

KRONOS: a low-cost data-logger for seismological applications

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Abstract – Modern seismology required high resolution, multichannel data-logger able to convert from analog to digital the signals acquired by multi-components broadband seismic sensors. Due to the high performance required, the high level of specialization and customization, and the limited market, a data-logger for seismological purposes is generally very expensive. In this paper we present a new 24 bit, 8 channels, 0.6 μV resolution data-logger called KRONOS, specifically designed for seismological applications and extensive use in seismic monitoring network. Project specifications are defined and laboratory test performed to determine the real resolution of the data-logger. The depth of knowledge of our data-logger performance, can allow us to configure it as best as possible as function of the input sensors, time to time, deciding the best compromise between sampling frequency and resolution as number of bits.

I. INTRODUCTION TO RECORDING SYSTEMS FOR SEISMOLOGICAL APPLICATIONS

Since the early 2000s, old seismic analog recording devices have completely replaced by modern digital one. Today, processing of seismic signals is completely digital. The technological progress in integrated digital circuits and digital signal processing have led to several data-loggers being available on the market that fulfill the basic requirements of a seismic recording instrument. A recording device designed for seismological application must be an autonomous, self-contained equipment, designed to measure the output signals of a seismometer, able to digitize and synchronize with high accuracy and precision the signals, recording and sending them in real-time using an appropriate seismological format.

A seismometer is a sensor able of recording the ground motion induced by an earthquake or related phenomena. The amplitudes and frequencies of interest for seismology are extremely variable. Amplitude could be range from imperceptible movements of the ground of the order of micrometers, such as those generated by seismic events of very small magnitude or earthquakes recorded at large distances (even several thousand or tens of thousands of kilometers), to several meters for very strong earthquakes recorded in the epicentral area. Also frequency could be

range from very low frequency of about 10^{-4} Hz, like those generated by tides or free Earth oscillations, to frequency of few hundred hertz, like those generated by shallow micro-seismicity. Such a wide range of amplitudes and frequencies cannot be covered by a single sensor; different co-installed sensors are needed. The main common seismic sensors are velocimeter, those called Short-Period (SP) seismometers (for weak to moderate ground motion in the frequency range 0.1 to 100 Hz), Broadband (BB) or Very Broadband (VBB) seismometers (for weak to moderate ground motion from approximately 0.01 to 50 Hz and 0.001 to 10 Hz, respectively) and Strong Motion (SM) sensors, generally accelerometers (for moderate to strong ground motion from DC to about 200 Hz).

SP seismometer are generally worldwide employed in seismic networks for local and regional earthquake monitoring [1-8], BB and VBB in large scale network [7] and SM mainly to measure the effects of strong earthquake in epicentral areas [8-11].

So a data-logger for seismological purposes must be extremely versatile, able to adapt to the sensor type in use. PGA (Programmable Gain Amplifier) and sampling frequency, as well as high resolution and wide dynamic range are mandatory. Furthermore, given the need to acquire signals from at least two 3ch seismic sensors (a channel for each component of the motion) with different amplitude and frequency responses (in order to cover the widest range of amplitudes and frequencies of interest for earthquake science), a seismic recording system must be provided with at least 6 conversion channels. Generally, a higher number of channels is preferred, at least 8, so you can record other type of sensors useful in the field of seismology like pressure in ocean bottom monitoring and acoustic/hydroponic sensors in volcanic areas [12-14]. For seismological purposes, the acquisition of the channels must be synchronous and synchronized with the absolute UTC time, with timing accuracy less than 100 μs . In addition, for use in real-time monitoring networks, the data-logger must implement standard data and transmission formats, that commonly employed by the seismological scientific community.

Due to the high performance required, the high level of specialization and customization, and the limited market, a data-logger for seismological purposes is generally very expensive, with costs that can exceed tens of thousands of

Euros. The high cost of seismic recording systems severely limits the development of seismic monitoring networks. High density seismic monitoring networks are essential for seismicity monitoring and seismic risk reduction [15-17]. For this reason, we have design and development of a low-cost data-logger for seismological applications called KRONOS, to be employed in the realization of high density, real-time, seismic networks. In the following we describe the KRONOS design and the lab tests carried out to evaluate its performance. Final remarks will be on the KRONOS data-logger performance, its suitability for seismological applications and possible future developments.

II. DATALOGGER DESIGN

The KRONOS data-logger is based on the Texas Instruments ADS1256 but its structure allows you to easily customize the project using others ADC or directly sensors with digital output. The operating scheme of the data-logger is shown in Fig. 1.

