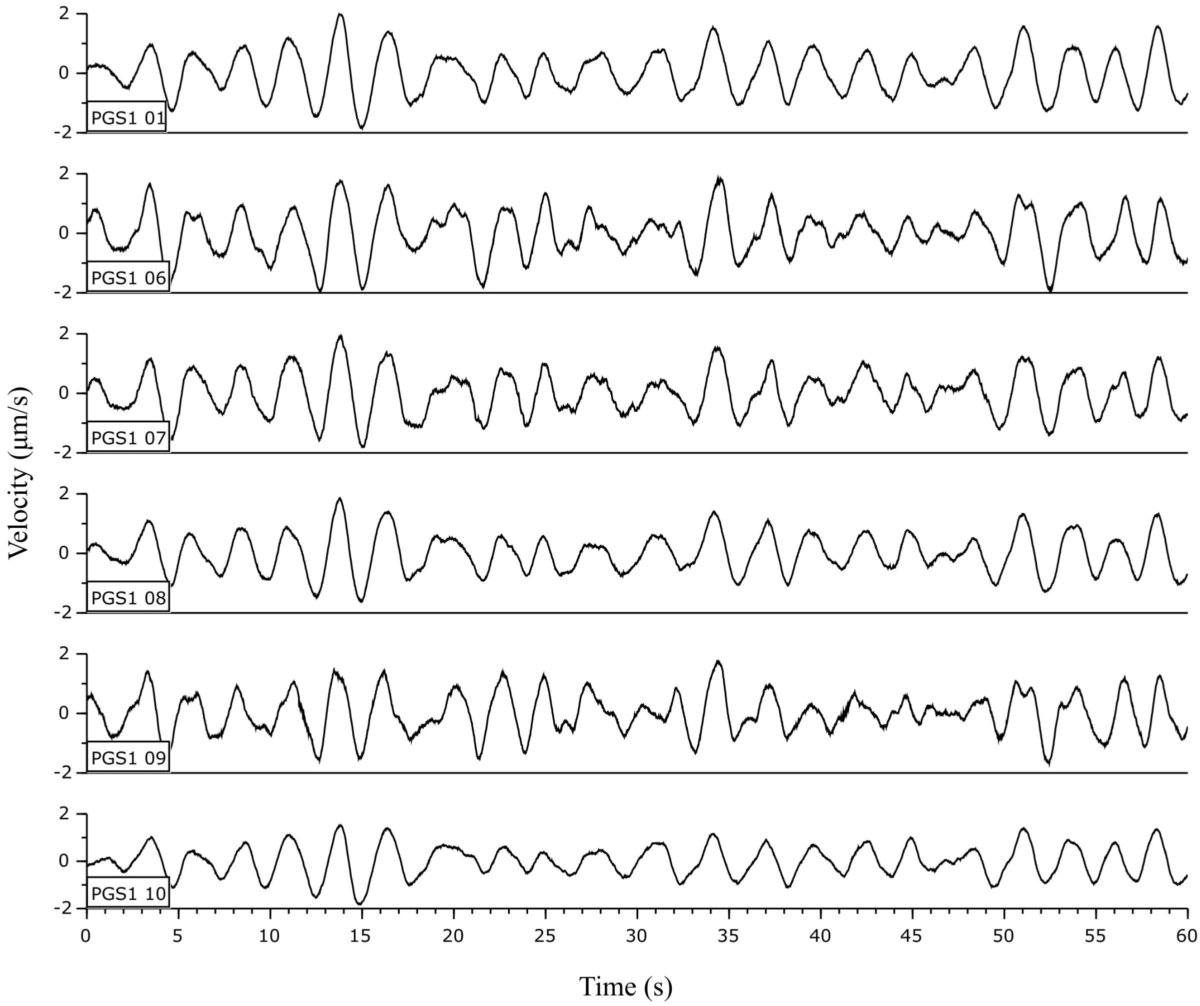

Figure 11. Ambient noise recorded in Sulcis in 2017. Only the E/W axis is shown. The time series produced by PGS1 9 are affected by strong noise, in the form of a train of periodic pulses, due to a faulty electrical connection. The data segment above was chosen so that the pulses are not visible.

The last test presented in this paragraph is a comparison with another node of the Italian national seismic network, the node GIB, located at Osservatorio Geofisico di Gibilmanna, Italy. The two seismic stations operated in parallel for a few weeks, and on October 1st 2020 both recorded an earthquake of magnitude 5.2, occurred in Greece at 11:05:37 UTC time. Figure 13 shows the complete waves on the left, and the phase arrival on the right. The node GIB has a higher period than PGS1 and is capable of achieving a much higher dynamic range, especially at low frequencies, thanks to the seismic sensor Nanometrics Trillium 120 s. For this event though, the two wave sets compare well without additional filtering, as shown in figure 13. In the same figure, mean values were cancelled from every wave. This test, once more, confirmed the correct behavior of the analog circuits implemented in both the sensor and recorder. Furthermore, the plots show no time shift between the waves, meaning that PGS1 clock was synchronized to GIB when the earthquake was recorded.

