MICROPROGRAM RECORDING OF HYDROLOGICAL DATA ON READ-ONLY MEMORY

J.M. FRITSCH* and P. MAILLACH**

1. INTRODUCTION - GENERAL CONSIDERATIONS

The search undertaken by us for new data collection instrumentation in the field of hydroclimatology was based on the following objectives:

(1) To provide data acquisition on a machine-readable medium by means of electronic processing, thus eliminating the manual or assisted processing of graphic recordings which has always been a difficult area in hydrological studies.

(2) To improve data collection reliability.

Graphic recorders are very sensitive to environmental characteristics and many devices and components, such as clockwork mechanisms, paper, styluses, pens, etc., are likely to be adversely affected. There is good reason to believe, however, that a well-designed electronic system will provide better performance.

(3) To store significant parameters only.

While access to a programmable microprocessor enables the sensors to be scanned almost constantly, the storage command is only triggered if the parameter variation in question differs significantly from the most recently stored data.

(4) To reduce costs. The cost of precision engineered and clockwork sensors and data acquisition control systems, which are only manufactured in limited numbers, can only increase in the current economic climate. On the other hand, microprocessor-based systems are already less expensive than these devices, and it may be assumed that the price difference between mechanical and microporcessor-based systems can only increase as time goes by.

This article describes two systems designed with to the above-mentioned objectives in view: the CHLOE hydrological processor (Centrale HydroLogique ORSTOM-ELSYDE) using silicon sensors and a sophisticated processing unit; and an OEDIPE (Organe d'Enregistrement Digital de l'Information PluviométriquE) raingauge, with mechanical sensors (tilting bucket) and a simple processing unit. The OEDIPE system is available at a modest price and is suitable for use by non-skilled personnel.

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* Research worker at ORSTOM, P.O. Box 165, 97323 Cayenne-Cedex, French Guyana

** Software Supervisor, ELSYDE, 95 route de Corbeil,
91700 Ste. Geneviève-des-Bois

World Meteorological Organization (ed.), Microprocessors in Operational Hydrology, 25-37.

Both systems use the recording medium and the data rereading unit described below:

2. CE64 MEMORY CARTRIDGE

The CE64 cartridge is a removable unit connected to the data acquisition system by a 96-pin connector. Its external dimensions are 115 mm x 115 mm x 20 mm.

The cartridge has a capacity of 64K bytes of programmable memory which may be erased by ultraviolet radiation (EPROM). This capacity is obtained through the use of eight chips of 64K bits each with standard 28 pin contacts (INTEL 2716, for example).

The primary advantage of the EPROM is the absence of an electric current to maintain the information stored in the cartridge, which makes this medium particularly solid and reliable.

In this technology, when the required bits are written to they are electrically set to zero. A return to the initial state is no longer possible unless energy amounting to 15 Watts per second per square centimetre is applied to the chip in the form of radiation of 250 nanometre wavelength supplied by an eraser lamp.

Erasure time is between 5 and 40 minutes depending on the position of the chip in the eraser tray. Once this operation is completed, all bits in the memory are reset to one.

The number of write-erase cycles that can be undertaken by a package is extremely variable, according to the various manufacturers. Some claim 1,000 cycles, others only 50. We therefore performed a series of bench tests on EPROMS in the CE64 cartridge and over 200 write-erase cycles were performed without damage to the memories.

In fact, the problem most likely to occur after a while is that some bits or bytes in a chip may jam instead of switching back to the zero state after a write instruction. The procedure used with RAM memories (new attempt at writing if the re-read information does not conform to the source information) cannot be used in EPROM technology - EPROM is a one-time shot! It would also be unwise to try to flag the next byte by an appropriate error code (which would enable the laboratory to invalidate the defective byte during read time) because it is quite possible that an entire zone adjacent to the memory, or even the whole 8K byte package, is defective. This considerable restriction has sometimes been cited as a major drawback when using EPROMs for data storage.

In the CHLOE and OEDIPE systems, we employ a special processing and reading procedure by using a microcomputer which enables us to clearly identify the defective bytes which were abandoned at write time. Consequently, the data acquisition system will continue to function, even if one or several packages are out of order. The effective capacity of the cartridge will be reduced, but the validity of the stored data will remain unaffected.