The converter is comprised of a 4th-order, delta-sigma ($\Delta\Sigma$) modulator followed by a programmable digital filter. A flexible input multiplexer handles differential or single-ended signals and includes circuitry to verify the integrity of the external sensor connected to the inputs. The selectable input buffer greatly increases the input impedance and the low-noise PGA provides gains from 1 to 64 in binary steps. The programmable filter allows the user to optimize between a resolution up to 23 bits noise-free and data rate up to 30k Samples Per Second (SPS). The converters offer fast channel cycling for measuring multiplexed inputs and can also perform one-shot conversions that settle in just a single cycle. The ADS1256 offers 9 analog inputs, which can be configured as four independent differential inputs, eight single-ended inputs, or a combination of differential and single-ended inputs. The input voltage in the single-ended case is in the range -1 to +5V and $\pm 5V$ in the double-ended case since the reference voltage is 2.5V.

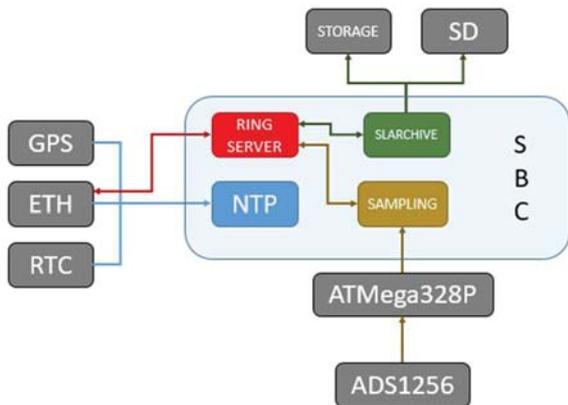


Fig. 1. SBC process.

The front-end (shown in Fig. 2) is a precision differential amplifier that can be used to amplify high gain differential voltages and reject high common-mode voltages for compatibility with common voltage levels for the signal processing.

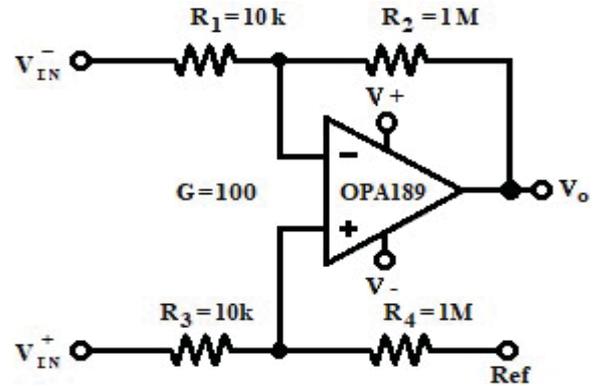


Fig. 2. Front-end electrical scheme.

The ADC is managed by the ATMEGA328P microcontroller via SPI port. To ensure that the system does not block due to sudden and external causes, the Watchdog has been activated. Once the communication between the devices has been initiated, the system performs the sampling procedure with a fast cycle. After reading all the channels, the data is transmitted via the serial port. The data output frequency depends on the number of active channels and the moving average filter. The transmission of the data takes place using a string of length dependent on the number of active channels. Specifically, each channel adds three bytes to the string. To identify the end of the information relating to that instant of time, four bytes are queued, they form the word "stop". It was not considered necessary to occupy the transmission band to insert start characters. A basic block diagram is shown in Fig. 3.

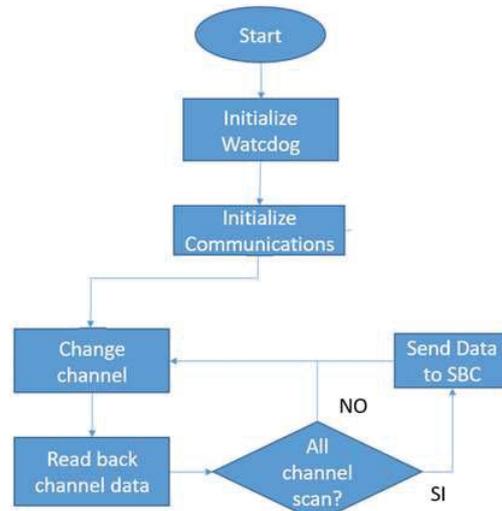


Fig. 3. Basic block diagram.

