COMPUTERIZING REMOTE FIELD DATA ACQUISITION

Thomas R. Clune
Computerization Specialist
Eye Research Institute
20 Staniford Street
Boston, MA 02114

ABSTRACT Aspects of remote field data loggers are considered, with particular emphasis on the choice of A/D converter. Commercially available field data loggers are then evaluated for appropriateness in unattended field operation for environmental monitoring. An annotated bibliography is included for further reading.

1.0 INTRODUCTION

The problems involved in computerizing remote field monitoring systems are different in kind from the problems involved in computerizing a laboratory instrument or experiment. Field conditions place a unique set of demands on sensors and data loggers alike. In this paper I will explore the ways that field operation affect the choice of data logging equipment, then examine the strengths and weaknesses of some commercially available products. I will not discuss the problems involved in unattended field use of sensors, as it is outside my area of expertise.

By and large, the problems field operation pose are obvious. First, the unit must be battery operated and therefore energy efficient. Two clear consequences of this are that the ideal field unit should be fabricated with CMOS technology and be capable of powering down to a battery-saving standby mode for the extended periods of latency that characterize environmental monitoring.

Second, the unit must be able to operate over a broad range of temperatures. The problem of variation with temperature will occupy much of what follows.

Third, there must be some provision for storing data in reasonable security until the field unit can be serviced. What this means in practice is not at all obvious. We will consider the trade-offs involved in data storage media as we proceed.

Perhaps surprisingly, dust, moisture, and humidity are not particularly difficult problems. In general, a NEMA enclosure for the data logger will protect the unit from dust and moisture. Solid state devices are generally indifferent to humidity, barring precipitation onto the printed circuit board itself. Tape media, however, are more sensitive to humidity extremes. If your mass storage is tape or floppy disk, humidity can become a limiting consideration.

2.0 ANALOG TO DIGITAL CONVERTERS

Commonly, people think that there is only one kind of analog to digital (A/D) converter. In fact, there, are at least five different kinds of A/D converters in common use. In order to determine what kind of data logger would best suit environmental monitoring applications, it is necessary to understand the strengths and weaknesses of the various A/D units. We will consider flash converters, successive approximation, up-down counters, voltage to frequency converters, and dual-slope integrators.

While there are substantial differences between the various kinds of A/Ds, they all have some basic components in common. These include a reference voltage, a comparator, and an input op amp to provide high input impedence.

The reference voltage is normally provided by a reverse-biased zener diode. Zener diodes block the flow of current below a precisely-definable critical voltage and offer essentially no resistance above the so-called "breakdown" voltage (typically about 5.6 V). So, if you connect a 9 V battery to a circuit with a zener diode, you will know precisely what the voltage drop across the zener is (5.6 V), even if the battery discharges to, say, 7.5 V. By itself, the zener´s thermal characteristics are not very good. It varies about 360 ppm/C. However, this thermal effect can be compensated for by including a forward-biased diode in series with the reverse-biased diode and using the voltage drop across both for the reference. As the reverse-biased diode´s breakdown voltage goes up, the forward-biased diode´s voltage goes down by very nearly the same amount. The resulting thermal drift can be lowered to about 5 ppm/C. In order to achieve this level of precision, the voltage reference should be buried in the A/D IC itself, rather than added during manufacture or by the end user.

The comparator and input op amp can, in practical terms, be ignored by the end user.

2.1 FLASH CONVERTERS

Flash converters are also called parallel converters. They are used when high-speed (>1 MHz), relatively low-resolution (<= 8 bits) conversion is needed. A major application of flash converters is digitizing video signals.

An 8-bit digital word can have any of 256 values, from 0 to 255. An 8-bit flash converter uses 255 comparators to test all possible values of the input signal at once. The advantage of flash converters is obvious: they are very fast. The disadvantages are equally obvious. First, they have limited resolution. Further, because each comparator has its own reference-voltage dividing resistance, the linearity is less than other methods with the same nominal resolution. Third, the complexity of the circuitry makes the units much more expensive than the other kinds of converters. Since environmental monitoring applications are very low-speed, flash converters are not appropriate here.