3. READING DATA BY USING A MICROCOMPUTER

CE64 cartridge read-outs in the laboratory are performed using a cartridge memory reader. A microprocessor is used for this purpose, capable of performing a conversational procedure with any micro- or mini-computer equipped with an asynchronous communications port, such as the RS-232C.

When this unit identifies a command of the "C AAAA FFFF" type from the computer, the cartridge contents included between the hexadecimal addresses AAAA and FFFF are transmitted to the processing system by means of the communications port at the rate of 4800 baud, in accordance with the ASCII code generally used in microcomputer data processing. The cartridge contents are also directly interpretable on a display console. By using the CHLOE system, the information stored on the cartridge is coded in BCD (four bits per character) and 128K characters will therefore be transmitted during the entire read-out operation of the cartridge.

This results in the transmission of 10 bits per character: 1 start, 7 data, 1 even parity, 1 stop. In addition to this transversal parity bit at byte level, the cartridge memory reader generates a longitudinal parity byte - an exclusive OR from all transmitted bytes. This (BCC) parity byte is transmitted at the end of each data stream, thus ensuring for the user virtually total security with respect to the conformity between data received and data stored on the CE64 cartridge.

An additional feature provided by the cartridge memory reader enables the user to ensure that the cartridge is completely empty after erasure by the ultraviolet rays. A push-button triggers the sequential reading of the 64K bytes by the cartridge memory reader microprocessor and a light-emitting diode blinks if an erasure defect is encountered. This feature is designed to avoid taking full or partially erased cartridges out into the field, only to be rejected by the data acquisition system.

The cost of a CE64 cartridge is approximately US$ 200. The read and cartridge memory reader test unit unit costs arouund US$ 650 (prices exclusive of tax, 1983).

4. THE OEDIPE RAINGAUGE

The function of the OEDIPE system is to store on the CE64 cartridge the times and dates of electrical impulses triggered by the tipping-bucket raingauge.

The OEDIPE system is housed in a (standard IP 569) plastic, impervious package which weighs approximately 5 kilogrammes and measures 350 mm x 250 mm x 150 mm.

The unit is equipped with a four-socket junction which connects the power lines and the lines linked to the mercury contact, which in turn is linked to the recording raingauge buckets. A light-emitting diode indicating the activation of the cartridge (read or write) completes the facade. This "black box" structure has been retained in order to simplify implementation procedures as much as possible and also to reduce manufacturing costs.

The recorder is automatically activated when a cartridge is inserted. The system is switched on and the microprocessor performs the following initiation programme:

- Reading of the 64K bytes in order to check that the CE64 cartridge is empty (all bytes are at 'FF');
- Writing of the recorder's serial number (factory-set) onto the first two bytes in the cartridge.

This sequence lasts approximately 30 seconds, during which time the 'cartridge activated' light-emitting diode is lit. If the procedure is successfully completed, the LED goes out. If the procedure is not successful a continuous blinking alerts the operator to the fact that the initialization procedure has failed.

This malfunction may be due to two possibilities:

(a) The cartridge is not 'clean';

(b) The write operation of the recorder serial number was not possible and the cartridge is defective.

The electrical current to the system is cut when the cartridge is removed.

When the cartridge is inserted, the OEDIPE internal time reference is initialized to zero. Each tilting motion will be referenced in time relative to this original instant. The user is responsible for noting the start-up date and time so that a recording raingauge card referenced in absolute time may ultimately be created. This procedure takes place in the laboratory when the cartridge is processed.

The temporal coordinates of each tilting motion are immediately stored in binary on four bytes in the following format:

Day of the month (day number)	10 bits
Hour	6 bits
Minute	8 bits
Second	8 bits

Using this coding, each CE64 cartridge can record 16,383 tilting motions, which correspond to the following 'climatological changes':

- 8191.5 millimetres of rain; 1 tip for every 0.5 mm rainfall (buckets 20 cm^3; funnel 400 cm^2);
- 1638.3 millimetres of rain; 1 tip for every 0.1 mm rainfall (funnel 2,000 cm^2).