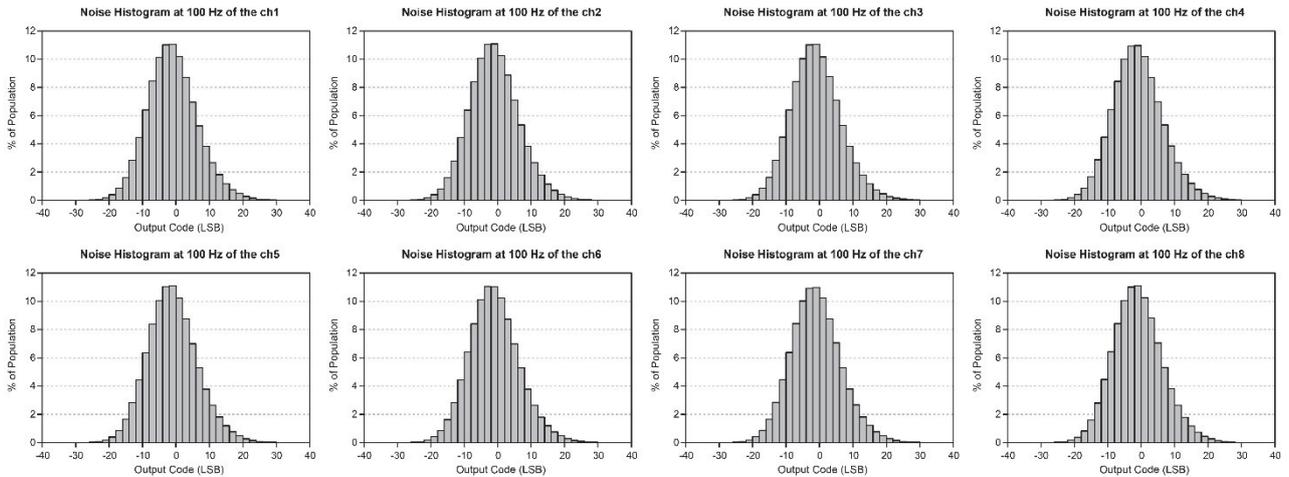


Fig. 4. Histograms obtained from the data acquired by the each of the 8 channels of the KRONOS data-logger (sampling frequency of 100 Hz).

The brain of the seismic station is a Single Board Computer (SBC). The ADC samples and transmits continuously, while the digital outputs are managed and processed by the SBC in the sampling process which waits for the arrival of the data to operate (Fig. 1).

The code is automatically executed when SBC starts. The sampling frequency is by default 100 Hz (can be varied from 1 to 500 Hz). Time Synchronization with UTC time is ensured by the NTP (Network Time Protocol) service which retrieves the time from the GPS integrated in the system or it relies on the servers used by the network. In the absence of connectivity, the system initially synchronizes via an RTC (Real Time Clock) waiting for the GPS fix.

Table 1. Cost of the acquisition system

Components	Costs (Euro)
Raspberry Pi 3	32.31
AC Power	5.70
SD 16gb Toshiba	5.82
GPS Ultimate Adafruit	35.53
Cable SMA femmina Femmina U.FL	3.33
GPS Antenna	7.66
Pannel RJ45 Femal	8.67
Arduino Nano	9.37
Prototype board ads1256	30.00
Front-End	20.00
Aluminum box	20.00
12-pole connector pannel	10.00
12-pole connector cable	10.00
4-pole connector pannel	9.00
4-pole connector cable	9.00
Consumables	10.00
Total	226.39

The data-logger support the miniSEED (or mSEED), a short version of the SEED (Standard for the Exchange of Earthquake Data) format, primarily intended for the storage and exchange of seismological time series data [17]. The data is stored in multi-track format (BigStreng).

The local transmission and storage of data takes advantage of the ring-server and slarchive, conceived by the Incorporated Research Institutions for Seismology (IRIS) for the transmission and storage of mSEED data; they are widely tested and used in the scientific community. The role of the ring-server is to connect the sample loop with the software that manages the seismic recording tracks (Fig. 1). The role of the slarchive is to query the server ring and create a local archive of all the signals.

KRONOS data-logger is generally equipped with modular battery pack to stabilize the energy supply and to provide up to several days of autonomous acquisition, all contained in a waterproof box.

The Table 1 shows the cost of the acquisition system.

III. DATALOGGER PERFORMANCE

One of the major trends for seismic data-logger is toward higher resolution multichannel ADC. Delta-sigma ADCs generally reach resolutions of 24 bits, like that employed in the KRONOS data-logger. However, all ADCs generate a certain amount of noise, which can significantly reduce the resolution of the data-logger. This noise includes both input-referred noise (also thermal noise), which is inherent to the ADC, and quantization noise, due to the analog-to-digital conversion process. Several indirect method can be used to measure data-logger noise (e.i [18-20]), but surely the most robust approach remains direct measurement.

To measure the input-referred noise, the input of the ADC is connected to ground signal or to a reference voltage source, and a large number of output samples are collected and plotted as a histogram. Since the noise is

approximately Gaussian, the standard deviation of the histogram, σ , which can be calculated, corresponds to the effective input RMS noise.

