Data Logger Fundamentals for Environmental Monitoring Applications

The following is a basic overview of data logger features and specifications with relevance to environmental monitoring applications. Although data loggers are used in many industries from space exploration, to oil refining, to drag racing, we will be focusing on their application for environmental monitoring.

What is a datalogger?

A data logger is an electronic instrument that records environmental parameters such as temperature, relative humidity, wind speed and direction, light intensity, water level and water quality over time. Typically, data loggers are compact, battery-powered devices that are equipped with microprocessor input channels and data storage. Most data loggers utilize turnkey software on a personal computer to initiate the logger and view the collected data.

Who uses Data Loggers?

The use of data loggers for environmental monitoring became common during the 1980's; coinciding with the explosion in personal computers (PC's). This is no coincidence since a data logger consists of many of the same, or similar, components used to manufacture a PC. In fact, a data logger is basically a stripped down 386 vintage PC with input channels, instead of a keyboard and floppy drive, which operates on battery power. As the price of PC components dropped, data loggers became more affordable for a wider array of applications. Before then, chart recorders were commonly used as well as manual measurements. Both of these methods were labor intensive and time consuming so the advent of stand alone data loggers was welcomed. In Canada some of the early adopters included Environment Canada (Atmospheric Environmental Service and Water Survey of Canada) and the Provincial Hydro companies (Quebec Hydro, Ontario Hydro, Sask Power, BC Hydro, etc.) as well as Provincial Ministries such as BC Ministry of Forests (Fire Weather Index Monitoring) and BC Ministry of Transportation (Snow Avalanche Monitoring). These organizations had a large stake in obtaining meteorological and hydrometric data to protect people, land and assets, as well as establish base line data sets from which long and short term plans could be developed. As the decade progressed a greater variety of data loggers were developed at lower costs, making data loggers affordable for not only large long term network application but also for smaller temporary projects.

With the rapid advent of microprocessor and memory technology, data loggers are now available for virtually any monitoring project from as little as $50.00. Hence, today's users of data loggers span from a single installation for measure temperature to meteorological networks of hundreds of stations monitoring temperature, relative humidity, barometric pressure, solar radiation, precipitation and wind speed & direction.

Why are data loggers used?

A data logger is used to collect readings, or output, from sensors. These sensors could be measuring industrial parameters such as pressure, flow and temperature or environmental parameters such as water level, wind speed or solar radiation. Today there are sensors available which can measure virtually any physical parameter. Senors have been developed to measure gas pressure within human cells to cloud height and density. Most sensors are based on physical and chemical theories that have been discovered long ago, such as the theory of partial pressure of gasses, the Doppler theory and metal resistance changes with temperature. Most environmental sensors were developed from sensors designed for industrial applications such as process control (refining, milling, distilling, etc.). Therefore many environmental sensors are designed with the same characteristics as industrial sensors such as 4-20 mA output & 12 VDC power supply.

How do data loggers work?

The 8 main components of a data logger are:

1 - Input Channels

The output from a sensor is inputted or connected to a data logger channel. A channel consists of circuitry designed to 'channel' a sensor signal (typically a voltage or current) from the sensor to the data logger processor. A single data logger can have a variety of channel types and from one to many channels (multi-channel data logger) - one channel is required for every sensor signal output. For example, four sensors can be connected to a four channel data logger and eight sensors to a eight channel logger. Typically, a multi-channel logger will have from four to 16 channels. Three types of channels are typically found on a multi-channel data logger, they are:

Analog Channel

Analog channels are the most common types of input channel found on multi-channel data loggers since most sensors have an analog output. Webster defines analog as:

*"of relating to, or being a mechanism in which data is represented by **continuously variable physical quantities**" and "being a timepiece having hour and minute hands"*

A characteristic of analog signals is they are continuous (i.e., do not change in fixed increments) over their range and most analog sensors are linear. An analog sensor will output an electrical signal, typically a voltage (mV), which is proportional to an environmental parameter such as air temperature. Graphically, the relationship between voltage and air temperature, will be a smooth curve or straight line (linear). For example a temperature sensor may have a range from 0 to 100 degrees Celsius and output a signal from 0 to 5 Volts:

Temperature	Output Voltage
0 degC	0 volts
100 degC	5 volts

Therefore if the temperature is 0 degC the sensor will output 0 volts, and if the temperature is 100 degC the sensor will output 5 volts. If the above sensor is linear (directly proportional) it will output 2.5 volts at 50 degC, and at 75.45 degC it will output 3.7725 volts. Typical analog sensors include:

Meteorology	**Hydrology / Water Quality**
Temperature	Pressure / Level
Relative Humidity	Temperature
Solar Radiation	pH
Barometric Pressure	Conductivity
Wind Direction	Dissolved Oxygen
Leaf Wetness	Turbidity