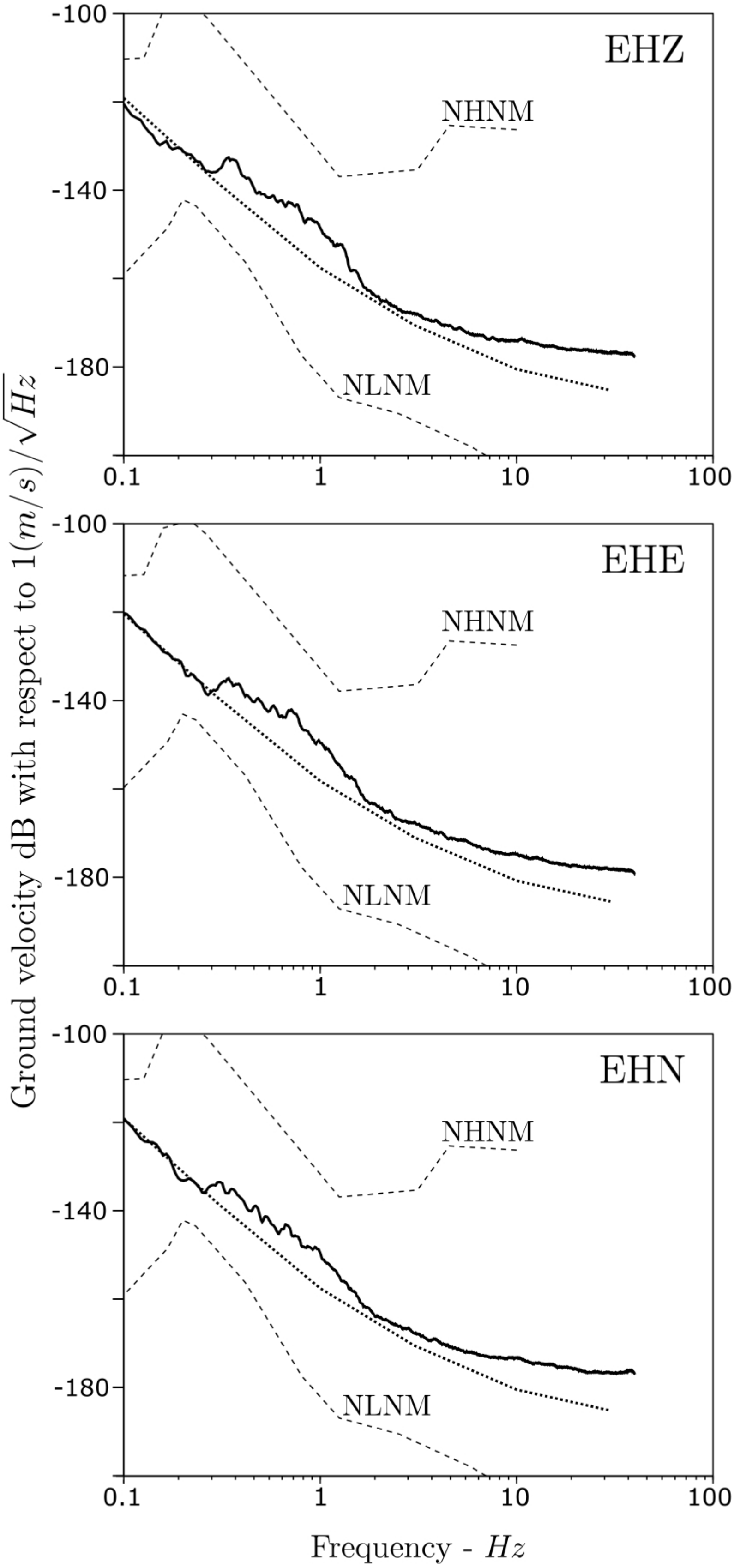

Figure 12. Component spectra of a data segment, recorded by PGS1 n° 06. The dotted curve is the sensor's self-noise, as resulted from a simulation; the dashed curves are the Peterson models, high and low; the continuous curve is the measured spectrum.