Specifications such as noise Root Mean Square (RMS_{noise}), noise Peak-to-Peak ($P2P_{noise}$), Effective Number Of Bits (ENOB), Noise-Free Resolution (NFR) and Dynamic Range (DR) could in large part define how accurate an ADC really is.

While RMS_{noise} and $P2P_{noise}$ are different ways of estimating the input-referred noise, ENOB and NFR are two different ways to estimate the real resolution of a ADC defined as follow:

$$ENOB = \frac{\ln(2^n / RMS_{noise})}{\ln(2)} \quad (1)$$

$$NFR = \frac{\ln(2^n / P2P_{noise})}{\ln(2)} \quad (2)$$

where n is the number of bit of ADC. It is proved that for Gaussian distribution noise, $NFR = ENOB - 2.7$. The DR instead is defined as $20 \log 2^b = 6.02 \cdot b$, where b here is set equal to ENOB. Another important parameter is the Differential NonLinearity (DNL) that is a term describing the deviation between two analog values corresponding to adjacent input digital values.

Several laboratory test was conducted to estimate the input-referred noise of the KRONOS data-logger. In each of these test at least a 1 hours of signals was acquired for each (short-circuited) channels, and the previously specified parameters have been determined. We performance our test for 4 different sampling frequency that are 4, 20, 100 and 500 Hz.

Fig. 4, as example, shows the 8 histograms obtained from the KRONOS data-logger at the sampling frequency of 100 Hz. Ideally, for grounded channel, the output code should be zero; as expected, however, it is possible to observe a spread of codes. The presence of inherent DNL could cause deviations from an ideal Gaussian distribution. However, as shows in Fig. 2 our noise data follows with a good approximation a Gaussian distribution (very low values of Skewness and Kurtosis).

Table 2 shows noise/performance specifications for KRONOS and relative standard deviations. As expected, the resolution of the data-logger does not reach the ideal 24bit resolution. Both the RMS and P2P values are far from zero and grow with increasing of sampling frequency. This leads to a significant reduction in the effective resolution of the data logger, which in the worst case (500 Hz) drop to about 20 bits if we referred to ENOB and to about 17.5 bits if we referred to NFR, with a DR of about 121 dB. Much better certainly the resolution at lower frequencies which, at the minimum frequency here analyzed of 4 Hz, reaches about 22.5 bits if we referred to

ENOB and to about 20.2 bits if we referred to NFR, with a DR of about 135.8 dB.

Surely, better results could be achieved by going further down in the sample rate, but lower sampling frequency would not be of interest for seismological applications and so not investigated in this work.

Table 2. Noise/performance specifications

	500 Hz	100 Hz	20 Hz	4 Hz
RMS	14.83 (±0.02)	4.82 (±0.01)	4.51 (±0.05)	2.72 (±0.03)
P2P	87.29 (±7.54)	30.74 (±1.89)	23.73 (±0.83)	13.87 (±1.01)
ENOB	20.11 (±0.00)	21.73 (±0.00)	21.82 (±0.01)	22.55 (±0.02)
NFR	17.56 (±1.12)	19.06 (±0.09)	19.43 (±0.05)	20.21 (±0.11)
DR	121.07 (±0.01)	130.82 (±0.03)	131.41 (±0.09)	135.79 (±0.11)

IV. CONCLUSIONS AND REMARKS

In this paper we present a new 24 bit, 8ch, data-logger, called KRONOS, specifically designed for seismological applications, based a commercial ADC produced by Texas Instruments (ADS1256). In this work we focus on the analysis of the data-logger real resolution. All ADCs, have a certain amount of input-referred noise. Input-referred noise could not be confused with quantization noise, which is only of interest when an ADC is processing time-varying signals.

It is very important, to quantify the real performance of a data-logger, especially if this is used in important applications such as earthquake monitoring. Real ADCs deviate from ideal one in many ways; DNL and input-referred noise is certainly a departure from the ideal and must be correctly estimated.

The depth of knowledge of the performance of our data-logger, can allow us to configure it as best as possible as function of the input sensors, time to time, deciding the best compromise between sampling frequency and number of bits. In the present work, one of the objectives was to create a low cost data-logger for seismological applications, and so employing a single ADC to keep costs low. The KRONOS data-logger is excellent for use with different types of seismic sensors, showing sufficient resolution and dynamic range, and thanks to its low cost, to the large-scale use.

Clearly, by using an ADC for each channel, the performance of our data-logger can be increased take full advantage from the application for example of oversampling techniques and of the implementation of a digital moving average like the media Blue or Best Linear Unbiased Estimate. Moreover, the mux would not be used during the sampling operations further decreasing the

noise due linked to the input stage. In short, the next step will be to design the KRONOS-HR which can be used in a very high resolution application.

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