Design and implementation of a sigma delta technology based pulse oximeter’s acquisition stage.

E E Rossi¹, A Peñalva¹, F Schaumburg¹.
Laboratorio de Instrumental electromédico para diagnóstico y monitoreo. Universidad Nacional de Entre Ríos, Ruta provincial Nº 11, Argentina

E-mail: rossiesteban@gmail.com, schaumburg.f@gmail.com, elpenia@gmail.com

Abstract. Pulse oximetry is a widely used tool in medical practice for estimating patient’s fraction of hemoglobin bonded to oxygen. Conventional oximetry presents limitations when changes in the baseline, or low amplitude of signals involved occur. The aim of this paper is to simultaneously solve these constraints and to simplify the circuitry needed, by using ΣΔ technology. For this purpose, a board for the acquisition of the needed signals was developed, together with a PC managed software which controls it, and displays and processes in real time the information acquired. Also laboratory and field tests where designed and executed to verify the performance of this equipment in adverse situations. A simple, robust and economic instrument was achieved, capable of obtaining signals even in situations where conventional oximetry fails.

1. Introduction
Pulse oximetry is a technique used to estimate arterial oxygen saturation (SpO₂). It is widely used because of the advantages which presents compared to the other accepted methods to measure this variable, namely continuity of the record, non invasiveness, simplicity to use and lower cost. All this at the expense of an improvable accuracy. [1][2][3].

Transmittance pulse oximetry, consists of measuring the intensity of the light which an irrigated tissue (such as a finger or the earlobe) is capable of transmitting. The light used is composed by two different wavelengths, typically 660 nm and 940 nm. Time variation of the transmitted intensity for any wavelength is called the plethysmographic signal. [1][3][4].

These signals consist of a high amplitude DC level (due mainly to static components of tissue and ambient light) and a low amplitude AC level (due mainly to volumetric changes in vascular tissues, due to heart’s activity). Numerically AC component represents between 0.1% and 2% of the plethysmographic signal. The plethysmography signal’s bandwidth is 10 Hz. By comparing the AC and DC components for each wavelength is possible to obtain a highly SpO₂ correlated index (R). [3][5][7][9].

This particular waveform, together with the need for two different signals (one for each wavelengths) leads conventional approaches, which are those that use low resolution (less than or equal to 16 bits) digital-analog converters (ADC), to implement complex and expensive analog processing stages. The large difference in magnitude between AC and DC, requires to digitize them separately, so that they can receive different amplification, thus achieving good resolution for AC components without causing saturation. This implies that there should be four analog processing
channels: one for AC due to 660 nm emission, one for DC due to 660 nm emission, and similarly for the AC and DC due to 940 nm emission. Figure 1 shows a block diagram of a conventional pulse oximeter. [8].

![Block Diagram of Conventional Pulse Oximeter](image)

**Figure 1.** Conventional pulse oximeter’s acquisition stage block diagram. M&R: Sample and Hold, PB: lowpass filter, PBD: bandpass filter.

On the other side, to get acceptable resolution with those ADC is necessary to amplify signals as much as possible. As a consequence, large variations in the DC signal imply overpassing conversion’s range. This phenomenon is also called “saturation of the ADC input” or “ADC saturation”, and implies the loss of information. This is why conventional oximeter readings are incorrect or are not valid in situations involving large variations in signal’s DC level or baseline (such as patient or sensor movement, or intense light in operating room) or situations where signal’s amplitude is poor (low blood differential pressure, hypothermia, hypotension, hyper-pigmentation, bad sensor anchorage). [1][2][4][9].

ΣΔ AD converters have three characteristics of great interest for biomedical signal acquisition: High resolution (up to 24 bits), allowing signal’s low amplification without loss of useful information, together with large DC level variations without involving ADC saturation; Oversampling (which in some ΣΔ ADC is greater than the bandwidth of operational amplifiers) and; Intrinsic behavior as a lowpass filter for the input signal, solving the aliasing problem without the need for complex filters or directly without filters. [6].
2. Objective
To develop an oximetry’s acquisition stage, which by the use of a ΣΔ ADC will give solution to the previously appointed problems of conventional pulse oximeters, and which also will minimize the analog processing stage, resulting in a more robust and economic design. This device must be able to be used in the context of a laboratory for teaching purposes.