2.2 SUCCESSIVE APPROXIMATION METHOD

Successive approximation is the most widely used method of A/D conversion. An example of its operation will readily explain how it works. To convert an analog signal that can be anywhere from, e.g., 0 to 10 volts, the converter first determines whether the signal is greater than 5 volts. If so, it establishes whether the signal is above 7.5 V, and so on to the level of precision of the unit. Stated slightly differently, the successive approximation method determines the most significant bit (MSB) of the digitized value first, then the second MSB, and so on down to the least significant bit (LSB).

Internally, the converter uses a digital to analog (D/A) converter in conjunction with the reference voltage to generate each test voltage in sequence. The D/A unit uses an op amp and a switchable resistance ladder to generate the different test voltages from the reference voltage. The primary disadvantage of this approach is that the resistors have a thermal bias of their own. The 5 ppm/C thermal bias of the reference voltage is increased to, typically, 50 ppm/C because of the D/A thermal bias. To see what this means in terms of resolution, let us imagine that our operation is subject to a reasonably moderate 60 C swing in temperature over the course of our monitoring. Further, we will rashly assume that the sensors have no thermal bias of their own. Our hypothetical system would have a theoretical maximum resolution of 60 x 50 = 3000 ppm, or 3 ppt. An 8-bit board resolves a voltage into 256 parts, and a 9-bit board yields 512-step resolution. Thus, the maximum resolution would be approximately 8 1/2 bits for a board with 50 ppm/C that is subject to 60 C variation in temperature.

The thermal bias can be considerably worse for some boards. In particular, most successive approximation boards have sample-and-hold (S/H) circuitry on them. A S/H is basically a capacitor that sits between the analog input and the digitizing unit. The capacitor is charged by the analog signal for a specified time period, and then it -- rather than the analog signal -- is converted by the A/D unit. The advantage of a S/H is that it allows the successive approximation converter to track signals as much as a thousand times faster than could be done without it, because the value being converted is held constant through the conversion. Using S/H, successive approximation converters can track transients as fast as about 10 KHz, whereas without them, the method is limited to a few hertz. The disadvantage of S/H is that capacitors are very sensitive to temperature variations. Since the sensors used in environmental monitoring will generally be essentially DC devices, changing over a period of minutes or more rather than a period of milliseconds, S/H is neither necessary nor desirable on environmental monitoring equipment. A further disadvantage to having a capacitor as a critical component is that capacitors age more rapidly than other electrical devices. In addition to being thermally biased, they are temporally unstable.

Successive approximation is by far the most common A/D method, because it presents a good compromise between speed and cost in a laboratory environment. So you may find yourself using it even though it is not the method of choice for field use. However, if you do end up with a successive approximation unit, you should make sure that it does not include a S/H.

2.3 UP-DOWN COUNTERS

Up-down counters are also called "servo" counters and "track/hold" converters. They are similar to successive approximation converters, except that they count up (or down) one unit at a time. That is, if an up-down counter were set to resolve an analog voltage to the nearest 0.1 V, the comparator would first check to see if the analog voltage were more than 0.1 V, then 0.2

V, and so on. For an 8-bit conversion, an up-down counter could go through 255 steps before finding a match, whereas the successive approximation method would require only 8 steps. Once the converter has homed in on the correct voltage, it tracks the voltage by stepping up one count if the comparator shows that the converter is reading low or stepping down one count if the comparator shows that the converter is reading high. So once a track/hold converter has locked onto the analog signal, it only has to go through one transition to track a voltage change. If a DC voltage is being tracked by an up-down counter, the count will oscillate between the count just above and just below the true DC value. Thus, even when carefully calibrated, a track/hold reading is always +/- 1 LSB.