Digital Channel

Digital channels are the second most common type of input channel found on multi-channel data loggers. Webster defines digital as:

*"of relating to, or using calculation by numerical methods or by **discrete units**" and "of or relating to data in the form of numerical digits"*

The main characteristic of digital signals is they increase and decrease in discrete or fixed intervals. Graphically the 'curve' of a digital signal would increase or decrease in a 'staircase' like pattern. The signal output has an on/off characteristic and is not continuous. For example, a wind speed sensor may contain a contact switch that closes each time the wind sensor does a revolution. Therefore, if the sensor does only 3/4 of a revolution the switch will not close, only when it does a full revolution it closes. After a second full revolution, it closes again. Graphically, the relationship between contact closures and wind speed would be in steps and could or could not be linear. Knowing the sensor characteristics, or calibration factor, and if the closures are measured over a fixed time interval, the wind speed can be calculated. For instance 100 revolutions per minute may equal a wind speed of 5 km/hr and 200 revolutions per minute may equal a wind speed of 10 km/hr. The datalogger accumulates, or totalizes, the discrete closures over a fixed time interval.

Revolutions per Minute	Wind Speed
100	5 km/hr
200	10 km/hr

Typical digital sensors include:

Meteorology	**Hydrology**
Wind Speed Sensor	Paddle Wheel Flow Sensor
Tipping Bucket Rain Gauge	Tipping Bucket Flow Sensor

SDI-12 (Serial Digital Interface)

Developed in the late 1980's to take advantage of reasonably priced microprocessors, SDI-12 is an abbreviation for Serial Data Interface at 1200 baud. It is a standard to interface data loggers with micro-processor based sensors designed specifically for Environmental Data Acquisition (EDA). SDI-12 is a standard communications protocol that provides a means to transfer measurements taken by an intelligent sensor to a data logger. A micro-processor in the sensor may calibrate the sensor, control sensor measurements, convert raw sensor readings into engineering units, and uses the SDI-12 protocol to transfer reading to the data logger. For example, a SDI-12 pressure sensor may take a series of pressure measurements, average them, and then output pressure in psi, inches of mercury, bars, millibars, or torrs to the data logger.

SDI-12 is ideal for use in applications with the following requirements:

- Battery powered operation with minimal current drain.
- Use of one data recorder with multiple sensors on a single cable.
- Use with microprocessor-based sensors that perform complex calibration algorithms or make internal computations such as temperature compensation.

Virtually any analog or digital sensor can, and has, been modified into a SDI-12 sensor, however the cost is prohibitive in many cases.

2 - A/D converter (Analog to Digital Converter)

All sensor signals, analog, digital and SDI-12, must be in binary format in order for the data logger to record them. Binary data format is not specific to data loggers but is the fundamental data format used by virtually all computers from digital cameras to NASA mainframe computer.

Binary Data Format

Binary describes a numbering scheme in which there are only two possible values for each digit: 0 and 1. The term also refers to any digital encoding/decoding system in which there are exactly two possible states. In digital data memory, storage, processing, and communications, the 0 and 1 values are sometimes called "low" and "high", respectively. A bit represents a positive "high", or negative "low" electric charge (which is stored in a silicon chip). These are the only two digits the computer can understand. Because of this, computers work on a binary number system, instead of the decimal system we are familiar with. The word bit stands for binary digit. The computer interprets the negative and positive electric charges as binary digits (bits), and groups eight bits together into a byte. Just as a word is made up of letters, a byte is made up of bits.

While words have a variable number of letters, all bytes have eight bits. The sequence of the eight 1's and 0's identifies one byte from another. Binary data is also commonly referred to as digital data.

> *Bit - A bit is the smallest and simplest piece of information that a computer can manipulate. A bit is either 0 or 1, with 0 meaning off, and 1 meaning on. The term binary means a choice between two possible options - 0 and 1. Computers combine collections of bits into more complex forms in order to represent data.*
>
> *Byte (A byte is 8 bits) - A byte usually represents a single character or value.*
>
> *Binary - A number representation consisting of 0's and 1's used by practically all computers because of its ease of implementation using digital electronics and Boolean algebra.*

Binary numbers look strange when they are written out directly. This is because the digits' weight increases by powers of 2, rather than by powers of 10 (used in the decimal system we are familiar with). In a binary digital numeral, the digit furthest to the right is the "one's" digit; the next digit to the left is the "two's" digit; next comes the "four's" digit, then the "eight's" digit, then the "16's" digit, then the "32's" digit, and so on. The decimal equivalent of a binary number can be found by summing all the digits. The far right side bit in a byte (8-bits) is referred to as bit #0, and each bit to its left is one bit number higher than the previous bit. Therefore, the far-left bit in a byte is bit #7.