3. Materials and Methods

3.1. Spiral development model.
The "spiral development model" was chosen in order to implement this acquisition module. In this model, the life of a development is divided into stages which are driven in a cyclical manner while the product progresses. When starting a spiral cycle, the risks associated with product in the state it is are assessed, then its aspects to be improved are determined, and a new design aimed at meeting them is made. The spiral has an angular component that indicates the progress of the project in a cycle, and a radial component indicating the cost and complexity of development. [10][11].

During design some of the IEC 60601-1, ISO 14971:2007 and the IRAM-FAAA 37226 AB requirements, where taken into account. The decision to leave out the rest of the guidelines imposed by these regulations, was based on the intended use of this device, which is within the scope of a laboratory, under controlled conditions.

3.2. Validation.
A validation process was followed, in which the result of the design and implementation process was assessed in order to ensure compliance with requirements and specifications defined. It consisted of laboratory and field testing.

The former consisted of measurements carried out in a laboratory in order to verify the correct functioning of the various blocks that compose the designed device, by simulating the conditions to which it would be exposed, in a controlled manner. These tests were carried out at the “Laboratorio de Ensayo y Calibración de Equipos Médicos” (LEyCEM, FI-UNER). The equipment used for this purpose was: A FLUKE 196C oscilloscope, a Fluke 271 DDS Signal generator, and a TES 1330 lightmeter. Three repetitions were performed for each laboratory test, with the aim of reducing the influence of the uncertainty of measurement process.

Field tests are tests performed on volunteers in order to check the overall operation of the device. Those tests were designed to verify compliance with the objectives set for this work (that is not losing information of plethysmographic signals, which is the first step for solving the problems they entail). All field tests were performed three times on two volunteers. The emission intensity of the emitters used, in each case was constant and equal to half the maximum attainable with the device.

3.2.1. AD conversion. In this laboratory test, in order to assess that the frequency response of the AD conversion block was the desired, signals of known amplitude and frequency were injected in this block, and records of the digitized signals were obtained. This scanning was performed using 1 Vpp amplitude sinusoidal signals, and the following frequencies: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1 000, 2,000 and 5 000 Hz. Records obtained were analyzed using MATLAB®.

3.2.2. Light emission. Light emission. In this laboratory test, in order to evaluate if the relationship between emitted light intensity and the current driver control signal (see 4.1.1) was linear, a sweep of this signal was performed, and illuminance was measured for each wavelength using the light meter mentioned. Emitters were placed inside an opaque container. To achieve reliable measurements with the lightmeter, emissions were continuous, and not pulsed as it in the normal operation of the device.
3.2.3. *Light reception.* In this laboratory test in order to verify that the relationship between light intensity incident on the photodiode and the amplifier output voltage, is linear, this voltage was measured for increasing values of the current drivers control signal. For this purpose, the transmitter and receiver were placed facing each other, inside an opaque container. Prior to this linearity was observed between current drivers control signal, and the emitted light intensity.

3.2.4. *Record during movement.* In this field test, in order to verify the continuity of the records (i.e. no information loss) during patient movement (which also implies sensor movement), records were taken in the following format: 25 s in a quiet state, followed by 35 s with the volunteer doing a light jog on a treadmill. To prevent complete detachment of the sensor, its cable was fixed to the finger using tape (as it is done in clinical practice). Data collected was analyzed in order to determine the changes in the signal’s baseline, and the absence of ADC saturation.

3.2.5. *Record with strong ambient light.* In this field test, in order to verify the ability of the designed device, to keep record in situations which involve intense ambient light, plethysmographic signals records (for both wavelengths) were obtained, with three different ambient light levels: 50, 500 and 5 000 lux. The lightmeter was used to measure those levels. Records obtained were analyzed for determining the absence of saturation, and the correct AC components acquisition.

3.2.6. *Record during low perfusion.* In this field test, in order to verify the ability of the device to acquire adequately low amplitude plethysmographic signals, records were obtained on voluntaries with low perfusion in the limb the sensor was placed on. To induce this, a cuff for non-invasive blood pressure measuring was placed in the same arm than the sensor was. The cuff remained inflated at a pressure between the volunteer’s maximum and minimum (previously determined). Records obtained were analyzed in order to verify the correct acquisition of plethysmographic signals.