While up-down counters can be used to track up to about a 1 KHz signal, they are generally not pushed nearly that far. In fact, they are most commonly used as digital chart recorders. The features that make them ideal for such applications are first, they track relatively smooth changes quickly, reliably, and inexpensively. Second, they make coordination of multiple readings easy -- the reason that they are called track/hold converters is that, in addition to tracking a voltage, they can be make to hold a count by pulling a HOLD line high. Since many HOLD lines may be tied to the same command line, coordination of different units' sampling time can be achieved automatically. By contrast, successive approximation units are expensive enough that usually a single unit is multiplexed for sequentially reading multiple analog lines, so coordinating readings is normally not supported. A further advantage of the track/hold architecture is that there is no need for S/H circuitry: once the unit has settled into tracking a voltage, it will only be changing a single bit at a time anyway.

The primary disadvantages of the up-down counters are that it has a relatively long settling time when first triggered and is slower than either flash or successive approximation. The thermal characteristics of track/holds are essentially the same as successive approximation units without S/H circuitry.

2.4 VOLTAGE TO FREQUENCY CONVERTERS

A voltage to frequency converter uses the input analog signal to charge a timing capacitor of a multivibrator, which thus outputs a pulse stream whose frequency is proportional to the input voltage.

There is a lot to like about VFCs. First, they have exceptional resolution. Since the analog voltage is determined by a frequency counter, the resolution can be increased simply by increasing the integration time of the counter. Second, they have good noise-rejection characteristics, since the unit transmits a pulse stream instead of an analog voltage. And third, they "lend themselves to acoustic transmission through water (or air), as well as to the modulation of RF or microwave carriers," according to Analog Devices [1, p. 98]. This last property sounds very promising for remote environmental monitoring. Unfortunately, however, VFCs are very sensitive to temperature variation because of their reliance on a timing capacitor. Typical thermal specifications for VFCs are 500 ppm/C. A second disadvantage in some contexts is that they are quite slow, but for our purposes the feature that takes the blush off their rose is the thermal characteristics.

2.5 DUAL SLOPE CONVERTERS

Dual-slope converters, like VFCs, are integrating converters. They work as follows: a capacitor is exposed to the analog voltage for a specified period of time, rather like a S/H. This step is the first "slope" of the dual slope converter. Then, the capacitor is discharged by being exposed to the reference voltage of opposite sign to the charge. The length of time necessary for the capacitor to discharge is timed by the same timer that set the capacitor's charging time. The digital value of the input signal is thus a ratio of the capacitor's charge to discharge times.

The great virtue of dual slope converters is that they are virtually free of thermal bias. The bias introduced by the capacitor and timer on the first leg of the conversion process is exactly offset by the same capacitor and timer bias on the second leg of the conversion process, assuming that the unit is thermally stable during the conversion process (which takes less than a second). The only thermal bias that they cannot escape is the thermal bias of the voltage reference. Thus, thermal drift is typically 5 ppm/C for units with imbedded references.

Dual slope converters are more familiar to you than you may realize. They are commonly used in digital multimeters. The major drawback to them is that they are slow (1 to 10 Hz). One advantage beyond thermal stability is the unit's excellent high-frequency noise rejection because of its slowness. Further, the clock frequency in DMM applications can be chosen to make the integration time an even multiple of 60 Hz, so line noise will sum to zero during integration.

2.6 CONVERTER CONCLUSIONS

Dual slope converters are ideal for environmental monitoring because they have such a low thermal response coefficient and because they are so slow that they do not respond to relatively high-frequency noise. Even without a filter, lightening should not introduce significant error into a reading unless it is very near. However, it would be a mistake to over-emphasize the importance of this design in a data logger. The thermal properties of track/hold converters and successive approximation converters without S/H circuitry are quite regular. While the calibration curve for these devices plus your sensors may be more complex than the calibration curve for a dual slope device, the data should be equally reproducible for a noise-free or properly filtered environment. The real significance of purchasing a track/hold or successive approximation data logger is that they must be calibrated. If you have developed the habit of using instruments without calibrating them first, a dual slope converter will provide you with the most reliable uncertain results. If, on the other hand, you observe good laboratory practice and calibrate your instruments before using them, there is no reason to avoid track/hold or successive approximation as long as the unit lacks S/H circuitry. The real villain in temperature-sensitive contexts is a critical capacitive component.