Bit	**#7**		**#6**		**#5**		**#4**		**#3**		**#2**		**#1**		**#0**		
(1) Value when 'on'	128	+	64	+	32	+	16	+	8	+	4	+	2	+	1	=	255
(0) Value when 'off'	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	=	0

A byte can represent 256 values (2 to the power of 8 equals 256), and so a computer can use a byte to identify 256 different values (one value for each number from '1' to '255' plus a value for the number '0' makes 256 values in total). For example, if all the bits are 'on', the value will equal 255, and in computer binary code would look like eight one's, *11111111*. And if all the bits are 'off', the value will equal 0, and in computer binary code would look like eight zero's, *00000000*. Any number between 0 and 256 can be created by 'turning on' a specific combination of the bits. Here are some more examples:

Binary Code		Decimal Value	Binary Code		Decimal Value
00000001	=	1	*00011001*	=	25
00000010	=	2	*01011001*	=	89
00000011	=	3	*10111010*	=	186
00000111	=	7	*11011001*	=	217

Binary Data Format and Data Loggers

As previously mentioned, all sensor signals, analog, digital and SDI-12, must be in binary format in order for the data logger to record them.

SDI-12 signals are already in binary format and require no conversion.

Digital signals are easily converted to binary format since digital signals are 'counted' on a digital channel. Therefore, if the digital channel is 8 bits it can record 225 counts over a given time period.

Analog signals however need to be converted to binary data via an A/D converter (Analog to Digital Converter). The amount of bits the A/D converter utilizes will determine the resolution to which the signal can be recorded. According to Webster, resolution is:

"the process or capability of making distinguishable the individual parts of an object"

For example, if a temperature sensor is linear from 0 to 100 degC with a 0 to 5 volt output and connected to an 8 bit channel, the following relationships will exist:

Temperature	0 degC	to	100 degC
Output Voltage	0 volts	to	5 volts
Binary Value	0	to	255
(Binary Code	*00000000*		*11111111)*

Therefore, the resolution of the A/D converter is 100 degC / 255 bits = 0.39 degC per bit, or 5 volts / 255 = 0.0196 volts per bit.

However, if the A/D converter utilizes 10 bits [255 (Bit #0 to 7) + 256(Bit #8) + 512(Bit #9) = 1023], then a total of 1024 values can be represented. Therefore the resolution in the above example would be, 100 degC / 1024 = 0.098 degC per bit. Hence, if we utilize a logger channel with 10 bit resolution, we increase the resolution by four times compared to an 8 bit channel.

Sensor Accuracy and Channel Resolution

Webster defines accuracy as:

"the degree of conformity of a measure to a standard or a true value"

All sensors are specified with range and accuracy. The accuracy indicates how closely the sensor can measure the actual or real world, parameter value. Generally the more accurate a sensor is, the more expensive it is. Therefore, in order to take full advantage of the sensors accuracy a data logger channel should be used which has a resolution equal or better than the sensor accuracy.

If the above temperature sensor only has an accuracy of 0.5 degC, then an 8 bit channel (0.39 degC resolution) is suitable, but if the temperature sensor has an accuracy of 0.1 degC, then a 10 bit channel (0.098 degC resolution) should be used since we want to be able to record temperature changes at least equal to the sensors accuracy. Some loggers have channels that can be programmed to different resolutions. Most loggers have a minimum of 8 bits resolution, with 10 to 12 bits being common. Some loggers even have 16 bit (one part in 65536) resolution!

3 - Microprocessor

A processor is the logic circuitry that responds to and processes the basic instructions that drive a computer or data logger. A microprocessor is a computer processor on a microchip. It's sometimes called a logic chip. A microprocessor is designed to perform arithmetic and logic operations that make use of small number-holding areas called registers. Typical microprocessor operations include adding, subtracting, comparing two numbers, and fetching numbers from one area to another. These operations are the result of a set of instructions that are part of the microprocessor design. When a data logger is powered on, the microprocessor is designed to get instruction from the operating system that is loaded in the data logger memory. The operating system is "driving" the microprocessor and giving it instructions to perform. The operating system of the microprocessor usually resides on an EEPROM chip (see below) which is upgradeable.

4 - Memory

Two types of memory are used in data loggers:

RAM (Random Access Memory)

Unlike a PC's RAM which is used as a 'workshop area', a data logger can use RAM to store data (readings from the input channel). RAM chips are inexpensive but must be battery backed up in order to retain the data. RAM chips are downloaded via the serial port of a PC.

EEPROM (Electronically Erasable & Programmable Read Only Memory)

Developed for data loggers in the late 1980's EEPROM memory does not need to be backed up by a battery. Many data loggers use EEPROM chips for both storing the operating system of the microprocessor, as well as for data storage. An EEPROM chip can be programmed, read (stored data) and erased via the serial port of a PC. Data loggers may also use PCMCIA data cards for memory; these cards consist of EEPROM memory.