The supply voltage required may vary between 15 and 11.5 volts DC. Because of the CMOS technology involved, the OEDIPE system only consumes 3mA at 12 volts at rest. During one write cycle, i.e. at each tipping motion, the current required is 400 mA for a period lasting approximately one second. Thus, monthly consumption - at the rate of 2,000 tipping motions per month - may be as low as 2,5 Ah. Electrical independence may thus be achieved by using rechargable batteries, mini solar panels or even dry cells.

It is planned that OEDIPE systems will be inspected and checked while on service in the field. This operation will be made possible by using a pocket mini-terminal, equipped with an LCD display which communicates the most recent OEDIPE recordings to the user, that is:

- The number of tipping motions recorded;
- The amount of memory used;
- The number of defective bytes encountered;
- The time and date of the most recently recorded tipping motion;
- Elapsed time since start-up;
- Battery voltage.

These data may be sent by a transmitter in the ARGOS satellite data-collection system. In this way the OEDIPE functions can be monitored by remote control and cartridge changes in far-off sites with difficult access can be optimized.

The cost of an OEDIPE recorder is approximately US$ 550 and the inspection terminal costs around US$ 600 (prices exclusive of tax, 1983).

5. THE CHLOE MULTI-PARAMETER HYDROLOGICAL RECORDER

Contrary to the OEDIPE system, which is equipped with a mechanical sensor and relatively simple software, the CHLOE system comprises an underwater (SPI) unit, equipped with silicon sensors, a microprocessor, program storage, input-output interface, a veritable underwater data processing system, and an aerial check (SET) unit, the face of which is composed of a keyboard with 12 watertight push-buttons, two 2-digit wheels, one 4-digit dip-switch and an LCD display (Figure 1). It is therefore a more sophisticated system than the OEDIPE and is capable of measuring continuously varying parameters. Setting up the CHLOE system is more complex than for the OEDIPE system.

5.1 THE UNDERWATER PIEZO-RESISTIVE TRANSDUCER (SONDE PIEZO-RESISTIVE IMMERGEE): SPI

5.1.1 Functions and thermal characteristics

The primary function of the SPI system is to measure the true value of the water level of a river in the site's reference hydrological system (set of staff gauges).

This information is obtained by differentially measuring the hydrostatic pressure and the atmospheric pressure. The SPI also measures temperature. Moreover, while testing the prototype in French Guyana, the density of water was measured (using the so-called SPI2 version), as well as the conductivity (using a supplementary probe - the PONSELLE-CTS10.

A piezo-resistive sensor is used to measure pressure. The sensor is made up of a silicon strain gauge which is implanted into a metallic membrane and which deflects under the pressure of the fluid. The deflection causes changes in the internal resistance of the piece of silicon, which causes the voltage across it to vary when subjected to a constant electric current.

This voltage, converted into a frequency, is analyzed by the microprocessor and converted into pressure, then into water level on the staff gauge using the pressure-frequency curve which is specific to the sensor and is established by calibration. The sensitivity of the procedure is such that, by using a sensor capable of supporting 1.5 bar (c.15 metres of water), a 0.1 pressure difference of millibar (i.e. approximately 1mm water) is identifiable at the frequency metering.

5.1.2 Thermal compensation for electronic components and sensor

The SPI system is designed to operate in a fairly variable thermal environment (0 to 50°C). Unfortunately, however, temperature variation has the same effect on silicon as the deflection caused by pressure. It therefore generates irrelevant parasitic information. Similarly, the analogue electronics which formulate the signal for the microprocessor (amplification and frequency conversion) vary significantly with temperature changes. However, thermal effects on the SPI digital electronics are negligible.

Two distinct influences need to be corrected with respect to the sensors and the analogue electronics.

Temperature correction in sensors

The piezo-resistive sensors used comprise various silicon chips which are fixed to a membrane and wired together in a Wheatstone bridge. The temperature variation effects, which in theory are identical on all gauges, is cancelled. In fact, despite these precautions, the gauges frequently remain unmatched after assembly. When static, this causes an imbalance in the bridge and, when in motion, a non-linear temperature drift. Manufacturers suggest on the calibration card of each sensor that several resistance values be planted in either branch of the bridge, in series or in parallel with the gauges, in order to compensate for these imbalances as much as possible. If the imbalance is still not corrected, it is corrected using software, by programming the results of a laboratory calibration in which temperature and pressure were varied. For a given temperature, the output frequency of the sensor is taken every 20 mb between 0 and 1000 mb for temperatures varying at 10° intervals.