3.0 MASS STORAGE

The only thing that is easy to determine in mass storage is what kind of storage system is inappropriate for field work.

Bubble memory is inappropriate because it consumes too much power and requires mild temperatures (approx. 10 to 55 C typical). Disk drives require too much power, are sensitive to humidity (operating ranges about 25% to 75% r.h.), and require mild temperatures (approx. 10 to 40 typical). Tape drives suffer similar disadvantages to disk drives, except that tape units are more energy-efficient. Printers are inappropriate because they consume too much power and require you to re-enter the data if you will be doing any further analysis. Onboard RAM is unacceptable because a power failure would result in loss of all data.

Unfortunately, there are no mass storage devices left. So we must return to our list above and try to decide what we can live with. In general, high power consumption is not acceptable, so we are left with tape drives or onboard RAM. If your operating conditions are mild enough to allow you to use a microcassette, you should do so. The security of saving data even in the event of drained batteries is desirable. On the other hand, the piece of equipment most likely to have caused the battery drain is the microcassette. The ideal set-up would have the microcassette powered by a different set of batteries than the data logger, and the data stored both in RAM and on cassette.

4.0 COMMERCIAL PRODUCTS FOR FIELD USE

There is a wide variety of equipment that could be considered suitable for some field use. I have selected three companies´ products that illustrate the kinds of capabilities available. In addition, Teledyne Semiconductor has published plans for a minimal data logger that would be suitable for some applications, and I will briefly describe that system.

4.1 HEWLETT PACKARD´S 3421A

Hewlett Packard (1820 Embarcadero Road, Palo Alto, CA 94303) makes a data acquisition and control unit for field use, which they designate 3421A. The unit employs a dual slope A/D converter with a multiplexed input to allow it to monitor 10 channels at a time (expandable to a maximum of 56 channels), and can read DC volts from 300 V full-scale to 0.3 V full-scale, with 5 1/2 digit resolution. It will also read resistance from 30 Mohms down to 300 ohms full-scale with 5 1/2 digit resolution or AC volts from 30 V to 3 V full-scale with 4 1/2 digit precision. In addition, it has a frequency counter mode that will read from 1 Hz to 10 K Hz and has type T thermocouple linearization with a built-in reference junction.

The unit can only store 30 readings on-board, but may be controlled by an HP-41C or the more recent HP-75D portable computer via the HP-IL serial interface loop. The computer, of course, may store thousands of readings. The 3421A is CMOS and capable of receiving a sleep-mode instruction from the computer to prolong battery life. Thus, the 3421A for all intents and purposes needs the HP-41 or 75 to be usable.

There is a battery-powered cassette available, model number 82161A, with an HP-IL interface, which can be used for mass storage in conjunction with the 3421A and an HP portable computer. Alternatively, the 82162A battery-powered printer with HP-IL interface can be used. Each of these units uses its own battery pack.

The 3421A is rated for operation between 0 and 55 C, which is a bit narrow for field use in all seasons. Further restricting the range is the computer's operating temperature of 0 to 45 C. The cassette drive is limited to the expected 10-40 C, 20-80% humidity. However, the printer can be used from 0 to 45 C, and humidity is not a limiting consideration.

As is often the case with HP products, the 3421A is not inexpensive. The unit with an HP-75D controller sells for approximately $2400. Cassette or printer will add another $500 to $600 to the cost. Nonetheless, if winter conditions are not being monitored, the quality and reliability of Hewlett Packard equipment make this a system worthy of consideration.

4.2 ELEXOR DATA LOGGERS

Elexor Associates (P.O. Box 246, Morris Plains, NJ 07950 (201) 299-1615) offers two data loggers for environmental data acquisition. The first is the PL-1000. This unit is designed to be controlled by an external computer via its RS-232 port or by a program burned into EPROMs and placed on the system motherboard. The CPU is the 6303, a CMOS version of the 6800. The basic unit supports 16 12-bit-plus-sign dual-slope A/D converter inputs with a switch-selectable range of +/-4.095 V or +/-409.5 mV. There are 2 analog output lines, 16 lines each of digital input and output, and 2 expansion slots for additional A/D, D/D, or counter/timer boards if necessary. The unit is said to be suitable for solar-powered recharging with its onboard rechargable battery option. Alternatively, the unit can be powered by external batteries. There is not a sleep mode option. The operating temperature is reported to be 0 to 60 C, in essentially any noncondensing humidity. The basic unit sells for $899, with the built-in battery option adding $69 to that price.