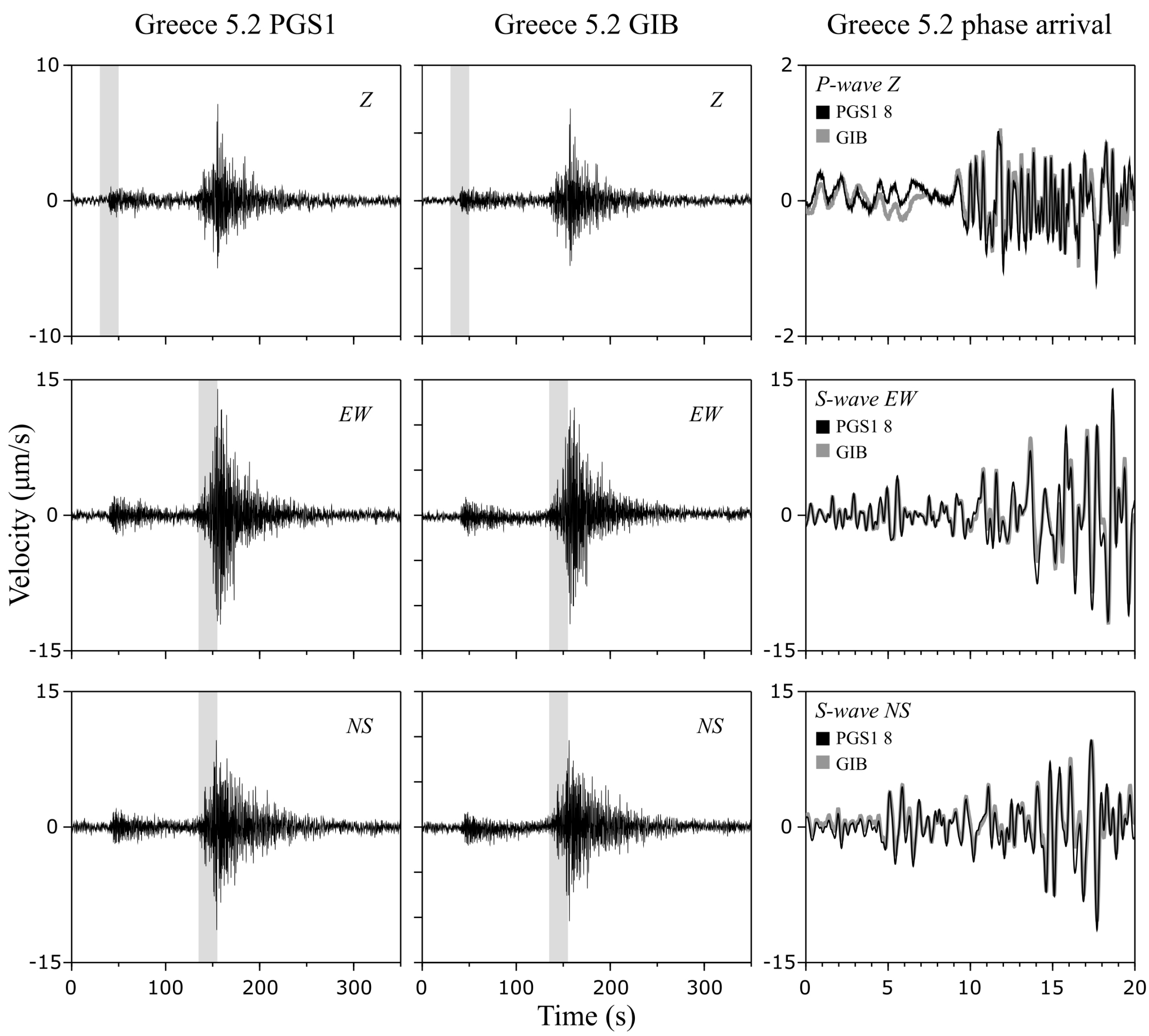

Figure 13. Earthquake of magnitude 5.2, occurred in Greece on Oct 1st 2020, UTC time 11:05:37, as recorded by PGS1 n°8 and by the seismic station Gibilmanna (code GIB).

5. Discussion and conclusion

In this work the new low cost and low power Portable Geophysical Station "All in One" PGS1 has been presented. This station was designed and assembled at INGV OBS and Earth Lab of Gibilmanna, Italy.

3D modeling played a key role; through virtual modeling it was indeed possible to select commercial components, to design new parts, to customize existing ones, and finally, to choose the most suitable distribution of the internal components in order to obtain a convenient position of the centre of gravity. Furthermore, 3D modeling allowed selecting a proper configuration of the electronic components, which could minimize the risk of EMI problems.

The PGS1 is equipped with a photovoltaic panel that extends the battery life. In the natural environment, many agents, like snow or growth of vegetation, can cause complete or partial obscuration of photovoltaic panels, reducing the energy production rate and causing discontinuities in the data acquisition. PGS1 has very low power consumption, because its electronics is derived from battery-powered marine instruments. As a result, the station can operate for long periods without solar energy production.

PGS1 is equipped with a compact sensor and a high-resolution acquisition system, which combined produce high quality data, as confirmed by various recordings of ambient noise and seismic waves.

The final cost of the station, including an estimate for the sensor calibration and PGS1 assembly, is of about 3500 Euros. However, a significant margin for cost reduction could come from scale manufacturing and process engineering.

Future developments include the release of a new user interface, based on a web-server.

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