This group of curves is stored as a table, in the probe's software, which makes the necessary interpolations.

During the calibration process, only the sensor is submitted to temperature variations in the container because the electronic processing card remains at a constant temperature.

Temperature correction on the electronic processing equipment

Compensation for the drift of electronic components is performed both in hardware and software in accordance with the auto-calibration principle of the components: two ultra-stable reference sources simulate the sensor responses corresponding to the two extreme pressure limits to be measured. The discrepancy between the frequencies transmitted by the two sources compared to those obtained at calibration temperature enables the data processing program to supply the required corrections to the signal as a linear correction.

Figure 2 presents a section of a calibration curve for two sensors, C1 and C2. Along the H = f(K) curve, which gives the water level as a function of the output frequency for a given temperature (18.7° for C1 and 21.5° for C2), the discrepancy is represented in Hertz for two temperatures flanking the calibration temperature (K = f(H,t)).

Note that both sensors present different behaviour: in C1 the output frequency increases with the temperature, whereas exactly the opposite occurs with the C2 sensor. The relative frequency deviations of approximately 4.5% drift per 10°C, in the neighbourhood of zero are significant when the intended uses are taken into consideration, especially with in the case of low pressures.

The individual frequency-temperature-pressure calibration of the sensors is therefore a vital phase in the quality-control of SPI-transmitted measurements.

5.1.3 Housing and flow of SPI operations

The pressure and temperature sensors and the processor card are housed in a PVC tube measuring 70 mm in diameter and 300 mm in height. The probe is connected to the SET central processor by means of an ovoid cable measuring 16 x 8 mm comprising a reinforced atmospheric pressure setting tube and a reinforced electric cable. When equipped with a 12 metre cable, the probe weighs 6 kilogrammes.

The SPI is powered by the SET at 12 volts DC. Consumption rates are 13 mA at rest and 17 mA when measuring and transmitting.

When the SPI microprocessor receives a request for a message from the SET logic, it triggers the counting procedure of the frequencies on the low sensor, on the upper self-calibration reference, on the lower reference and on the temperature sensor. In the 2-pressure sensor SP12 version (see section 5.1.4 - SP12), this procedure is repeated for the frequencies from the 'upper' sensor and from the 'upper' temperature (Figure 3).

All decoding, temperature correction and scaling of units (i.e. water level in cm, temperature in tenths of a degree Celsius) procedures are then carried out and a message is prepared. It is transmitted to the central processor via a synchronous communications link, insulated by an opto-electronic coupler, at the rate of 100 bps.

Once the processing has taken place the final precision of level measurements exceeds 0.1% of full scale (± 1 cm). Message preparation time is approximately seven seconds and the maximum speed for tracking of levels is 0.5 cm per second.

The message is binary coded and includes 45 bits formatted as follows (SPI 1 sensor):

SPI serial number
16 bits
Water level
10 bits
Temperature
11 bits
Longitudinal parity (BCC)
8 bits.

5.1.4 Density measurement

In light of the sensitivity performances of the piezo-resistive sensors, it was worthwhile measuring the density of the fluid by differential pressure between the two sensors separated by a known veritical distance. This is the SP12 configuration. A sensor is placed at the upper and lower extremities of the cylinder acting as the probe.

This adaptation enabled us to both correct the water levels by associating pressure and density, and to transmit and memorize the variations of the density itself which, according to the environment, may be linked to salinity or turbidity. Vast areas of application are thus opened to this probe (oceanography, solid transports, sanitation, etc.).

Assuming P1 is the pressure on the upper sensor, P2 the pressure on the lower sensor, and D the vertical distance separating the two sensors, then the density ρ is expressed as follows:

$$\rho = \frac{P2 - P1}{gD}$$

This expression shows that three conditions must be necessarily combined before the density can be measured:

(a) Distance D must be as great as possible in order to obtain a large P2 - P1 with respect to the precision with which P2 and P1 are known. If the sensors' sensitivity is taken into account, the density precision would be 1% for D = 30 cm, but 0.2% for an SPI measuring one metre in height.