The second offering is the PL-100, an I/O expansion box for use with the TRS Model 100 or 200 or the NEC PC-8201 portable computer. The unit has 3 expansion slots that can be outfitted with essentially the same acquisition boards as the PL-1000. The PL-100 configured for the same A/D capabilities as the PL-1000 basic unit is called the PL-100H, and retails for $719 (exclusive of computer). The cost/capability ratio of either unit make these systems worthy of a closer look if the temperature range is compatible with your needs.

4.3 TERRASCIENCE DATA LOGGERS

Terrascience Systems Ltd. (1574 West 2nd Ave., Vancouver, B.C., Canada V6J 1H2 (604) 734-3443. United States dealer: Instrumentation Northwest, Inc., P.O. Box 447, Kenmore, WA 98028 (206) 885-3729) makes two environmental monitoring systems. The first, called the Microscout, is about to be discontinued. The Microscout is a TRS 80 model 100 computer that has been specially modified for field use. The CPU has been changed to a CMOS 1802A with a 2 MHz clock rate. (Decreasing the system clock rate is the major requirement to expanding the temperature range of solid state devices. In cold temperatures, the propagation delay for the many gates in a solid-state chip increases, requiring more time for fault-free operation. In hot temperatures, the lower clock speed means that the device runs cooler, so less heat has to be dissipated and the temperature differential between the processor and the ambient conditions can be less. If you need to use a system in temperatures outside its rated range, try simply substituting a slower crystal in the system clock. If you are not using tape storage, that should be enough to expand the operating range.) The Microscout includes 8 channels of 10-bit successive approximation A/D, with user-selectable ranges of 0-5 V, 0-1 V, and 0-100 mV. The unit makes multiple readings of each channel and averages the readings to decrease noise. It does not use S/H circuitry. However, the thermal response coefficient of successive approximation converters will be above noise for any data that spans a temperature range of 20 C or more, so the Terrascience offerings should be calibrated for thermal bias before use. Nonetheless, the unit is capable of operating in essentially any weather conditions. The operating temperature range for the unit is -25 to 85 C. The Microscout is capable of sleep mode operation. Tape units are available, but should be used only in the appropriate weather conditions. The Microscout basic unit costs about $2000, Signal-conditioning firmware is available at extra cost.

The unit that is displacing the Microscout is the Terra 8, which is controlled by the NSC 800 CMOS CPU. The unit is designed to be programmed by an off-board computer via the RS-232 port (with a nonstandard connector on the Terra 8, unfortunately. However, cabling to your computer is supplied with each unit) or by burning the program into EPROMs that can reside on the mother board. There are audio cassette and parallel printer interfaces on the Terra 8, also with nonstandard connectors. The basic unit ($1250) supports only 1 successive approximation A/D channel, but is expandable to 32 channels. A reasonable 8-channel system runs about $2400. The voltage ranges selectable are 0 to 5 V, 0 to 100 mV, and 0 to 10 mV. The operating temperature range is -40 to 70 C. The unit is capable of sleep mode operation. The Terra 8 comes in two kinds of enclosures, the basic unit in extruded aluminum or the Terra 8/D, in an ABS cylindrical enclosure for placing in boreholes. This helps lessen interference from man or animal with the monitoring equipment, but the cylinder size effectively limits the number of A/D channels that can be used to four. There are solar power modules available from the company for extended field operation. The end-user support provided by Instrumentation Northwest is reputed to be supurb.