5 - Power Supply

A feature that clearly distinguishes data loggers from PC's is the low power requirements of data loggers. Data loggers are designed to operate in remote locations for long periods of time void of main AC power. Most data loggers require a 12 VDC power source. Battery capacities are measured in Milli-Amp hours (mAh) which determines the length of time that the battery can provide power for a given load. Increased capacity requires greater battery size and weight. Below are the various types of batteries available for data logging applications:

Non-Rechargeable Batteries

Lithium Batteries - The best non-rechargeable power source available today and are available in the same sizes as alkaline batteries (AAA, AA, C, D). They have a very high capacity vs size, work very well at cold temperatures and do not discharge over time. However they are expensive compared to alkaline batteries (about 5 times the cost!) and are not available in large capacity sizes.

Alkaline Batteries - One of the best sources of power for a data logger. Alkaline batteries have a high capacity vs size, do not discharge over time, work well at cold temperatures and most importantly are widely available at a reasonable cost.

Rechargeable batteries

Sealed Lead Acid Batteries - Commonly used for ATV's, snowmobiles and motorized wheel chairs. These batteries are very similar in design to automobile batteries however the acid liquid is impregnated in a foam matrix and are sealed and therefore not refillable. The advantage to these batteries over automobile batteries is they can be orientated in any position, including upside down. The Deep-Cycle version of these batteries, as their name implies, can safely be discharged to low levels and recharged unlike automobile batteries. Also, Deep-Cycle batteries are available in very large capacities, work well at cold temperatures and have good re-charging characteristic (no battery memory, see below Ni-Cd). These batteries are widely available in a huge array of sizes at a reasonable cost and are commonly used for data logger applications requiring minimal maintenance (visits). Solar panels are often connected to these batteries to keep them charged up.

The following 3 rechargeable battery types are not recommended for data logging applications, most are custom made for portable devices such as PC's, cell phones and GPS receivers:

Nickel Cadmium (Ni-Cd) batteries - Are the least expensive rechargeable battery and were commonly used for cell phones, video cameras, laptops and other portable appliances during the 1980's to early 1990's. The major problem with Ni-Cd batteries is that they are very prone to voltage depression, otherwise known as "memory effect". This occurs when recharging a battery before it is fully discharged, which causes the battery to "remember" its previous partial charge level and not charge to full capacity.

Sometimes conditioning (repetitive fully charging and discharging) can help erase built-up memory, but not always. Other disadvantages are; Ni-Cd batteries discharge over time, they do not have a high capacity vs size, and they can be damaged by excessive heat from overcharging.

Nickel Metal Hydride (Ni-MH) batteries - Which replaced Ni-Cd batteries during the early 1990's, are superior to Ni-Cd batteries because they are available in higher capacities and are virtually memory-free. That means you can charge the battery when it is convenient for you, not when the battery is "ready" (fully discharged). However, Ni-MH can be damaged by excessive heat from overcharging (make sure to use a properly sized charger for the battery!).

Lithium Ion (Li-ion) batteries - Are the best rechargeable batteries available for portable devices. They offer long life and high capacity vs size and are memory-free. Li-ion batteries are the batteries available for many of today's cellular phones, PDA's and laptop computers.

Note: Faulty batteries are one of the most common causes of data logger failures!

6 - Data Output Port (PC Communication Port or RS-232 Port)

Most data loggers communicate with a PC via a serial port, which allows data to be transmitted in a series (one after the other). The RS-232 interface has been a standard for decades as an electrical interface between data terminal equipment, such as a PC, and data communications equipment employing serial binary data interchange, such as a data logger or modem. Data can be sent in both directions, and many loggers use 9600 baud as a standard communication speed. Since the RS-232 is so popular, many modems are available that can be connected to a data logger to retrieve data remotely or to program the data logger. Both land line and cell phones can be used with dataloggers, as well as GOES (Geostationary Orbiting Environmental Satellite) receivers, LOE (Low Earth Orbiting) satellite transceivers and radio transceivers.

7 - Weatherproof Enclosure

Since environmental data loggers are usually installed in remote and harsh locations, a weatherproof case is an obvious requirement. Most loggers are packaged in weather resistant plastic cases. For installations prone to vandalism, a steel enclosure should be used. **Intrusion of moisture into the data logger circuitry is a primary cause of data logger failures**. Therefore, loggers should be installed in as dry a location as possible, also desiccant packs can also be placed inside the case to absorb moisture.

8 - Software

Proprietary software is usually required to program and download data from a data logger. Data logging functions such as sensor scan rate and scaling, log interval, communication protocol and output format (Excel, ASCII, plot, etc.) are programmed using software loaded on a PC. Most loggers available today have a Windows software package and many manufactures have developed software to run on a Palm or similar device. Usually only one license is required per user regardless of the number of loggers they operate.