3.2.7. *Record of a SpO₂ variation.* Calibration of the device, as well as algorithms for R and SpO₂ calculation are issues beyond the scope of this work. Either way, a change in a volunteer’s SpO₂ induced by a voluntary apnea episode, should cause the value reported by the device to drop after this maneuver. Also, after normal breathing is restored, the SpO₂ value should return to a value similar to the initial. In order to verify this, in this field test, records were taken in volunteers who followed this breathing pattern: Normal breathing for 10 s, Forced expiratory reserve volume expiration, Avoiding inspiration for 25 s, Normal breathe during 50 s. Records obtained were analyzed to assess if there was correspondence with the expected behavior.
4. Results

4.1. ΣΔ ADC based pulse oximeter’s acquisition stage

4.1.1. Hardware. Sensor was manufactured by reusing the mechanical components of a commercial sensor. Narrow spectrum LED emitters were selected with emission peaks at 660 nm and 940 nm respectively. As a receptor, a photodiode with spectrum including both emission wavelengths was chosen. A transimpedance amplifier was included in the same sensor, so as to amplify and convert to voltage the photocurrent, and to decrease tribological noise effects due to cable movement. The only block included between this amplifier and ADC, was anti-aliasing filter. The ΣΔ ADC was chosen to allow sampling of the three signals (plethysmographic signals and ambient light signal) at a rate greater than or equal to ten times the maximum signal’s frequency, with a resolution allowing at least 100% baseline variations, and 1% resolution for plethysmographic signal’s AC component. For circuit’s control and communication a microcontroller (µC) was used. A pulse width modulated signal (PWM) provided by the µC, was chosen for controlling emission intensity. Acquisition stage-PC connection was accomplished by the means of a USB 2.0 port. Emission’s control was accomplished by using current drivers, which are circuits that generate currents that control when and for how long a LED emits, together with emission’s intensity. Circuit was mechanically protected by the means of an ABS plastic cabinet. Figures 2, 3 and 4, show hardware achieved.

![Figure 2. Block diagram for the circuit achieved.](image1)

![Figure 3. Thimble containing two emitters, a photo-receiver and a transimpedance amplifier.](image2)

![Figure 4. Cabinet containing the circuits for the acquisition stage.](image3)
4.1.2. **Software.** As shown in Fig. 5, the PC managed software allows real-time visualization of the acquired signals and calculation of SpO2 and R. The screen has two plotting areas: one for AC components, and one for DC components and ambient light. On these charts, amplitude and time scales can be changed using the zoom controls. There also is a bar menu which allows record operating (starting, pausing, completing, saving, etc.), selection of signal to be plotted, PWM duty cycle selection, among others.

![Figure 5. PC managed user interface, for processing, plotting and storing the acquired data.](image1)

4.2. **Validation.**

4.2.1. **AD conversion.** The obtained ADC’s frequency response, matched its datasheet. No aliasing was found in the analyzed records. In figures 6 and 7 respectively, ADC’s frequency response and laboratory setup used for this purpose, can be observed.

![Figure 6. ΣΔ ADC’s frequency response.](image2)

![Figure 7. Laboratory setup. The device and the equipment used can be seen.](image3)
4.2.2. **Light emission.** Relationship between the emitted intensity (in lux) and PWM duty cycle (in %), was obtained. Linearity between those magnitudes was found. In figures 8 and 9 respectively, this relationship and laboratory setup, is shown.

![Figure 8](image8.png) **Figure 8.** Relationship between light emitted intensity (for each LED) and PWM duty cycle for current driver controlling.

![Figure 9](image9.png) **Figure 9.** Laboratory setup. The device and the equipment used can be seen.

4.2.3. **Light reception.** Relationship between incident light intensity on the photodiode, and transimpedance amplifier’s output voltage, was obtained for each LED. In both cases, linearity was found. Figure 10 shows this relationship.

![Figure 10](image10.png) **Figure 10.** Relationship between light intensity received by the photodiode (for each wavelength) and PWM duty cycle. The regression lines used to evaluate the linearity between the measured variables, and a close to the unit $r^2$ parameter supports this linearity.
4.2.4. **Record during movement.** Records were obtained during volunteer movement. It was found that there was no ADC saturation, i.e. ADC input signal’s amplitude never exceeded ADC’s voltage reference. In the worst of recorded cases, there was a near 100% baseline variation. Also, this variation could have been as large as 360% without causing problems. That record is shown in figure 11.

![Figure 11](image)

**Figure 11.** Worst case record obtained during movement. DC components and ambient light are shown. It can be observed that after the second 25, DC increases to nearly twice its previous value ($\Delta DC = 100\%$) as a result of movement. As the ADC’s reference voltage used was 2.048 V, DC variation could have been close to 360% without causing saturation.