The Terrascience systems have been tested by Dr. Paul Whitfield and Norman Dalley of the Water Quality Branch of the Inland Water Directorate of Canada. While I cannot speak for them, of course, it is my understanding that they found the systems quite reliable. If you are considering the Terrascience data loggers, you would probably be well-advised to seek their expert guidance. They may be reached at the Water Quality Branch, Inland Water directorate, Pacific and Yukon Region, 502-1001 West Pender St., Vancouver, B.C., V6E 2M9 Canada.

4.4 TELEDYNE DATA LOGGER DESIGN

The final option I will present is not a commercial product at all. That is both its strength and its weakness. The bad news is that you will have to build it yourself. The good news is that the parts will cost less than $50 per unit, so if you need hundreds of them and are on a tight budget, this may be a very attractive option. Wes Freeman of Teledyne Semiconductor (1300 Terra Bella Avenue, Mountain View, CA 94043. (415) 968-9241) has designed a dedicated data logger using eight ICs. The unit is built around the Teledyne TSC7109 CMOS dual-slope 12-bit plus sign A/D converter. The TSC7109 includes an imbedded voltage reference, and can operate within 5 ppm/C precision. It is available in military grade (-55 to 125 C), industrial grade (-25 to 85 C) and commercial grade (0 to 70 C), so you can select the best operating conditions/ price tradeoff for your application.

The data logger is fully described, including circuit diagram, in Teledyne's application note 24, "TSC7109 Records Remote Data Automatically," by Wes Freeman (available from Teledyne's Literature department at the above address). Mr. Freeman's design is for a free-running unit with 2048 bytes of memory, that can be set in hardware to make conversions at regular intervals of up to 68 minutes. At a data rate of one conversion per hour, the unit could collect data for 7 weeks before overflowing its memory. The data is easily downloaded via the parallel port of any standard 8-bit computer, as is explained in the application note. Each unit is designed to read one and only one analog voltage source. This has both advantages and disadvantages. The main disadvantage is that the coordination of multiple analog sources' readings is more difficult. The main advantage is that there need not be long cable strung to various sensors, which can prove to be enticing to the local fauna.

Other pluses include: the unit can be powered by hearing aid batteries, so it can be recharged in the field by simply changing batteries. With built-in battery units, you may need two units per monitoring site -- one to monitor, and the other to recharge. By using a separate unit for each sensor, there is some built-in security from data loss. A catastrophic failure of one unit only loses data from one sensor. With the commercial units, the expense of the units requires you to service as many sensors as practical with a single data logger.

The minuses include: you have to build the unit yourself (or have it built). This is probably the single biggest hurdle for Mr. Freeman's approach. Second, the unit is hard-wired, and so it is inflexible. For example, it has no intelligence in the system to allow it to adjust its monitoring rate in response to changing weather conditions. Nonetheless, it is an interesting and very low-cost option for environmental monitoring.

5.0 CONCLUSION

The ideal environmental monitoring system is low-cost, insensitive to large temperature variations, provides back-up storage for data in the event of a power failure, has enough intelligence onboard to monitor what you want monitored under all possible conditions, and is easy to program. Unfortunately, it does not seem to exist. My hope is that at least one of the systems that I have discussed will be close enough to the ideal to be usable for your purposes. When you computerize your data acquisition, you will need a great deal of specific information to facilitate the process. To help your search for further information, I end with a listing of books and papers that I have found helpful in my computerization efforts.

ANNOTATED BIBLIOGRAPHY

[1] Analog-Digital Conversion Handbook, 3rd edition, by the engineering staff of Analog Devices, Inc. Daniel H. Sheingold, ed., Prentice-Hall, Englewood Cliffs, NJ, 1986.
Analog Devices is a superb company, filled with some of the best A/D engineers in the world. Anything that they have to say is worth reading, and this collection of papers is generally readable and of use to end-users.

[2] "Applications of the AD537 IC Voltage-to-Frequency Converter" by Barrie Gilbert and Doug Grant, Analog Devices Application Note, Analog Devices, Route 1 Industrial Park, P.O. Box 280, Norwood, MA.
A detailed look at V/F converters, how they work, and various applications for them.