(b) Quite apart from the sensor sensitivity, great care must be given to the sensor accuracy and, consequently, to the calibration accuracy if a two-sensor SPI is to be used. An accuracy error equivalent to 0.4 cms water will not greatly influence a one-sensor SPI which gives the water level to the nearest centimetre. However, it will induce an error of 13 per 1000 in an SP12 measuring 30 cm high - quite a considerable error when one considers the range of densities to be measured.

(c) The probe must be placed in a vertical position so that the altitude difference between the two sensors is indeed equal to D. If the current is strong and there is a great deal of turbidity, this may entail mounting the probe on a rig.

The density is transmitted to the SET in binary using 11 bits, interposed between the water level and the temperature. The SPI2 therefore generates 56 bit messages.

5.2 Conductivity measurement

In the prototype series, condictivity was measured by a PONSELLE device, comprising a CTS10 probe with 4 moulded electrodes and an analog electronic card within the SET. The voltage output calibration, established by the manufacturer, ranges from 0 to 55,000 micro-siemens, for a published precision of 1%.

6. THE SET RECORDER TRANSMITTER SYSTEM

The SET (Système Enrégistreur Transmetteur) is housed in a watertight plastic box measuring 350 x 250 x 150 mm and weighs approximately 5 kg.

The functions of this unit are: interrogation of the SPI sensor, and collection of the information transmitted back by the sensor and by the conductivity probe. The SET also ensures that storage takes place on the CE64 cartridge and that a message is prepared in a format that is compatible with the ARGOS satellite data-collection system.

The SET has an absolute chronological basis of one year to the minute, set by adjustment buttons and displayed on a liquid crystal display. A synchronization button sets the recorder's time basis and logic.

The user accesses two 2-digit wheels which correspond to the interval (ΔT) of the SPI sensor scan, expressed in minutes (1 to 99 minutes), and to the significant water level ΔH threshold for the location, expressed in centimetres (0 to 99 centimetres). The water level is only stored on the EPROM cartridge if the variation measured between two scans exceeds ΔH. This conditional recording of the water level is called an 'intermediary message'. The cartridge also includes so-called 'half-hour' messages, the storage of which is obligatory, on the hour and on the half-hour containing in addition to the water level, conductivity, temperature and density. Some 'half-hour' message parameters may be omitted: a rocker switch on the face of the device enables the user to choose between recording or ignoring conductivity, temperature and density.

Once the time set has been switched on, the selection and display of ΔH and ΔT have taken place, the parameters to be measured have been selected and a fresh cartridge has been inserted, the normal procedure continues by initializing the cartridge, triggered by a command from the operator (push-button).

After having checked that the cartridge is empty, the system copies the characteristics chosen by the operator onto it for this particular data collection, i.e.:

Parameter	Code	Length (bytes)
SET number	Hexadecimal	4
SPI number	"	4
Parameter selection	"	2
Height sensitivity threshold (ΔH)	BCD	2
Sensor interrogation interval (ΔT)	"	2
Start-up date		
Year	"	2
Month	"	2
Day	"	2
Hour/minute	"	4

If the procedure fails, an error message is displayed on the screen which means 'cartridge not fresh' or 'write impossible'.

The SET has push-buttons for activating the SPI and the conductivity probe and for instantaneously displaying the measured values.

A command enables the alignment of the level-pressure of the sensor with the staff gauges of the site (setting the system zero).

Finally, the most recent memory address of the cartridge can be displayed at any time and its contents can also be scrolled across the display.

An ARGOS message is generated every 30 minutes, which enables the transmission of all parameters collected during the preceding two-and-a-half hours (five sensor-blocks of 6 bytes). Two bytes remain available in the message for transmission of the address of the most recent data in the CE64 cartridge.