4.2.5. **Record with strong ambient light.** Records with three different levels of intense ambient light were obtained. In none of them ADC saturation occurred, and in every case it was possible to visualize AC components correctly. Figure 12 shows a record obtained in the worst lighting scenarios (5000 lux ambient light).

![Figure 12](image)

**Figure 12.** Above: ambient light (green) and DC components (blue for 940 nm, and red for 660 nm) in a measuring scenario with strong ambient light (5 000 lux). Below: AC components obtained correctly under these conditions.
4.2.6. *Record during low perfusion.* Records were obtained under the named conditions. In all cases plethysmographic signals were acquired properly, as shown in Figure 13. In the worst case, the AC component was acquired with a 0.5 resolution.

![Figure 13](image13.png)

*Figure 13.* Low amplitude register due to a non invasive pressure cuff, used in the same limb where the oximetry sensor was placed. This condition was normalized after the second 30. The magnitude difference in the signal before and after this moment can be observed.

4.2.7. *Record of a SpO₂ variation.* SpO₂ records were obtained in volunteers who followed the breathing pattern mentioned. The behavior of this variable was the expected, as shown in Figure 14.

![Figure 14](image14.png)

*Figure 14.* SpO₂ register in two volunteers. After the apnea episode, a SpO₂ decrease can be observed, followed a subsequent return to its initial value.
5. Conclusions
A ΣΔ ADC based pulse oximeter’s acquisition stage prototype was achieved successfully. Since this prototype was designed for laboratory use, a PC managed software which allows hardware control and communication was implemented, also successfully.

During laboratory tests, compliance with requirements defined for each prototype’s block was verified. In addition, during field tests and meeting this article’s objectives, the device proved to be able to provide records during adverse situations, without loss of data due to ADC or sensor saturation, or low-amplitude signals. In all cases plethysmographic signals were recovered correctly.

Furthermore, although the device was not calibrated, the correlation between SpO2 value changes thrown by the prototype, and the expected variations during apnea, is an indicative of acquired data validity.

Moreover, comparing block diagrams shown in Figures 1 and 2, it can be concluded that the reduced complexity of the proposed circuit, means component reduction and also cost savings.

Calibration of the device, microcontroller implementation of algorithms for R and SpO2 calculation, improvement of those algorithms, isolation of the patient circuit, a PC independent user interface, and the expansion of the validation process (i.e. performing the field tests detailed in this article, but over more volunteers) remains for future work.

References
[1] Mardirossian, George; Schneider, Roland E., “Limitations of Pulse Oximetry” (Anesthesia Progress, v.39, pp.194-196, 1992)
[2] Niederbacher Velásquez, J., García Niño, M., Gómez Moya, G., “Valores de referencia de saturación arterial de oxígeno mediante pulso-oximetría en niños sanos de Bucaramanga”, (Med UNAB, v.6, Nº17, pp.63-69, ago 2003)
[3] Zamora, B.W.G, Pérez Barriga, R., “Oxímetro de pulso a PC con interface de Pic16F877”, (XV Congreso Argentino de Bioingeniería)
[4] Sola, A.; Chow, L.; Rogido, M., “Óximetría de pulso en la asistencia neonatal en 2005. Revisión de los conocimientos actuales” (Anales de Pediatría, v.62, Nº3, pp.266-281, 2005)
[5] Townsend, Neil, “Medical Electonics” (Michaelmas Term, 2001)
[6] YaoJ., Warren, S., Ph.D., “Stimulating Student Learning with a Novel “In-House” Pulse Oximeter Design”, (2005 American Society for Engineering Education Annual Conference & Exposition)
[7] Jubran, Amal, “Pulse Oximetry: Review” (Critical Care, v.3, pp.11-17, 1999)
[8] Park, Sangil, “Principles of Sigma-Delta Modulation for Analog-to-Digital Converters” (Strategic Applications: Motorola Digital Signal Processor Operation)
[9] López-Herranz, Patricia G., “Óximetría de pulso: A la vanguardia en la monitorización no invasiva de la oxigenación” (Revista Médica del Hospital General de México, v.66, Nº3, pp.160-169, jul-sep 2003)
[10] Boehm B.W., “A spiral Model of Software Development and Enhancement” (Computer, v.21, pp.61-72, 1988)
[11] Lerendegui, N. M., “Diseño de Equipos y Software”