[3] "A Calibration Service for Analog-to-Digital and Digital-to-Analog Converters," NBS Technical Note 1145, T.M. Souders, D.R. Flach, and B.A. Bell, U.S. Department of Commerce, National Bureau of Standards, U.S. Government Printing Office, Washington, D.C., July 1981.
The NBS provides a calibration service for A/D boards which is described in this technical note. The booklet can be used to develop your own testing procedures, but NBS standards of evaluation are probably excessive for a field unit.

[4] "Correcting Errors Digitally in Data Acquisition and Control" Burr-Brown Application Note 101, Burr-Brown, P.O. Box 11400, Tuscon, AZ
How to use a microprocessor to compensate for thermal bias.

[5] Digital Interfacing with an Analog World by Joseph J. Carr, Tab Books, Blue Ridge Summit, PA, 1978.
Mr. Carr has written a number of books for Tab on A/D. They are all informative and accessible. This one is as good as any of them.

[6] Electronic Design with Off-the-shelf Integrated Circuits by Z.H. Meiksin and Phillip C. Thackray, Parker Publishing Company, West Nyack, NY, 1980.
This is a tremendous source of practical information if you are going to be building data loggers, filters, or preamplifiers.

[7] "Getting Transducers to ´Talk´ to Digital Computers" Burr-Brown Application Note 91, Burr-Brown, P.O. Box 11400, Tuscon, AZ
Matching your A/D converter to your transducers.

[8] Handbook of Digital System Design for Scientists and Engineers by Wen C. Lin, CRC Press, Boca Raton, FL, 1981.
This is an excellent handbook on digital components of data acquisition systems. The focus of the book is on components, not systems.

[9] The HP-IL System by Gerry Kane, Steve Harper, and David Ushijima, Osborne/McGraw-Hill, Berkeley, CA, 1982.
A rather thorough examination of the HP-IL interface by three HP engineers. This is the only such book I have ever encountered, so if you´re going to work with the 3421A, make every effort to obtain a copy.

[10] The IBM PC/XT: Making the Right Connections by Martin D. Seyer, Prentice-Hall, Englewood, NJ, 1985.
The title of this book has not got a lot to do with its content. It is mostly a discussion of the Centronics port and the many ways of wiring up an RS-232 port. If you will be working with either of these ports on any computer, this book is a good investment.

[11] "The Integrating A/D Converter" by Lee Evans, Datel Application Note, Datel Corporation, 11 Cabot Boulevard, Mansfield, MA
A discussion of the way integrating A/Ds work and the kinds of errors to which they are succeptable.

[12] Intelligent Instrumentation by George C. Barney, Prentice-Hall International, London, 1985.
An overview of data acquisition from sensor to software. The book devotes a fair amount of time to sensors and provides at least an introduction to every aspect of computerized data acquisition.

[13] "Principles of Data Acquisition and Conversion" Burr-Brown Application Note 79, Burr-Brown, P.O. Box 11400, Tuscon, AZ
A short overview of data acquisition parameters by a major manufacturer of A/D devices.

[14] "Principles of Data Acquisition and Conversion" by Eugene L. Zuch, Datel Application Note, Datel Corporation, 11 Cabot Boulevard, Mansfield, MA
An overview of A/D from another major manufacturer of A/D devices.

[15] "Selecting A/D Converters" by Dave Fullager, Datel Application Note, Datel Corporation, 11 Cabot Boulevard, Mansfield, MA
An engineer´s view of the strengths and weaknesses of different kinds of A/D converters.

[16] "TCS7109 Records Remote Data Automatically" by Wes Freeman, Teledyne Application Note 24, Teledyne Semiconductor, 1300 Terra Bella Ave., Mountain View, CA
How to make and use the data logger discussed in section 4.4 of this paper.

[17] "Testing of Analog-to-Digital Converters" Burr-Brown Application Note 100, Burr-Brown, P.O. Box 11400, Tuscon, AZ
Calibrating an A/D with a digital multimeter.

[18] Transducers for Microprocessor Systems by J.C. Cluley, Springer-Verlag, New York, NY, 1985.
A survey of sensor technology that gives a good basic introduction into the strengths and limitations of different alternatives.