The SET voltage is 12 volts DC (11.5 to 15 V) and consumption is 18 mA when recording is not taking place and 400 mA when the cartridge is written to. The prototype unit tested in French Guyana was fed by an 8 Watt solar panel, powering both the CHLOE (SET + SPI) and the ARGOS (CEIS - LAMD82) transmitter.

Data are coded in BCD in the following fashion:

"Intermediate" message (three bytes)	
Minute number (0 to 59)	1 byte
Water level (0 to 999)	1.5 bytes
Alignment character ('F')	0.5 bytes
"Half-hour" message (3 to 7 bytes)	
Minute number (00 to 30)	1 byte
Water level (0 to 999)	1.5 bytes
Optional:	
Conductivity in hundredths of micro-siemens (0 to 550)	1.5 bytes
Density (0 to 99) ($\rho - 1000$)	1 byte
Temperature in 1/10 degree (000 to 500)	1.5 bytes
Alignment character ('F')	0.5 bytes

In late 1983 the cost of a CHLOE processor, comprising one SET and one 1-sensor SPI, was approximately US$ 2,600; and with a 2-sensor, density measuring SPI the cost was approximately US$ 3,000.

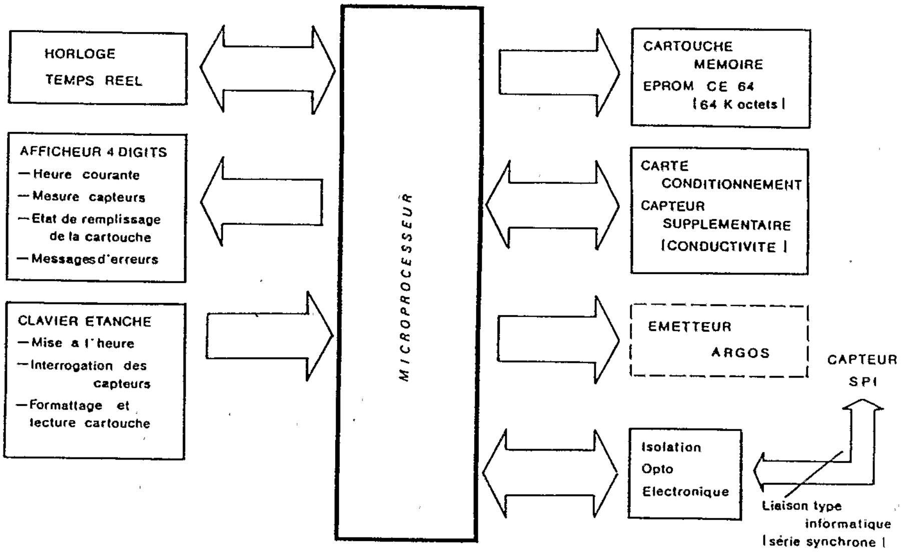

Figure 1. Chloe Processor
Block diagram of the SET recording-transmitting system

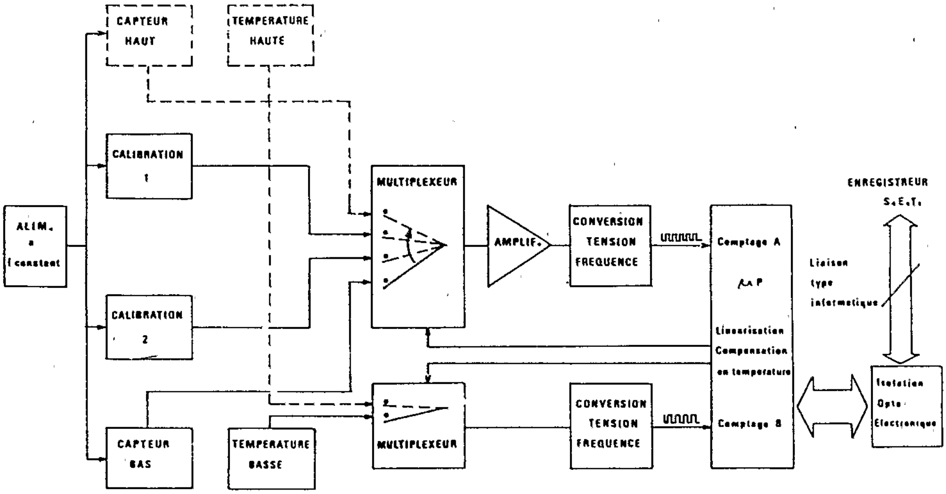

Figure 3. Block diagram of the SPI sensor

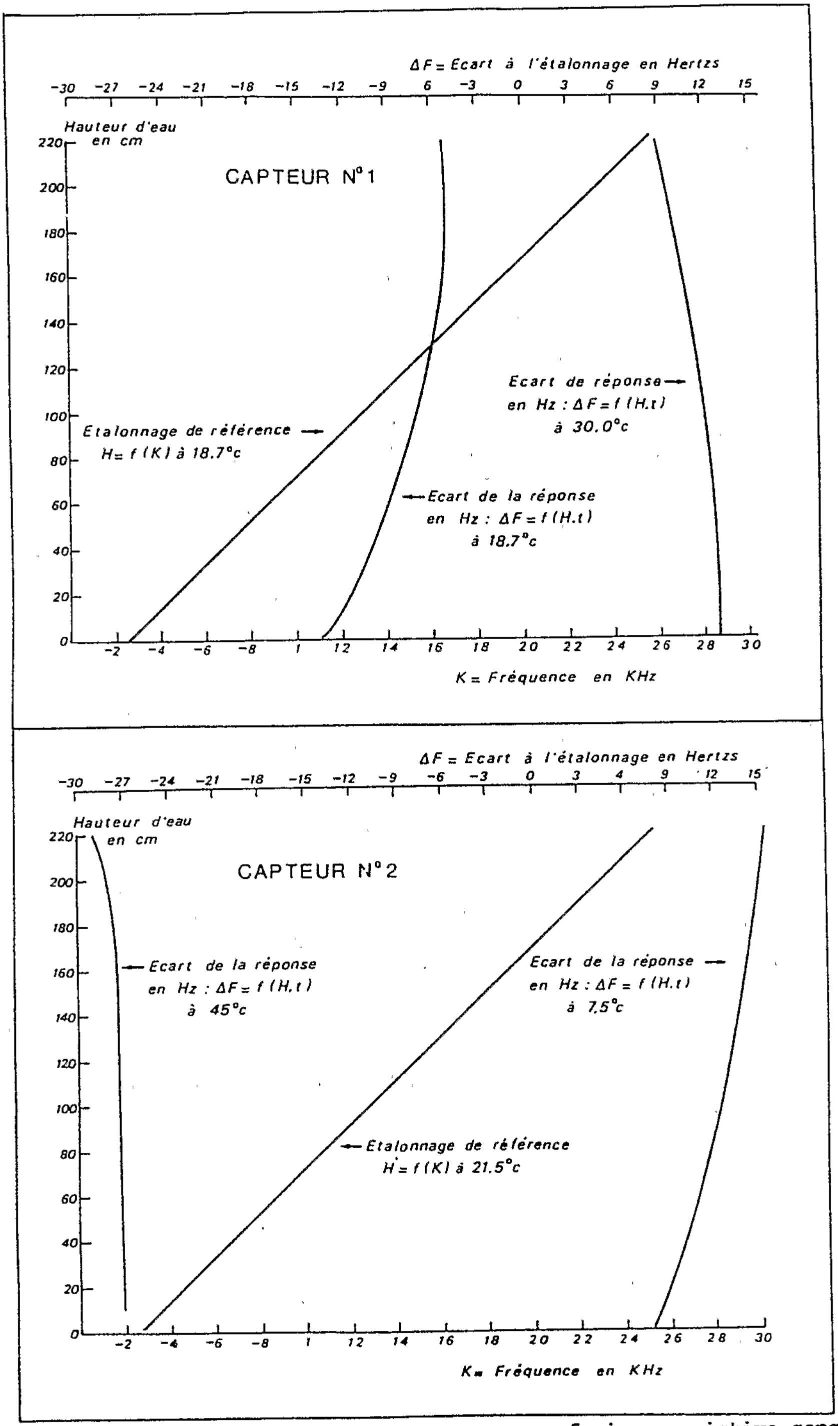

Figure 2. Pressure and temperature responses of piezo-resistive sensors